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1 Gradually increasing forest fire activity during the Holocene in the
2 northern Ural region (Komi Republic, Russia)

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18 **Abstract**

19 In many boreal regions of Russia the past natural variability of forest fire activity remains largely
20 undocumented, preventing accurate assessment of the impact of current climate warming on forest
21 ecosystem dynamics. This study aims to reconstruct the Holocene fire history of the northern Ural
22 mountain foothills, in the Komi Republic, based on analyses of charcoal particles from peatland deposits
23 and coupled with dendrochronological investigations. The results shows that there was a gradual
24 increase in forest fire activity during the last 11 000 years. Between 11000 and 5100 cal. yr BP, the
25 mean Fire Return Interval (FRI) oscillated between 600 to 200 years. During this period, regional data
26 showed that cold temperature, humid climatic conditions, combined with steppe vegetation between
27 11000-9000 cal. BP, and then the development of spruce-dominated forest between 9300-4600 cal. yr
28 BP, were less conducive to fires. After 5100 cal. yr BP, a gradual increase in drought conditions through
29 reduced precipitations, associated with the establishment of a Scots pine forest favored fire frequency,
30 with a mean FRI under 200 years (range 200 to 40 years). Nowadays (since CE 1500), human activity
31 induces an unprecedented fire activity with a mean FRI below to 100 years (range 100 to 40 years).

32 **Keywords:** Boreal Forest ; Peatland ; Charcoal particles ; Dendrochronology ; Tree-rings ;
33 Wildfires

34 **1 Introduction**

35 The northern boreal forest represents almost 30% of the world's forested areas and contains the largest
36 reservoir of terrestrial carbon stored in soil and peatlands (Gorham, 1991; Sheng et al., 2004). Boreal
37 forest dynamics have an impact on the carbon composition of the atmosphere and global climate
38 dynamics (Foley et al., 1994; Kasischke and Stocks, 2012).

39 Fire is the main natural disturbance in this biome, impacting the diversity, composition and structure of
40 the forest. Projected climate warming may therefore increase fire activity through extension of the fire
41 season and drought severity (Flannigan et al., 2009; Bergeron et al., 2011). Current global warming may
42 also increase net biomass production (Flannigan et al., 2009) and forest fuel, creating more favorable
43 conditions for fire activity (Gauthier and Vaillancourt, 2008; Flannigan et al., 2009). In the boreal zone,
44 fire is an important environmental and socio-economic issue for governments (Conard and Ivanova,
45 1997; Weber and Flannigan, 1997; Stocks et al., 1998; Randerson et al., 2006; Soja et al., 2007; Stocker,
46 2014). For example, in Canada, fire suppression policy expenditure and costs have been increasing since
47 the 1970s (Stocks and Martell, 2016) and, based on current projections, will continue to increase.

48 The impacts of fire on boreal forest vegetation depend on different variables that define the fire regime,
49 *i e* its frequency, severity and intensity. (Keeley, 2009). In North American boreal forests, wildfires are
50 generally crown fires (Kasischke and Stocks, 2012; de Groot et al., 2013; Stocks and Martell, 2016),
51 destroying stand canopy and leading to a total renewal of pre-fire cohorts. In contrast, in the Eurasian
52 boreal forest, a mixed severity fire regime dominates, with a considerable proportion being surface fires
53 (Goldammer and Furyaev, 1996). Across this eco-zone, NOAA-AVHRR satellite data have shown an
54 increase in burned areas, with an annual average of 9.3 million hectares for the period 1996–2005
55 (Goldammer, 2015), and the number of fires has varied between 10000 and 30000 per year (Gauthier
56 and Vaillancourt, 2008).

57 To better understand the mechanisms that link climate, vegetation and fire, particularly under the yoke
58 of climate change, it is important to characterize the natural range of variability of fire events over time.
59 For this, paleoecological investigations are needed to provide a better understanding of fire activity and

60 interactions with both climatic oscillations and human activity (Randerson et al., 2006; Whitlock et al.,
61 2010; Clear et al., 2014). According to our knowledge such data is not available for the northern Ural
62 Mountains foothills, preventing the accurate assessment of the impact of current climate change on fire
63 frequency.

64 Here we reconstruct Holocene fire frequency for the north-western foothills of the Ural Mountains, in
65 the Komi Republic based on charcoal particles sequestered in two peatlands coupled with
66 dendrochronological investigations. Our goal is to give an overview of the fire frequency changes
67 during the Holocene in the study zone, and then to indicate the first lines of thought to understand the
68 mechanisms underlying fire activity, which is intrinsically linked to the dynamic of vegetation, climate
69 and human activities. We hypothesized that periods with dry climatic conditions (either with warm or
70 cold temperatures) would be more conducive to fires compared with cold and/or wet periods (either with
71 warm or cold temperatures). For example, in Québec, in Alaska and in Scandinavian boreal forests
72 (Higuera et al., 2009; Ali et al., 2012; Girardin et al., 2013; Blarquez et al., 2015; Drobyshev et al.,
73 2015), results showed a warm and dry period favorable for fires before 4000 cal. (calibrated) yr (years)
74 BP (before present), followed by colder and wetter conditions less favorable to fire activity. The same
75 pattern has been recorded in Fennoscandia (Clear et al., 2014; Drobyshev et al., 2016). In the study zone,
76 we suspect greater fire activity at the end of the Holocene, when the human population increased and its
77 impact on forest fires became more significant (Naryshkin et al., 1999; Drobyshev et al. 2004).

78 **2 Methods**

79 *2.1 The study area*

80 The Komi Republic (415 900 km²) is situated between 59°12' and 68°25'N and between 45°25' and
81 66°10'E (Figure 1). The mean annual temperature varies between -6°C and +1°C from south to north,
82 and the annual precipitation varies between 450 and 700 mm (Drobyshev et al., 2004). Moraine and
83 surface loams (Zaboeva, 1997; Drobyshev et al., 2004) with podzolic soils (Naryshkin, 2003) dominate
84 in the region. There is discontinuous permafrost (Christensen and Kuhry, 2000). The majority of the
85 relief is flat, except near the Ural Mountains (Naryshkin, 2003). Light taiga forests are observed in the

86 Komi Republic, mainly composed of Scots pine (*Pinus sylvestris*), birch (*Betula pendula* and *Betula*
87 *pubescens*) and spruce (*Picea abies* s.l.).

88 The Komi Republic was only sparsely inhabited during the Holocene until about 1500 CE (Common
89 Era). Before this time there was likely no human activity in this area. After that, human population
90 density increased significantly from 20000 inhabitants in the 16th century to more than 1.12 million
91 inhabitants at the beginning of the 21st century (Drobyshev et al., 2004; Klein Goldewijk et al., 2011). The
92 population density is less than two people/km², and for the study area, it is less than one person
93 people/km². The nearest settlements to the sampling points are Timsher and Lopyuvad, which were
94 created in 1932 (<http://timsher.selakomi.ru/>).

95 2.2 *The study sites*

96 The Ural region is divided into sub-regions based on topography, from north to south: the polar Ural,
97 pre-polar Ural and northern Ural regions. The study sites named Yak1_dendro, Yak2 and Yak3
98 (unofficial names) are located in the northern Ural region, 200 km east of Syktyvkar (Figure 1; Figure
99 A 3; Table 1). They correspond to forested peatland with *Pinus sylvestris* and *Betula pubescens* stands
100 (Figure 1, Figure A 3). Because cores from the same peatland area can record different fire histories
101 (van Bellen et al., 2012), we developed a multi-site approach in order to provide a more holistic view of
102 the fire history (van Bellen et al., 2012). Yak1_dendro was peatland around which only
103 dendrochronology sampling was carried out, and no peat coring took place. A few kilometers away (14
104 and 19 km, respectively), the two other peatlands, Yak2 and Yak3, were cored. Two different cores were
105 collected from site Yak2: core Yak2-A at the center and core Yak2-B at the periphery level, 270 m from
106 core Yak2-A. Similarly, Yak3 provided 2 other cores: Yak3-A in the center and Yak3-B at periphery
107 level) (Figure 1; Table 1), separated by about 250 meters. The cores were taken using an 8-cm diameter
108 Russian peat corer.

109 2.3 *Dating and chronologies of the peat cores*

110 For each core, the chronology was based on five to seven radiocarbon measurements taken from charcoal
111 particles, plant macroremains and bulk peat sediments, when sufficient macro-remains were not

112 available (Table 2). The charcoal sample was used for the Yak2-A site and allowed the oldest dating of
113 this core. Significant differences in dates may appear between the different materials. Especially with
114 regard to charcoal particles, which could come from old trees (more than 200 years old) and therefore
115 have an "in-built age" effect (Oswald et al., 2005). However, in the case of peatlands and macrocharcoal,
116 the timelapse due to migration in the peat recording is probably very small (unlike what sometimes
117 happen in lakes (Oswald et al., 2005)). Whenever possible, we used macro-remains. When this was not
118 possible, we used peat sediment samples directly from organic gyttja. The use of this panel of material
119 for ^{14}C dating has been realized in many studies in boreal regions (Ali et al., 2009a; van Bellen et al.,
120 2012; Ouarmim et al., 2014). The radiocarbon dates were calibrated using the R package CLAM 2.2
121 (Blaauw, 2010), IntCal13 was used for the calibration curve (Reimer et al., 2013), and the NH1 post-
122 bomb calibration curve was used for modern radiocarbon (Hua et al., 2013). A smooth spline function
123 was used to fit the four age models (Blaauw, 2010) with a 0.95 confidence interval.

124 2.4 *From charcoal particles to fire frequency reconstruction*

125 In the laboratory, each peat sequence was divided into 0.5-cm slices. A 1-cm³ subsample was then taken
126 from the center of each slice. These subsamples were soaked in 25 ml bleach with 3 g NaPO₃ and 0.5 g
127 KOH, for at least 24 h on an agitator (Carcaillet et al., 2001). Then the material was gently rinsed through
128 a 160- μm sieve. Commonly, in boreal zone affected by crown and severe wildfires a bigger sieve is used
129 (> 300 μm) to collect charcoal particles from peat deposits, notably to infer *in situ* fire events (van Bellen
130 et al. 2012; Adolf et al. 2018). In our case, with surface fires and expected low concentration of charcoal
131 into sediments, we securely used a 160 μm even if long distance transportation of charcoal particles
132 could have been occurred (Oris et al., 2014). Nevertheless, several studies conducted in lake sediment
133 deposits have shown that this charcoal particle size was mostly associated to local fire events, between
134 0-1km from the coring point (Higuera et al., 2007; Ali et al., 2009a; Oris et al., 2014).

135 The charcoal particles were counted and measured under a 20 \times stereo microscope and equipped with a
136 digital camera connected to an image-analysis software system (WinSEEDLETM software; Regent
137 Instruments Inc., <http://regent.qc.ca/>). We used the area measurement, notably in regard to Ali *et al.*,
138 (2009) which concluded that area or count measurements display comparable fire history if locally-

139 defined threshold is used to infer fire events. Charcoal measurements are reported as charcoal
140 accumulation rates (CHAR, $\text{mm}^2 \text{cm}^{-2} \text{yr}^{-1}$) based on numerical age/depth models.

141 To linearize the results because of varying sedimentation rates, individual CHAR series were
142 interpolated using a constant time resolution corresponding to the median sample resolution of each peat
143 sequence (Higuera et al., 2011). Statistical analyses were performed using the CharAnalysis program
144 (Higuera et al., 2009), <http://CharAnalysis.googlepages.com>), following the method used by Brossier et
145 al. (2014). The CHAR series comprise low-frequency (background; $C_{\text{background}}$) and peak (or residual
146 series; C_{peak}) components. We estimated $C_{\text{background}}$ with a robust Lowess using a 300–500 years window
147 width, corresponding to the most suitable window for which signal-to-noise Index (SNI, signal strength
148 relative to accompanying noise) was the best (cutoff value of SNI = 3) (Kelly et al., 2011; Brossier et
149 al., 2014). C_{peak} values were obtained by subtracting $C_{\text{background}}$ from $C_{\text{interpolated}}$, which corresponded with
150 a resampled record of the CHAR series. We then divided the C_{peak} series into two subpopulations: (i)
151 noise, which represented variability in sediment mixing, sampling and noise induced by numerical
152 analyses; and (ii) fire events (C_{fire}), representing fires occurring 0–1 km from the peat core sites (Lynch
153 et al., 2004a; Higuera et al., 2007). For each sample, we used a Gaussian mixture model to identify the
154 noise distribution, with a 99th percentile threshold for separating samples into fire and non-fire events
155 (Higuera et al., 2007). The fire return interval (hereafter FRI) values, which corresponded to the time-
156 span between two consecutive fire events, were obtained from the raw C_{fire} series. A Kernel density
157 function (Mudelsee et al., 2004) was used to compute a temporally smoothed FRI. All analysis were
158 conducted using the softwares taust (Mudelsee, 2002), kernel (Gasser and Müller, 1979, 1984) and
159 redfit (Schulz and Mudelsee, 2002). The mean FRI (hereafter mFRI) was determined to reconstruct fire
160 history at regional spatial scale (Gavin et al., 2006; Courtney Mustaphi and Pisaric, 2013). The mFRI
161 was made on the basis of pooled FRI for all peat sequences, and the 90% confidence intervals were
162 calculated from the true distribution of the 1000 resampled FRI series, and are presented for a 300-year
163 bandwidth. Significance between each millennia was also assessed using box-plot analysis and
164 Wilcoxon rank sum test.

165 2.5 *Tree-ring records of fire history*

166 To establish a master chronology, we sampled tree-rings from trees that did not show fire scars, around
167 the Yak1_dendro, Yak2 and Yak3 sites (Table A 1). Then, to evaluate the fire activity from tree rings,
168 we sampled trees that had at least one fire scar. Within each site, the sampling took place within 200 m
169 of the peatland shores (Brossier et al., 2014). A partial cross-section was taken as close to the root collar
170 as possible, to date the establishment of the fire scars (Arno and Sneek, 1977). We sampled 14 cross-
171 sections from dead and living pine wood (*Pinus sylvestris*) at Yak1_dendro, 18 from Yak2 and 34 from
172 Yak3. For each sampled tree, the diameter at breast height, spatial coordinates and orientation of the
173 scars were recorded. The preparation and analysis of the samples followed standard methods (Cook and
174 Kariukstis, 1990). The cross-sections were allowed to dry for several days, and sanded using a
175 progression of sandpaper grits from P80 to P600 (Schweingruber et al., 1988; Brossier et al., 2014).

176 Tree-ring analysis was carried out using a binocular microscope (Leica M80) according to standard
177 dendrochronological methods (Niklasson et al., 2010; Stokes and Smiley, 1968). Pointer years (narrow,
178 wide, incomplete growth rings, fire scars) were identified visually and used for cross-dating on living
179 trees (Schweingruber et al., 1990). Tree-ring widths were measured along two radii using LINTAB 6.
180 For dead trees, the tree-rings were counted and measured along two radii. Cross-dating was achieved
181 using TSAPWin 4.80 software (Rinn, 2012). The same software was used for verification of cross-
182 dating accuracy. For all scars, the calendar date was recorded. A fire event was validated when at least
183 three trees had a fire scar dated to the same year.

184 **3 Results**

185 3.1 *Age models and chronologies*

186 The peat cores measured 168.5 cm from Yak2-A, 171.5 cm from Yak2-B, 350 cm from Yak3-A and
187 187.5 cm from Yak3-B. For Yak-2A the date 7605 yr BP (Table 2) was rejected by the best-fit age-
188 depth model reflecting the sedimentation pattern (Blaauw, 2010). Based on the different age models
189 (Figure 2), the Yak2-A core covers almost the entire Holocene period, from 11015 to -58 cal. yr BP,

190 with a mean temporal resolution of approximately 65 yr cm^{-1} (standard deviation ~ 29 years). The Yak2-
191 B core represented the last 9750 years, with a mean temporal rate of 57 yr cm^{-1} (standard deviation ~ 24
192 years). Yak3-A and Yak3-B represented the mid-Holocene to the present day, 6000 and 4619 cal. yr BP
193 to 0 and -65 cal. yr BP, respectively. The Yak3-B core had a mean temporal resolution of approximately
194 25 yr cm^{-1} (standard deviation = 11 years), and Yak3-A 19 yr cm^{-1} (standard deviation ~ 10 years).
195 Therefore the Yak3-A and Yak3-B sequences displayed a finer time resolution from the mid-Holocene
196 to the present day, compared with the other sequences.

197 3.2 *Fire history*

198 3.2.1 *Charcoal data*

199 The charcoal analysis from Yak2-A indicated that the FRI fluctuated at around 500 years (median value
200 387 years) from 11000 to 8000 cal. yr BP (Figure 3), then decreased rapidly until 7000 cal. yr BP, when
201 values oscillated around 250 years. The FRI then remained stable before decreasing again after 1000
202 cal. yr BP to the present day, with values falling to about 100 years (Figure 3). Yak2-B showed a
203 different trend, with a slight increase in FRI during the Holocene, starting at around 200 years from 9000
204 cal. yr BP and reaching values close to 300 years at 450 cal. yr BP (Figure 3).

205 For Yak3-B, the FRI fluctuated around 130 years between 4500 and 900 cal. yr BP, then reach values
206 close to 95 years at present (Figure 3). For Yak3-A, there was a sharp decrease in FRI between 6000
207 and 4000 cal. yr BP, dropping from 200 to 70 years.

208 These results indicate a spatial variability in the fire records, inferred from very close sequences. Despite
209 this variability, the pooled reconstruction (mFRI) displayed a consistent decrease in FRI over the last
210 10000 years (Figure 4). Between 11000 and 5100 cal. BP, the mFRI was above 200 years (range 600 to
211 200 years). After 5100 cal. BP (excepted for 1000 cal. BP), a gradual increase in fire frequency was
212 recorded, with mean FRI reaching values below 200 years (range 200 to 40 years). Nowadays (since CE
213 1500), a fire activity with a mean FRI below 100 years was recorded. However, before 6000 cal. yr BP
214 only Yak2-A and Yak2-B contributed to the reconstruction of the mFRI; for the period from 4500 cal.
215 yr BP to the present day, the mFRI was based on all sequences. The CHAR outputs for each sequence

216 are presented in the Appendix (Figure A 1). Limiting the analysis to 4600–0 cal. yr BP, which included
217 the four chronosequences, confirmed a trend of decreasing FRI (Figure A 2).

218 *3.2.2 Dendrochronology data*

219 In total, we dated 122 fire scars from live and dead pine woods within the three sites (Figure 5). The six
220 main fires (present on at least on three trees) were dated to 1791, 1851, 1861, 1868, 1917 and 1936 yr
221 CE (Figure 5). Fire events in 1791, 1851 and 1917 yr CE were detected at Yak2. Fire events in 1861
222 and 1936 yr CE were common across the three sites. A fire event in 1868 yr CE was common to
223 Yak1_dendro and Yak3. At Yak1_dendro, the fires in 1861, 1868 and 1936 yr CE provided a mean FRI
224 of 37 years. At Yak2, the fires in 1791, 1851, 1861, 1917 and 1936 yr CE provided a mean FRI of 36
225 years. At Yak3, the fires in 1861 and 1936 yr CE provided a 75-year FRI (Table 3).

226

227 **4 Discussion**

228 *4.1 Spatial variability in fire activity*

229 Yak2-A, Yak3-A and Yak3-B showed a decrease in FRI during the Holocene, while Yak2-B showed a
230 slight increase. This discrepancy demonstrates the importance of conducting multi-site analyses in order
231 to have a synthetic view of fire history at local spatial scale. However, such differences in fire history
232 from the same peat deposit are not surprising, and have been observed in several regions dominated by
233 boreal forests (van Bellen et al., 2012). In eastern Karelia, Kuosmanen et al. (2014), also showed
234 differences in fire activity across the Holocene at local spatial scale: three sites were analysed, separated
235 by 800m and 70km. Yet the three sites have a completely different fire history. Other studies in boreal
236 zone have shown that there may be significant differences between fire histories at a local scale (Gavin
237 et al., 2006; Ohlson et al., 2011; Genries et al., 2012). There are several possible explanations for this.
238 Firstly, within a peatland, local humidity can have high spatial variability (Zoltai et al., 1998; Hellberg
239 et al., 2004; van Bellen et al., 2012). This explains that some areas of the peatland can be wet while
240 others are dry. This can in turn lead to high spatial variability in fire propagation (Zoltai et al., 1998).

241 Secondly, peatland vegetation can have a strong impact on the spread of fire, in particular the presence
242 and distribution of shrubs and trees within the peatland (Camill et al., 2009). Thirdly, fires in the Russian
243 boreal forests are mainly surface fires (Soja et al., 2007; Gauthier and Vaillancourt, 2008), and such
244 fires tend to be scattered and burn forest litter, shrubs and the bases of trunks (Zoltai et al., 1998).

245 The dendrochronological fire reconstruction also revealed differences within and between the three sites.
246 The Yaksha River separates the sites, thus providing a natural barrier to the spread of fire from
247 Yak1_dendro to Yak2 and Yak2 to Yak3. Some fires were recorded at all three sites (such as in 1861
248 and 1936) and some only at two sites (such as in 1868). Finally, three fires were found only on one site
249 (1791, 1851 and 1917). Within each site, fires have affected some trees and not others. This could mean
250 that a fire has occurred within the site but has not burned its entire surface, which is possible due to wind
251 conditions and local topography (Schweingruber et al., 1988; Kulakowski and Veblen, 2002; van Bellen
252 et al., 2012). These results again underline the fact that using a multi-site approach and different proxies
253 are necessary to obtain an overview of fire activity than using only one site and only one core (Rius et
254 al., 2011).

255 In order to provide an overall view of the FRIs from our study area, we pooled the four cores using a
256 Kernel density function (Figure 4), which took into account inter-site variability and provided a
257 confidence interval for evaluating whether the observed trends were significant (Mudelsee et al., 2004).
258 Fire activity from before 6000 cal. yr BP was only determined with results from the two cores Yak2-A
259 and Yak2-B. Additional sites need to be studied to provide a more detailed view of fire activity for this
260 period. However, it is clear that during the first half of the Holocene fire activity was much lower than
261 after 5000 cal. yr BP, and a generally decreasing trend in mFRI was recorded over the Holocene. The
262 mFRI decreased from almost 600 years at *c. (circa)* 10000 cal. yr BP to less than 100 years at present
263 (Figure 4). The boxplots highlight the progressive decrease in mFRI and the Wilcoxon test showed that
264 the decrease is significant each millennium ($p\text{-value} = 5.723e-06$).

265 Fire scars on a tree trunk and trapped charcoal in sedimentary deposits are both different indicators of a
266 fire event. A charcoal peak identified from sedimentary CHAR series can come from one or more fires,
267 with a spatial scale of about 0 to 1 km (Higuera et al., 2007) but nevertheless mild to low severity fires,

268 as surface fires generally are, may be more difficult to detect in sediment records, while a fire event
269 dated by dendrochronology represents only one fire at the spatial scale of the tree and is more accurate
270 (Higuera et al., 2005; Brossier et al., 2014; Oris et al., 2014). Spatial variability is greater with charcoal
271 proxies than with dendrochronology. The complementary use of these two proxies allows fire events to
272 be detected more clearly, as shown in Brossier et al. (2014), and Waito et al. (Waito et al., 2018), around
273 lakes in Canadian boreal forest. In our study, FRI values from charcoal series, oscillating between 100
274 and 40 years for the last 300 years, are of the same order of magnitude as dendrochronological analyses,
275 which provided FRI values of less than 100 years at all three sites. The present-day mFRI determined
276 by both the charcoal and dendrochronological analyses is by far the lowest recorded over the last 10000
277 years from our study area.

278 It is possible that at the local level, fire dynamics are not linked to the climatic driver because
279 of the topographic, vegetation and soil variables that may be more important at these scales. Studies by
280 Kuosmanen et al. (2014 and 2016), on fire-vegetation interactions at the local scale, based on the study
281 of three hollows in Karelia (west of the Komi Republic) did not show strong links between fire dynamics
282 (which differed from one site to another) and climate or vegetation during the Holocene. However, it
283 may be interesting to discuss the overall decline of the FRI in our study site. Climate, vegetation and
284 human activity factors are, initially, the three tracks that can be explored (Johnson, 1992; Swetnam,
285 1993; Gauthier and Vaillancourt, 2008; Power et al., 2008; Flannigan et al., 2009). An increase in fire
286 activity during the Holocene has also been observed for northern extratropics (Figure 6A) (Marlon et
287 al., 2016), Sweden from 4000 cal. yr BP (Figure 6B) (Drobyshev et al., 2016) and all of Fennoscandia
288 and Denmark (Figure 6C) (Clear et al., 2014.). It is important to keep in mind that, the decrease in mFRI
289 in our study corresponds with an increase in the influx of charcoal in others.

290 4.2 *Climatic imprint*

291 Trends in fire activity may be related to climate change, as shown by Marlon et al. (2016) (Figure 6A)
292 which associated their results showing an overall increase in fire activity across the Northern
293 Hemisphere with an increase in temperature, carbon dioxide concentration and biomass for the Northern
294 Hemisphere. In the same way, Drobyshev et al. (2016) showed that the increase in fires in Sweden was

295 related to cold and dry climatic conditions, which resulted from a decrease in the surface temperature of
296 the Atlantic Ocean redirecting the activity of the prevailing westerly winds. Climatic reconstructions
297 inferred from pollen, plant macrofossils, cladocera, chironomids and diatoms are available from North
298 America and Arctic Canada (Ritchie et al., 1993; Gajewski, 2015; Bajolle et al., 2018), in the pre-polar
299 region 380 km to the north of our study area (Kultti et al., 2003) and the polar Ural region 700–800 km
300 to the north of our study area (Andreev et al., 2005; Salonen et al., 2011). In North America and Arctic
301 Canada, an early Holocene thermal maximum (from about 8000 cal. yr BP to 5000 cal. yr BP) is
302 evidenced with summer temperatures at least 2° warmer than today (Axford et al., 2009; Viau and
303 Gajewski, 2009). In the pre-polar and polar Ural regions, the climate was probably moist and warm
304 (summer temperatures *c.* 4°C warmer than today) between 8000 and 4500 BP (Kultti et al., 2003). In
305 Arctic Fennoscandia, the influence of the Atlantic Ocean induced mostly colder climatic conditions
306 during the early Holocene (Kullman and Kjällgren, 2000; Korhola et al., 2002; Seppä and Birks, 2002),
307 while warmer conditions persisted in northern Russia and northern Europe (Tarasov et al., 2009; Elina
308 et al., 2010; Mauri et al., 2015). After 4500 cal. yr BP, a gradual decrease in temperature occurred across
309 most Arctic and boreal regions, corresponding to the Neoglacial period (4500-3000 cal. yr BP) in North
310 America (Barber et al., 1999; Viau and Gajewski, 2009) and including the Little Ice Age (*c.* AD 1400).
311 These climatic oscillations are notably associated with a gradual decrease in summer insolation (Berger
312 and Loutre, 1991), (Figure 6E). Closer to our sites, the study of the Vychegda River Basin (about 200
313 km west of our study area) by Sidorchuk et al. (2001) based on palynological analysis showed that onset
314 of the Holocene, from 10000 cal. yr BP to 6000 cal. yr BP, climatic conditions were very continental,
315 with temperatures much colder than today (-3.5°C to -2.5°C in January and -0.5°C in July). The climate
316 was also wetter than today from 10000 cal. yr BP to 8400 cal. yr BP (more than 150 mm), then drier
317 from 8400 cal. yr BP to 6000 cal. yr BP (-50 mm). From 6000 cal. yr BP to 0 ka, climate conditions
318 were warmed, in summer first (up to + 2 ° C compared to today) and then in winter (+ 1 ° C). The
319 precipitation weakly increased, especially in winter. In regard to the regional climate dynamic one can
320 assume that the study zone, the low fire activity recorded between 10 000 and 6000 cal. yr BP, could be
321 due to conditions (cold and wet) less conducive to fire compared to after, with the gradual establishment
322 of warmer conditions favorable to fire activity. However, the increase in humidity could have favored

323 lightning (Lynch et al., 2004b; Veraverbeke et al., 2017), which is a natural cause of ignition source and
324 increased the observed fire activity between 10000 and 8400 cal. yr BP (FRI increasing from more than
325 500 cal. yr BP to about 300 cal. yr BP). From 6000 cal. yr BP, the warmer temperatures, linked to
326 slightly more humid conditions, were also favorable for fuel built (Amiro et al., 2001; Veraverbeke et
327 al., 2017) and could explain the increase of fire activity recorded increase in fire activity observed.
328 Climate can have a direct influence on fire activity, but also an indirect influence through vegetation
329 dynamics (Higuera et al., 2008, 2009; Girardin et al., 2013; Goldammer, 2015).

330 4.3 *Vegetation interactions*

331 In boreal forest ecosystems, the vegetation composition is also related to the fire regime (Goldammer
332 and Furyaev, 1996; Girardin et al., 2013). Over time, the climate can have an initial impact on the
333 composition of the vegetation by promoting the development of some species under optimal conditions
334 of temperature and humidity but preventing the development of some others (Higuera et al., 2009). This
335 vegetation can then have an influence on fire activity for example, because of the soil moisture, the
336 vulnerability of the lower branches (Goldammer and Furyaev, 1996; Girardin et al., 2013). During the
337 early Holocene, around 10,000 cal. yr BP, a periglacial steppe forest system was present in the Vychegda
338 River basin, less conducive to the spread of fires (Golubeva, 2008; Sidorchuk et al., 2001). This is in
339 accordance with high FRI recorded at this time in Yaksha (more than 500 years). From 9300 cal. yr BP,
340 spruce forests and hardwood (*Corylus* sp., *Ulmus* sp. and *Tilia* sp.) emerged, thanks to the warming of
341 the climate and the increase in humidity (Sidorchuk et al., 2001; Giesecke and Bennett, 2004; Golubeva,
342 2008). At this time, FRI values (from about 280 years to 350 years) could favor species with low fire
343 tolerance, such as spruce (Goldammer and Furyaev, 1996). From 8000 to 4600 cal. yr BP, where FRI
344 decreased until 200 years, the spruce forest developed, but other species (pines, birches, firs and larches)
345 also increased (Golubeva, 2008). The increase in fire activity has favored the emergence of tolerant and
346 pioneering species, such as birches and pines (Goldammer and Furyaev, 1996), As well as the drier
347 climate, for which pines are well adapted (Kullman, 1986). From 4600 to 2500 cal. yr BP, these spruce
348 forests were progressively replaced by the light taiga, composed of pine forests (*Pinus sylvestris*), in
349 association with birches (*Betula* sp.), in line with the increase in temperatures (Goldammer and Furyaev,

350 1996; Golubeva, 2008). Both species are fire-resistant (Goldammer and Furyaev, 1996), which is
351 coherent with the FRI recorded at this time (around 150 years). Since 2500 cal. yr BP, Golubeva (2008)
352 documents the interruption of the light taiga by a phase of dark taiga between 1800 and 800 cal. yr BP,
353 which is associated with a slight increase in temperatures and called the small climate optimum
354 (Golubeva, 2008). At this time, FRI values increased around 200 years, reflecting the lower fire
355 tolerance for these species (Goldammer and Furyaev, 1996) From 800 cal yr BP, the FRI decreased
356 again to values around 50 years, which allowed the establishment of a light coniferous forest, composed
357 mainly of pyrophytes such as *Betula sp.* and *Pinus sylvestris*, is compatible with low FRI (Sannikov and
358 Goldammer, 1996; Hille and Den Ouden, 2004; de Groot et al., 2013) with FRI values recorded < 200
359 years. In this frame of natural and ecological dynamics link climate, vegetation and fire, human became
360 more and more present in the study zone in the recent time.

361

362 4.4 *Human impact*

363 From the 10th century (around 800 cal. yr BP) to the end of the 19th century (around 1700 cal. yr BP),
364 slash-and-burn agriculture was dominant in the Republic of Komi and other parts of Europe. The fire
365 dynamics was obviously influenced by human being. Then, at the end of the 19th century, slash-and-
366 burn agriculture was banned (Petrov, 1968), but farmers continued to practice it, without control
367 increasing the probability of fires (Chernyakova, 2013). Archaeological data indicate that the first
368 settlements in the territory date back 32-35 thousand years on the Pechora River (Taskaev, 2006). Then,
369 the colonies also settled along large rivers. Most of the Republic's territory was practically undeveloped.
370 In addition, the study area is directly adjacent to the UNESCO monument "Komi Virgin Forests". As a
371 result, the region has hardly suffered any human influence (Taskaev, 2006). Although the region was
372 sparsely populated at the beginning of the Holocene, the decline in FRI observed from 10000 to 9000
373 cal. yr BP (FRI around 500 years, decreased to less than 300 years), the Komi Republic may have been
374 affected by hunter-gatherer communities that had a good command of the use of the forest and that may
375 have had an impact on fire activity in the boreal forests, as shown by Kaplan et al., (2016) in Europe, at
376 the beginning of the Holocene. During the last century, human activities have become the main source

377 of fire ignition (an estimated 65% of effective ignitions) (Naryshkin, 2003) in the Komi Republic.
378 Simulations of demography and migration during the Holocene based on the History Database of the
379 Global Environment suggest that human population densities have generally been relatively low and
380 episodic in the Ural region during the Holocene (Karmanov et al., 2011; Klein Goldewijk et al., 2011).
381 Significant augmentation in human population density is recent,, increasing by a factor of 100 over the
382 last five centuries (Drobyshev et al., 2004). Since the fifth century AD, the increase in human population
383 with the development of slash-and-burn agricultural practices (Drobyshev et al., 2004) have affected the
384 fire activity of the area and could explain the very sharp decrease in FRI during the more recent period
385 (the last 500 years), with values below 100 years.

386 **5 Conclusion**

387 Our study provides the first reconstruction of fire activity in the northern Ural region of the Holocene
388 time period. The results, based on a multi-site and multi-proxy approach including charcoal and
389 dendrochronological data, indicate a gradual decrease in FRI over the Holocene, in particular during the
390 last 500 years. The causes of these fire dynamics are certainly multiple (climate, vegetation composition
391 and human impact). The gradual establishment of warmer conditions from the mid-Holocene, especially
392 during the summer, along with the development of a landscape including flammable conifers such as
393 *Pinus sylvestris*, have probably both contributed to the increase in fire activity since 4600 cal. yr BP.
394 Anthropogenic factors are probably associated with the rapid increase in fire frequency recorded
395 recently (the last 500 years). The present-day fire activity is by far the lowest recorded over the last
396 10000 years from our study area. So, the addition of impact of current global warming with human being
397 activities could lead to another increase of fire activity and the development of situations very far from
398 the natural range of variability (600-200 FRI) recorded over the Holocene.

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- 666

667 **Table captions**668 **Table 1: The main characteristics of the three study sites in the Komi Republic.**

	Yak1_dendro	Yak2-A	Yak2-B	Yak3-A	Yak3-B
Latitude	61°44'53.73"N	61°41'46.30"N	61°41'50.80"N	61°43'53.15"N	61°43'57.40"N
Longitude	55°15'0.04"E	55°34'27.60"E	55°34'28.30"E	55°29'39.6"E	55°29'30.70"E
Elevation (m a. s. l.)	132	140	140	131	128
Current local vegetation	<i>Pinus sylvestris</i> , <i>Picea abies</i> s.l., <i>Betula</i> spp., <i>Populus tremula</i> , <i>Larix sibirica</i> , <i>Abies sibirica</i> , <i>Sorbus aucuparia</i> , <i>Juniperus</i> spp., <i>Salix</i> spp., <i>Vaccinium uliginosum</i>	<i>Pinus sylvestris</i> , <i>Picea abies</i> s.l., <i>Betula</i> spp., <i>Populus tremula</i> , <i>Chamaedaphne calyculata</i> , <i>Carex</i> spp., <i>Vaccinium uliginosum</i>	<i>Pinus sylvestris</i> , <i>Picea abies</i> s.l., <i>Betula</i> spp., <i>Populus tremula</i> , <i>Chamaedaphne calyculata</i> , <i>Carex</i> spp., <i>Vaccinium uliginosum</i>	<i>Pinus sylvestris</i> , <i>Picea abies</i> s.l., <i>Betula</i> spp., <i>Populus tremula</i> , <i>Chamaedaphne calyculata</i> , <i>Carex</i> spp., <i>Vaccinium uliginosum</i>	<i>Pinus sylvestris</i> , <i>Picea abies</i> s.l., <i>Betula</i> spp., <i>Populus tremula</i> , <i>Chamaedaphne calyculata</i> , <i>Carex</i> spp., <i>Vaccinium uliginosum</i>
Peatland surface (ha)	1.88	4	4	2.4	2.4
Length of organic core (cm)		168.5	171.5	350	187.5

669

670

671 **Table 2: AMS 14C dating from Yak2-A, Yak2-B, Yak3-A and Yak3-B**

Site	Laboratory. code	Depth (cm)	¹⁴ C yr BP (± σ)	Materials dated
Yak2-A	ULA-6948	5-5.5	325 ± 15	Plant macroremains
Yak2-A	ULA-6958	45-46	1455 ± 15	Bulk
Yak2-A	ULA-6966	85-85.5	3795 ± 15	Bulk
Yak2-A	ULA-6959	124.5-125	5415 ± 20	Bulk
Yak2-A ^a	ULA-6960	163-163.5	7605 ± 20	Bulk
Yak2-A	BETA-455694	165-165.5	9410 ± 30	Charcoal

Yak2-B	ULA-7050	5-6	1130 ± 15	Bulk
Yak2-B	ULA-7051	41-41.5	1785 ± 15	Bulk
Yak2-B	ULA-7052	77-78	3275 ± 15	Bulk
Yak2-B	ULA-7053	113-113.5	4505 ± 15	Bulk
Yak2-B	ULA-7054	149-149.5	7090 ± 20	Bulk
Yak3-B	ULA-6970	5-5.5	90 ± 15	Plant macroremains
Yak3-B	ULA-6961	49-49.5	1410 ± 20	Plant macroremains
Yak3-B	ULA-6962	92.5-93.5	2000 ± 15	Bulk
Yak3-B	ULA-6972	137-137.5	2500 ± 15	Plant macroremains
Yak3-B	ULA-6963	181-181.5	3905 ± 15	Bulk
Yak3-A	ULA-6967	5-5.5	360 ± 15	Plant macroremains
Yak3-A	ULA-6965	63-63.5	1815 ± 20	Bulk
Yak3-A	ULA-6964	121-121.5	2370 ± 20	Plant macroremains
Yak3-A	ULA-6971	179-179.5	2835 ± 15	Plant macroremains
Yak3-A	ULA-6968	237.5-238.5	3330 ± 15	Bulk
Yak3-A	BETA-455692	298.5-299	4880 ± 30	Bulk
Yak3-A	BETA-455693	326-326.5	5280 ± 30	Bulk

672 *Age rejected by the age-depth model*

673

674 Table 3: Results of dendrochronological analyses

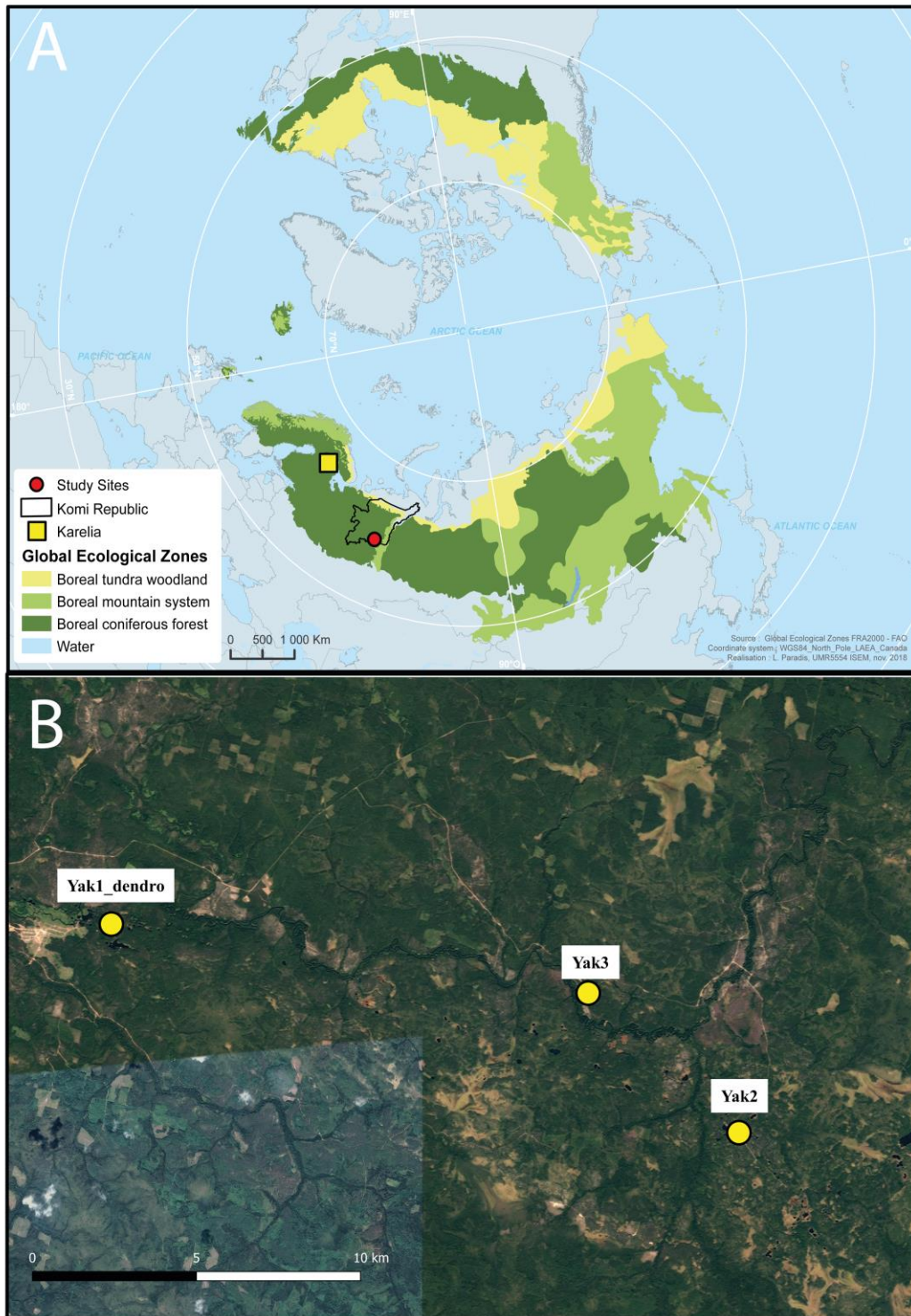
Site	Yak1_dendro	Yak2	Yak3
Dates of fires (CE)	1861, 1868, 1936	1791, 1851, 1861, 1917, 1936	1861, 1936
Fire return interval (FRI) (years)	37 years	36 years	75 years

675

676

677 **Figure captions**

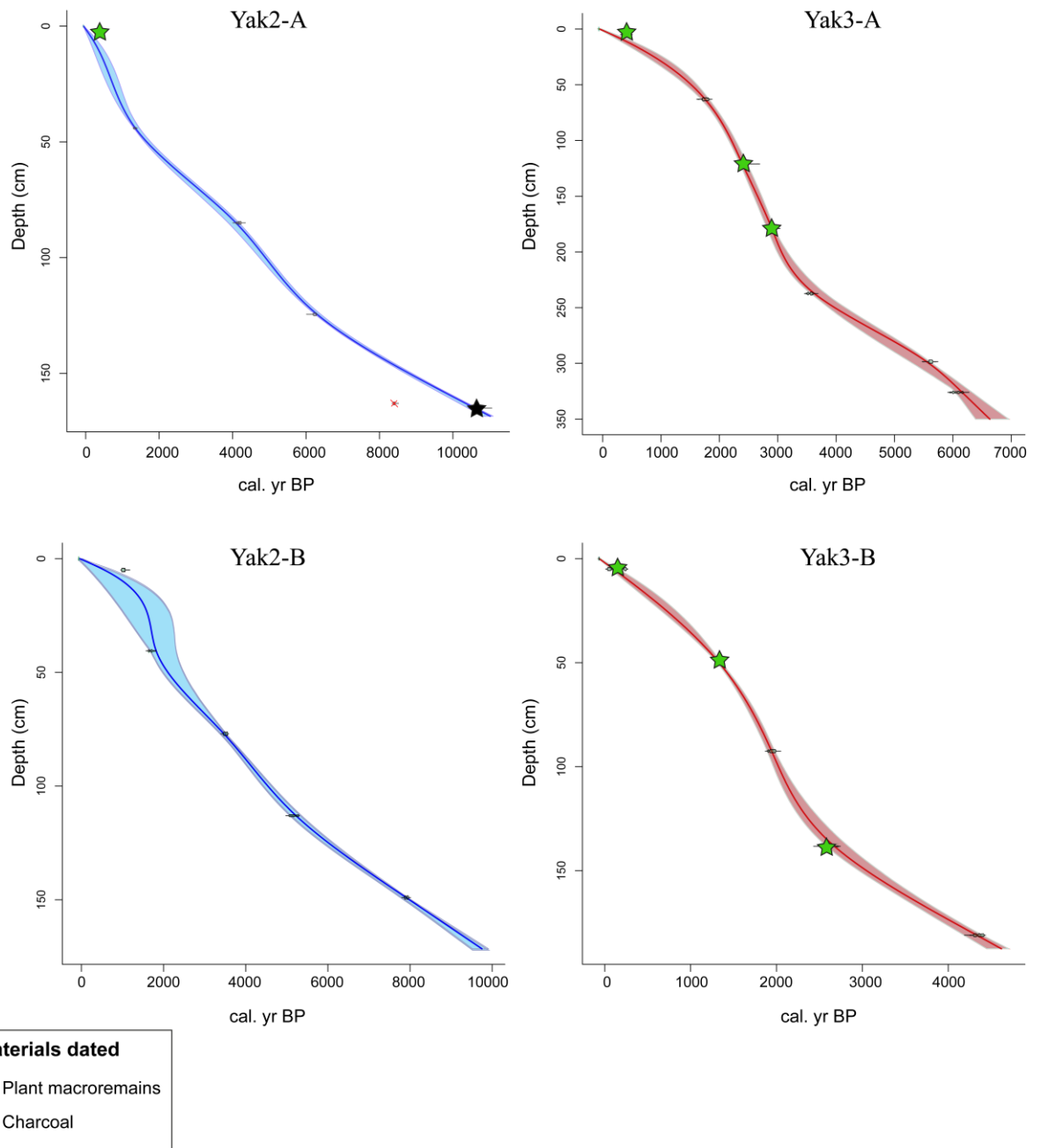
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679

680 Figure 1: A: Polar view of the extent of the boreal forest and location of the Komi Republic and the

681 study area. B: Study sites. Detail of dendrochronological samples by site in Figure A4.



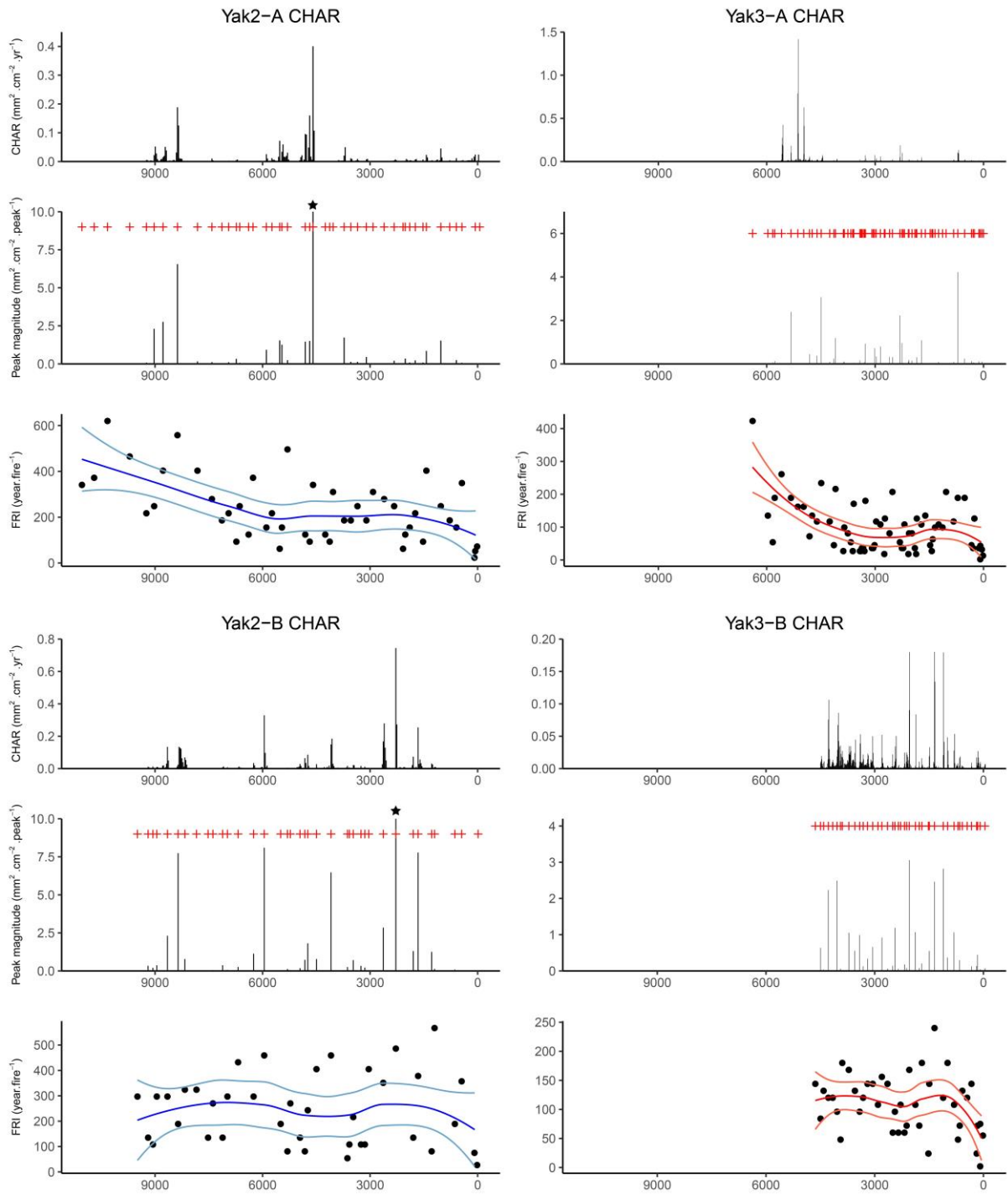
683

684 Figure 2: Age-depth model based on radiocarbon ages (see Table 2) from Yak2-A, Yak2-B, Yak3-A

685 and Yak3-B cores. The materials dated to ¹⁴C are bulk (single black lines), plant macroremains (green

686 stars), macrocharcoal (black star).

687



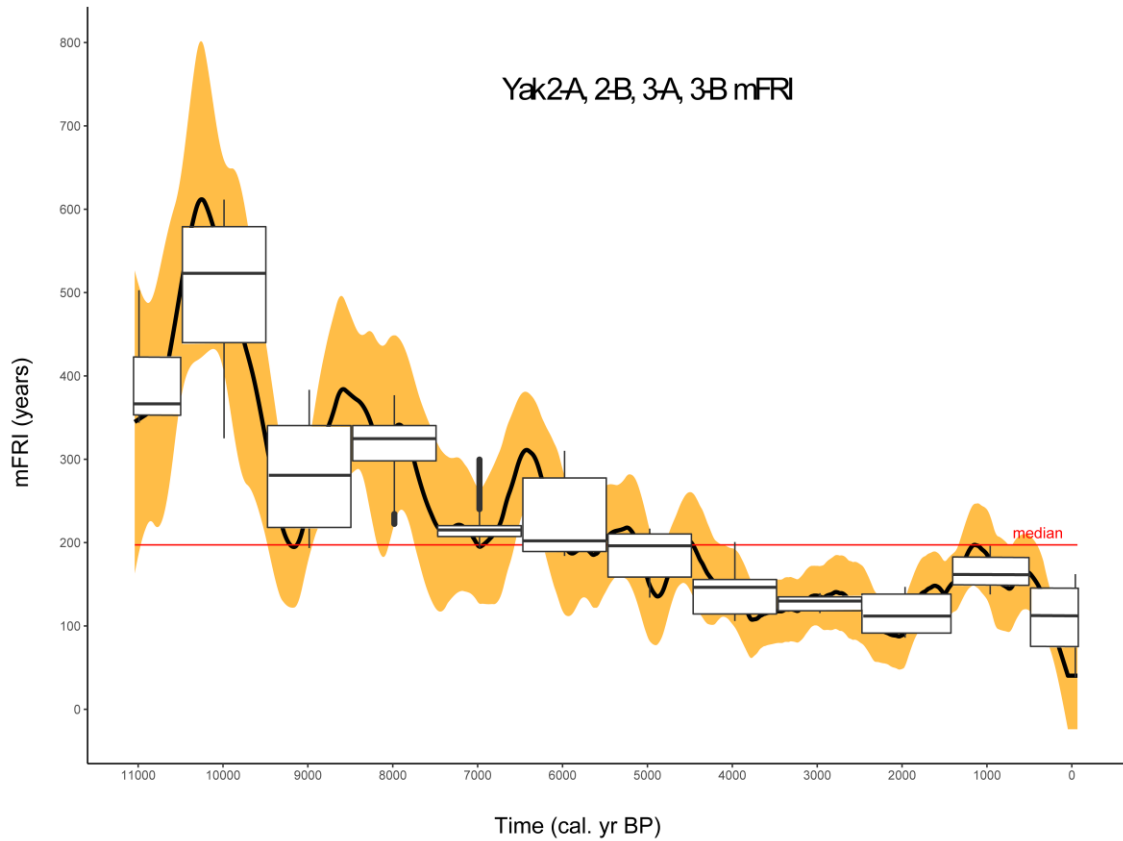
688

689 Figure 3: CharAnalysis results: interpolated charcoal accumulation rate, peak magnitude and Lowess

690 smoothed FRI for Yak2A, Yak2B, Yak3A and Yak3B. Red crosses are years with a fire event and black

691 stars correspond to peak magnitude $> 10 \text{ mm}^2 \text{ cm}^{-2} \text{ peak}^{-1}$ ($11 \text{ mm}^2 \text{ cm}^{-2} \text{ peak}^{-1}$ for Yak2A and 19 mm^2

692 $\text{cm}^{-2} \text{ peak}^{-1}$ for Yak3B).

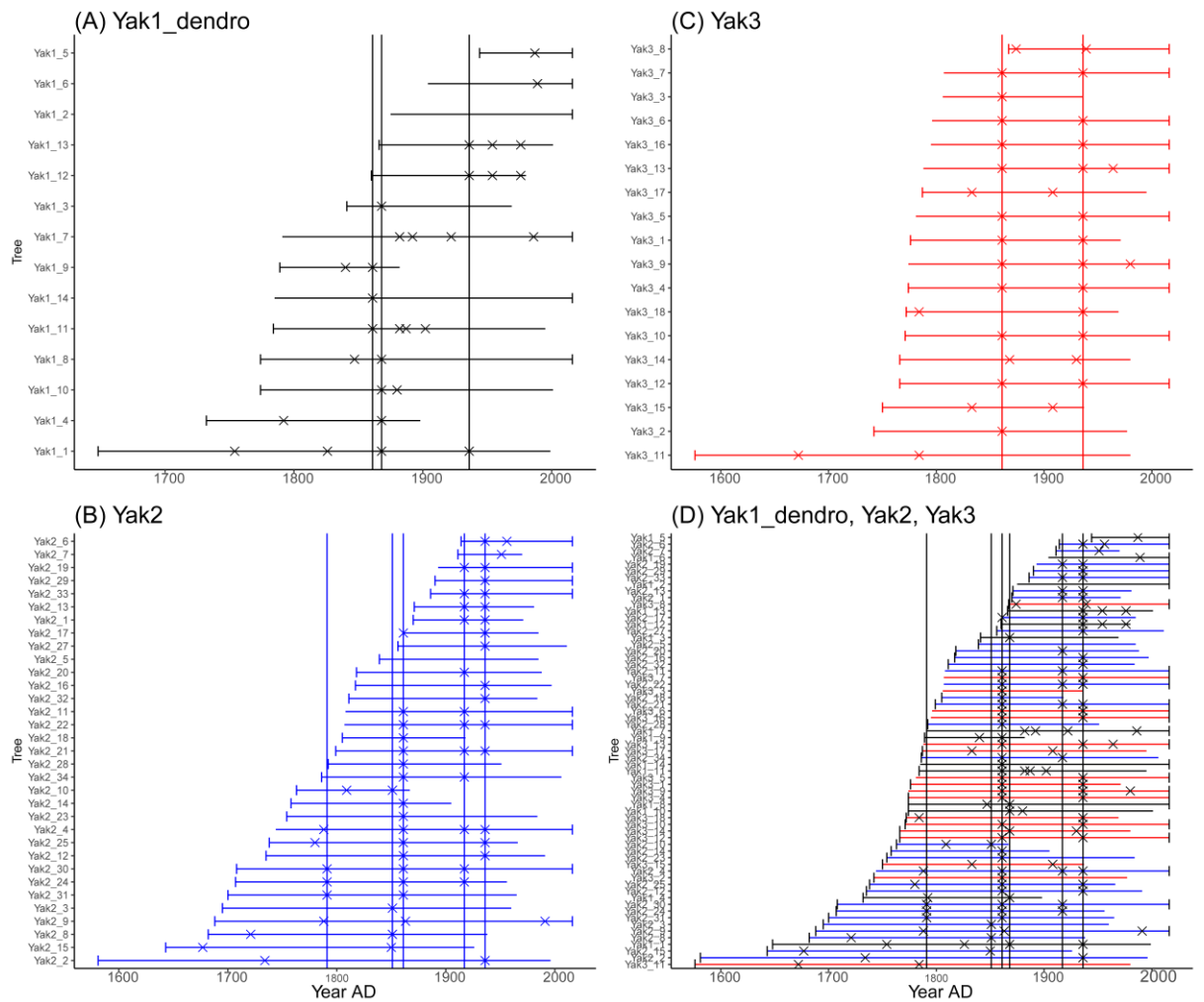


693

694 Figure 4: Pooled FRI reconstruction (mFRI) from Yak2-A, Yak2-B, Yak3-A and Yak3-B cores. The
 695 red line represents the median of the mFRI (197,29 years). Orange shaded area is confidence interval.

696 Detected trends are showed by box-plot analysis carried out for each 1000 years period (except for
 697 extremities) significance between millennia was assessed using the Wilcoxon rank sum test.

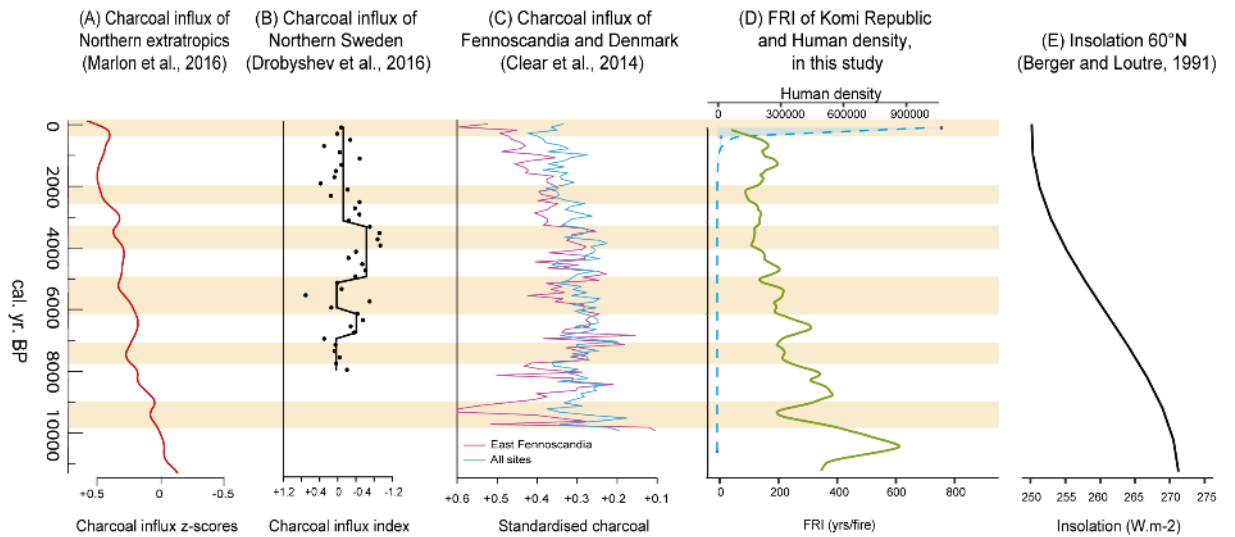
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699

700 Figure 5: Tree-ring records of fire activity. Each horizontal line is an individual tree. (A) Yak1_dendro;
 701 (B) Yak2; (C) Yak3; (D) The three sites together. Black horizontal lines indicate Yak1_dendro, red
 702 horizontal lines Yak3 and blue horizontal lines Yak2. Black crosses represent fire scars. Vertical gray
 703 bands indicate obvious fire events defined visually.

704



705

706 Figure 6: Proxies for Holocene fire history along a west-east transect from northern Sweden to the Komi
 707 Republic (A, B, C, and D). (A) Charcoal influx in the northern extratropics (Marlon et al., 2006) shown
 708 by z-score: an increase in the z-score represents an increase in fire activity. (B) Charcoal influx in
 709 northern Sweden (Carcaillet et al., 2007; Drobyshev et al., 2016). (C) Charcoal influx in Fennoscandia
 710 and Denmark (Clear et al., 2014). (D) FRI and human population density in Komi Republic (this
 711 study). (E) Insolation at latitude 60°N (Berger and Loutre, 1991). Yellow bands correspond to
 712 synchronized trends.

713

714

715 **Appendices**

716

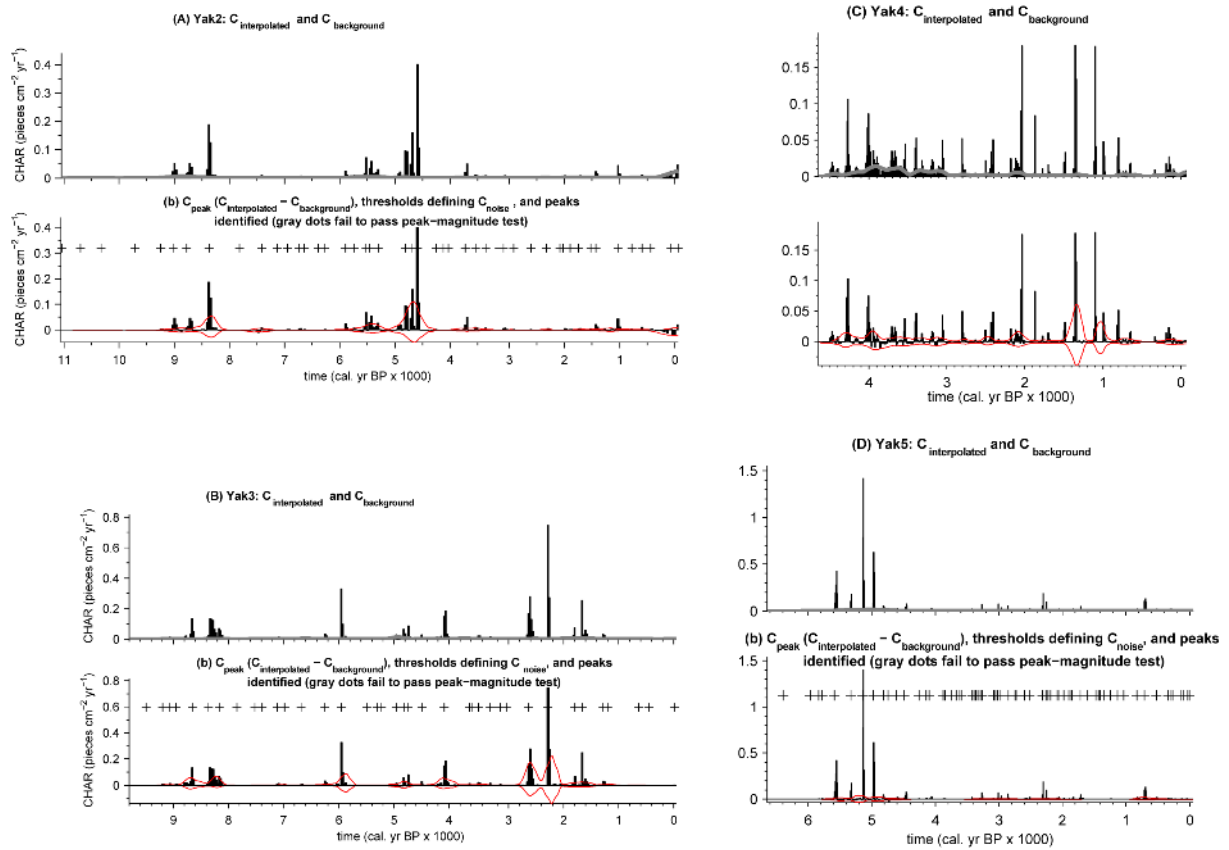
717 Table A 1: Geographical location of each dendrochronological sample

Site	Latitude	Longitude
Yak1_dendro_1	61.74929	55.22873
Yak1_dendro_2	61.7493	55.22884
Yak1_dendro_3	61.74893	55.22903
Yak1_dendro_4	61.7488	55.22922
Yak1_dendro_5	61.74904	55.22884
Yak1_dendro_6	61.74917	55.22887
Yak1_dendro_7	61.74981	55.22844
Yak1_dendro_8	61.7499	55.22826
Yak1_dendro_9	61.75003	55.22854
Yak1_dendro_10	61.75077	55.23019
Yak1_dendro_11	61.75084	55.23051
Yak1_dendro_12	61.75112	55.23059
Yak1_dendro_13	61.75131	55.23002
Yak1_dendro_14	61.75143	55.23011
Yak2_1	61.69495	55.57477

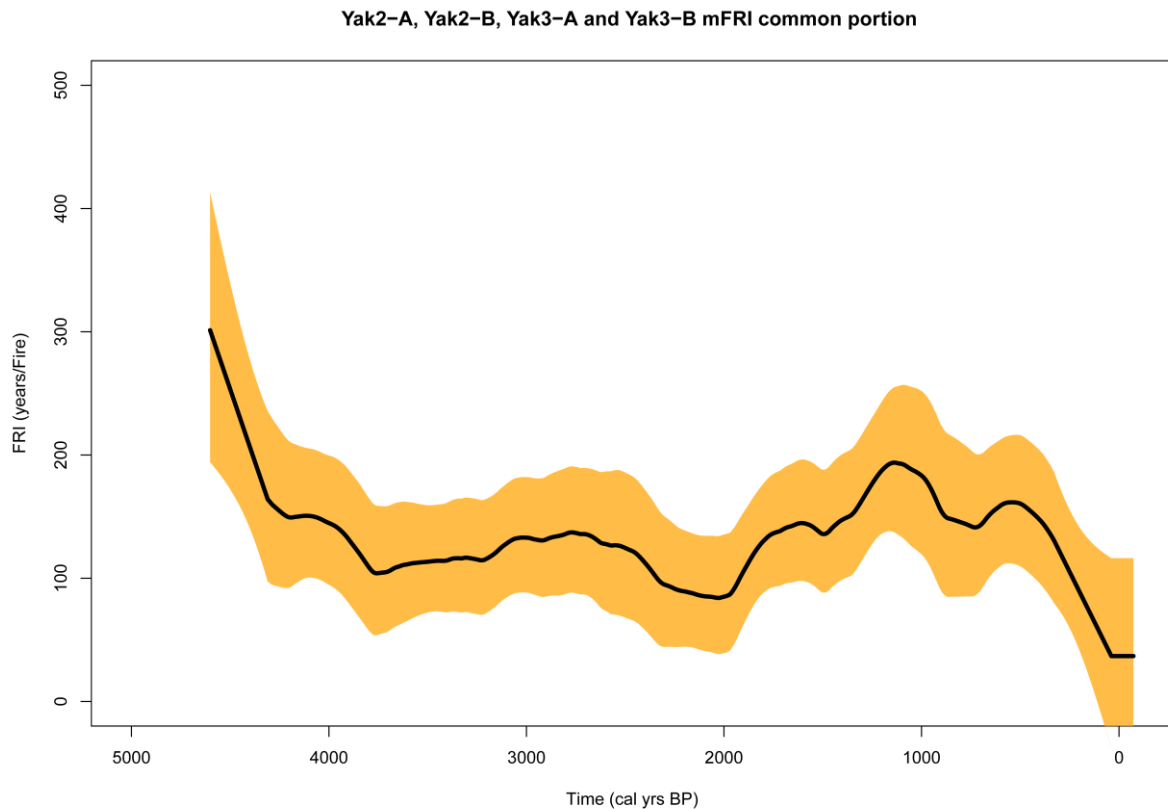
Yak2_2	61.69502	55.57498
Yak2_3	61.6951	55.57531
Yak2_4	61.69523	55.57465
Yak2_5	61.69558	55.57258
Yak2_6	61.69637	55.57367
Yak2_7	61.69617	55.57156
Yak2_8	61.6953	55.56931
Yak2_9	61.6952	55.56921
Yak2_10	61.69456	55.56897
Yak2_11	61.69395	55.56963
Yak2_12	61.69386	55.57186
Yak2_13	61.69421	55.57245
Yak2_14	61.69371	55.57324
Yak2_15	61.69356	55.57358
Yak2_16	61.69347	55.57384
Yak2_17	61.69296	55.57507
Yak2_18	61.69333	55.5756
Yak2_19	61.69438	55.57644

Yak2_20	61.6944	55.57689
Yak2_21	61.69453	55.57697
Yak2_22	61.69475	55.57683
Yak2_23	61.69492	55.57603
Yak2_24	61.69512	55.57902
Yak2_25	61.69557	55.57814
Yak2_26	61.696	55.57734
Yak2_27	61.69624	55.57744
Yak2_28	61.69694	55.57381
Yak2_29	61.69703	55.57388
Yak2_30	61.69767	55.57427
Yak2_31	61.69764	55.57453
Yak2_32	61.69707	55.5757
Yak2_33	61.69724	55.57622
Yak2_34	61.69718	55.57711
Yak3_1	61.73334	55.49385
Yak3_2	61.73293	55.49343
Yak3_3	61.73271	55.49438

Yak3_4	61.73228	55.49473
Yak3_5	61.73219	55.49484
Yak3_6	61.73225	55.49511
Yak3_7	61.73195	55.4949
Yak3_8	61.73196	55.49499
Yak3_9	61.73178	55.49424
Yak3_10	61.73154	55.49385
Yak3_11	61.7313	55.49396
Yak3_12	61.73037	55.49327
Yak3_13	61.73077	55.49218
Yak3_14	61.73048	55.49156
Yak3_15	61.73038	55.49056
Yak3_16	61.73046	55.49093
Yak3_17	61.73111	55.48955
Yak3_18	61.73324	55.4911



719 Figure A 1: Raw outputs of CharAnalysis representing Cbackground, Cinterpolated and the threshold
 720 (red line)



722 Figure A 2: Pooled FRI reconstruction (mFRI) of Yak2, Yak3 Yak4 and Yak5 sites on the common
723 chronological portion. Shaded areas are confidence intervals

724

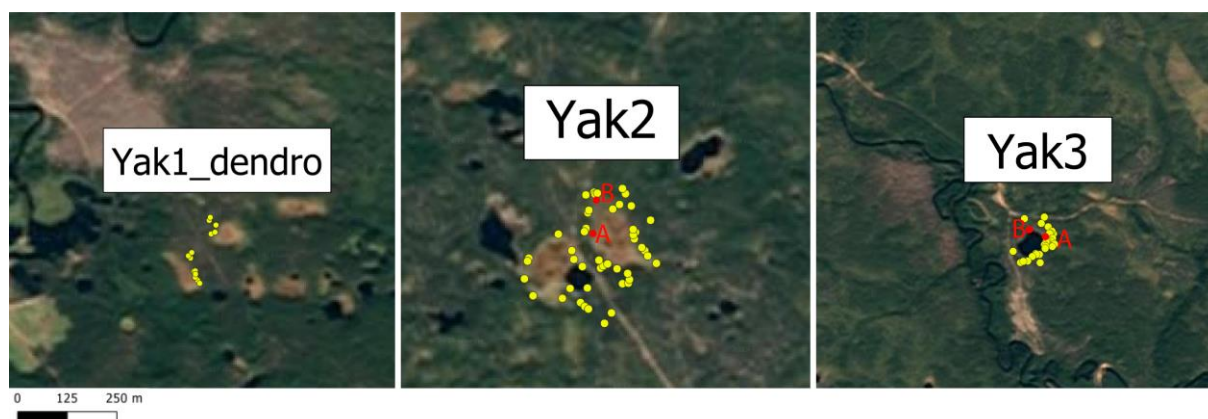
725



726

727 Figure A 3: Photo of the Yak2 forested peatland

728



729

730 Figure A 4: Focus on each study area. The yellow dots represent the dendrochronology samples and
731 the red dots represent the cores location.