

## **Response to the interactive comment on “Pollen-based quantitative land-cover reconstruction for northern Asia covering the last 40 ka”**

Dear Editor,

Both editor and reviewer proposed few helpful comments to improve our manuscript, and we have responded these comments one by one and revised our manuscript accordingly. As both of you mentioned the data availability of our pollen dataset, we clear our description about opening pollen data. All the used pollen data have been open on Pangaea and an introduction paper is of under reviewing; and we plan to open all PPE-based plant abundances for these 42 site-groups if this paper can be accepted. The responses are indicated in the responses letter (response-comments.pdf) and major changes are marked in the tracking version of this manuscript (Cao\_etal\_version\_3version-withmodification.pdf).

We hope that the reversion of this manuscript meets the requirements of Climate of the Past. If you have more comments, we will be very thankful and we are pleasure to improve our manuscript.

On behalf of all co-author.

All best wishes

Xianyong Cao

1 **Pollen-based quantitative land-cover reconstruction for northern Asia covering**  
2 **the last 40 ka**

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14

15 **ABSTRACT**

16 We collected the available relative pollen productivity estimates (PPEs) for 27 major  
17 pollen taxa from Eurasia and applied them to estimate plant abundances during the  
18 last 40 cal. ka BP (calibrated thousand years before present) using pollen counts from  
19 203 fossil pollen records in northern Asia (north of 40°N). These pollen records were  
20 organised into 42 site-groups, and regional mean plant abundances calculated using

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21 the REVEALS (Regional Estimates of Vegetation Abundance from Large Sites)  
22 model. Time-series clustering, constrained hierarchical clustering, and detrended  
23 canonical correspondence analysis were performed to investigate the regional pattern,  
24 time, and strength of vegetation changes, respectively. Reconstructed regional  
25 plant-functional type (PFT) components for each site-group are generally consistent  
26 with modern vegetation, in that vegetation changes within the regions are  
27 characterized by minor changes in the abundance of PFTs rather than by ~~invasions~~  
28 ~~of~~increase in new PFTs, particularly during the Holocene. We argue that pollen-based  
29 REVEALS estimates of plant abundances should be a more reliable reflection of the  
30 vegetation as pollen may overestimate the turnover, particularly when a high pollen  
31 producer invades areas dominated by low pollen producers. Comparisons with  
32 vegetation-independent climate records show that climate change is the primary factor  
33 driving land-cover changes at broad spatial and temporal scales. Vegetation changes  
34 in certain regions or periods, however, could not be explained by direct climate  
35 change, for example inland Siberia, where a sharp increase in evergreen conifer tree  
36 abundance occurred at ca. 7–8 cal. ka BP despite an unchanging climate, potentially  
37 reflecting their response to complex climate–permafrost–fire–vegetation interactions  
38 and thus a possible long-term-scale lagged climate response.

39 *Keywords:* boreal forests, China, Holocene, late Quaternary, pollen productivity,  
40 quantitative reconstruction, Siberia, vegetation

## 41 **1 Introduction**

42 High northern latitudes such as northern Asia experience above-average temperature  
43 increases in times of past and recent global warming (Serreze et al., 2000; IPCC,  
44 2007), known as polar amplification (Miller et al., 2010). Temperature rise is expected  
45 to promote vegetation change as the vegetation composition in these areas is assumed  
46 to be controlled mainly by temperature (Li J. et al., 2017; Tian et al., 2018). However,  
47 a more complex response can occur mainly because vegetation is not linearly related  
48 to temperature change (e.g. due to resilience, stable states or time-lagged responses;

49 Soja et al., 2007; Herzsuh et al., 2016) and/or vegetation is only indirectly limited  
50 by temperature while other temperature-related environmental drivers such as  
51 permafrost conditions are more influential (Tchebakova et al., 2005).

52 Such complex relationships between temperature and vegetation may help explain  
53 several contradictory findings of recent ecological change in northern Asia. For  
54 example, simulations of vegetation change in response to a warmer and drier climate  
55 indicate that steppe should expand in the present-day forest–steppe ecotone of  
56 southern Siberia (Tchebakova et al., 2009) but, contrarily, pine forest has increased  
57 during the past 74 years, probably because the warming temperature was mediated by  
58 improved local moisture conditions (Shestakova et al., 2017). In another example,  
59 evergreen conifers, which are assumed to be more susceptible to frost damage than  
60 *Larix*, expanded their distribution by 10% during a period with cooler winters from  
61 2001 to 2012, while the distribution of *Larix* forests decreased by 40% on the West  
62 Siberian Plain as revealed by a remote sensing study (He et al., 2017). Additionally,  
63 some field studies and dynamic vegetation models infer a rapid response of the  
64 treeline to warming in northern Siberia (e.g., Moiseev, 2002; Soja et al., 2007;  
65 Kirdyanov et al., 2012), but combined model- and field-based investigations of larch  
66 stands in north-central Siberia reveal only a densification of tree-stands, not an areal  
67 expansion (Kruse et al., 2016; Wieczorek et al., 2017).

68 These findings on recent vegetation dynamics that contradict a straightforward  
69 vegetation-temperature relationship may be better understood in the context of  
70 vegetation change over longer time-scales. Synthesizing multi-record pollen data is  
71 the most suitable approach to investigate quantitatively the past vegetation change at  
72 broad spatial and long temporal scales. Broad spatial scale pollen-based land-cover  
73 reconstructions have been made for Europe (e.g. Mazier et al., 2012; Nielsen et al.,  
74 2012; Trondman et al., 2015) and temperate China (Li, 2016) for the Holocene.  
75 However, vegetation change studies in northern Asia are restricted to biome  
76 reconstructions (Tarasov et al., 1998, 2000; Bigelow et al., 2003; Binney et al. 2017;  
77 Tian et al., 2018), which do not reflect compositional change. Syntheses of pure

78 pollen percentage data are not appropriate due to differences in pollen productivity,  
79 which may result in an overestimation of the strength of vegetation changes (Wang  
80 and Herzschuh, 2011). This might be particularly severe when strong pollen producers  
81 such as pine (Mazier et al., 2012) invade areas dominated by low pollen producers  
82 such as larch (Niemeyer et al., 2015). Marquer et al. (2014, 2017) also demonstrated  
83 the strength of pollen-based REVEALS estimates of plant abundance in studies of  
84 Holocene vegetation change and plant diversity indices in Europe. Accordingly,  
85 syntheses of quantitative plant cover derived from the application of PPEs to multiple  
86 pollen records (Trondman et al., 2015; Li, 2016) should be a better way to investigate  
87 Late Glacial and Holocene vegetation change in northern Asia.

88 In this study, we employ the taxonomically harmonized and temporally standardized  
89 fossil pollen datasets available from eastern continental Asia (Cao et al., 2013, 2015)  
90 and Siberia (Tian et al., 2018) covering the last 40 cal. ka BP (henceforth abbreviated  
91 to ka). We compile all the available PPEs from Eurasia and use the mean estimate for  
92 each taxon. Finally, we quantitatively reconstruct plant cover using the REVEALS  
93 model (Sugita, 2007) for 27 major taxa at 18 key time slices. We reveal the nature,  
94 strength, and timing of vegetation change in northern Asia and its regional  
95 peculiarities, and discuss the driving factors of vegetation change.

## 96 **2 Data and methods**

### 97 *2.1. Fossil pollen data process*

98 The fossil pollen records were obtained from the extended version of the fossil pollen  
99 dataset for eastern continental Asia containing 297 records (Cao et al., 2013, 2015)  
100 and the fossil pollen dataset for Siberia with 171 records (Tian et al., 2017). For the  
101 468 pollen records, pollen names were harmonized into genus level for arboreal taxa  
102 while family level for herbaceous taxa, and age-depth models were re-established  
103 using the ~~same procedures~~ Bayesian age-depth modelling (further details are described  
104 in Cao et al., 2013). We selected 203 pollen records from lacustrine sediments (110  
105 sites) and peat (93 sites) north of 40°N, with chronologies based on  $\geq 3$  dates and  $< 500$

106 year/sample temporal resolution generally, following previous studies (Mazier et al.,  
 107 2012; Nielsen et al., 2012; Fyfe et al., 2013; Trondman et al., 2015). Out of the 203  
 108 pollen records, 170 sites (83 from lakes, 87 from bogs) have original pollen counts,  
 109 while in the other 33 sites only pollen percentages are available. Due to overall low  
 110 site density, we decided to include these data. The pollen counts were back calculated  
 111 from percentages using the terrestrial pollen sum indicated in the original publications.  
 112 Detailed information (including location, data quality, chronology reliability, and data  
 113 source) of the selected sites is presented in Appendices 1 and 2.

114 Table 1 Selected time windows.

Time window (cal a BP)	Abbreviated name
-60~100	0 ka
100~350	0.2 ka
350~700	0.5 ka
700~1200	1 ka
1700~2200	2 ka
2700~3200	3 ka
3700~4200	4 ka
4700~5200	5 ka
5700~6200	6 ka
6700~7200	7 ka
7700~8200	8 ka
8700~9200	9 ka
9700~10200	10 ka
10500~11500	11 ka
11500~12500	12 ka
13500~14500	14 ka
19000~23000	21 ka
23000~27000	25 ka
36000~44000	40 ka

115 We selected 18 key time slices for reconstruction (Table 1) to capture the general  
 116 temporal patterns of vegetation change during the last 40 ka, i.e. 40, 25, 21, 18, 14,  
 117 and 12 ka during the late Pleistocene and 1000-year resolution (i.e. 500-year time  
 118 windows around each millennium, e.g. 0.7–1.2 ka, 1.7–2.2 ka, etc.) during the  
 119 Holocene. For the 0 ka time slice, the ca. 150-year time window (<0.1 ka) was set to  
 120 represent the modern vegetation. Since few pollen records have available samples at  
 121 the 0 ka time slice, the 0.2 and 0.5 ka time slices covered a 250-year or 350-year time

122 window (0.1~0.35 ka and 0.35~0.7 ka, respectively) to represent the recent vegetation,  
 123 following the strategy and time windows implemented for Europe (Mazier et al., 2012;  
 124 Trondman et al., 2015). For the last glacial period, even broader time windows were  
 125 chosen to offset the sparsely available samples (Table 1). Pollen counts of all available  
 126 samples within one time window were summed up to represent the total pollen count  
 127 for each time slice. In this study, we selected 27 major pollen taxa (with available PPE  
 128 values) that form dominant components in both modern vegetation communities and  
 129 the fossil pollen spectra and reconstruct their abundances in the past vegetation (Table  
 130 2).

131 Table 2 Fall speed of pollen grains (FS) and mean relative pollen productivity  
 132 estimate (PPE) with standard error (SE) for the 27 selected taxa. Plant-functional type  
 133 (PFT) assignment is according to previous biome reconstructions (Tarasov et al., 1998,  
 134 2000; Bigelow et al., 2003; Ni et al., 2010).

<b>PFT</b>	<b>PFT description</b>	<b>pollen type</b>	<b>FS (m/s)</b>	<b>PPE (SE)</b>
I	evergreen conifer tree	<i>Pinus</i>	0.031 <sup>1</sup>	9.629 (0.075)
I	evergreen conifer tree	<i>Picea</i>	0.056 <sup>1</sup>	2.546 (0.041)
I	evergreen conifer tree	<i>Abies</i>	0.120 <sup>1</sup>	6.875 (1.442)
II	deciduous conifer tree	<i>Larix</i>	0.126 <sup>1</sup>	3.642 (0.125)
III	boreal deciduous tree	<i>Betula_tree</i>	0.024 <sup>1</sup>	8.106 (0.125)
		<i>Betula_undiff.</i>		
III	boreal deciduous tree	<i>Alnus_tree</i>	0.021 <sup>1</sup>	9.856 (0.092)
		<i>Alnus_undiff.</i>		
III	boreal deciduous tree	<i>Corylus</i>	0.025 <sup>2</sup>	1.637 (0.065)
IV	temperate deciduous tree	<i>Quercus</i>	0.035 <sup>1</sup>	6.119 (0.050)
IV	temperate deciduous tree	<i>Fraxinus</i>	0.022 <sup>1</sup>	2.046 (0.105)
IV	temperate deciduous tree	<i>Juglans</i>	0.037 <sup>3</sup>	4.893 (0.221)
IV	temperate deciduous tree	<i>Carpinus</i>	0.042 <sup>1</sup>	5.908 (0.285)
IV	temperate deciduous tree	<i>Tilia</i>	0.032 <sup>2</sup>	1.055 (0.066)
IV	temperate deciduous tree	<i>Ulmus</i>	0.032 <sup>2</sup>	6.449 (0.684)
V	boreal shrub	<i>Betula_shrub</i>	0.024 <sup>1</sup>	1.600 (0.132)
V	boreal shrub	<i>Alnus_shrub</i>	0.021 <sup>1</sup>	6.420 (0.420)
V	boreal shrub	<i>Salix</i>	0.034 <sup>2</sup>	1.209 (0.039)
V	boreal shrub	Ericaceae	0.034 <sup>4</sup>	0.200 (0.029)
VI	arid-tolerant shrub and herb	<i>Ephedra</i>	0.015 <sup>8</sup>	0.960 (0.140)
VI	arid-tolerant shrub and herb	<i>Artemisia</i>	0.014 <sup>6</sup>	9.072 (0.176)
VI	arid-tolerant shrub and herb	Chenopodiaceae	0.019 <sup>6</sup>	5.440 (0.460)
VII	grassland and tundra forb	Poaceae	0.035 <sup>4</sup>	1.000 (0.000)

VII	grassland and tundra forb	Cyperaceae	0.035 <sup>5</sup>	0.757 (0.044)
VII	grassland and tundra forb	Asteraceae	0.051 <sup>7</sup>	0.465 (0.066)
VII	grassland and tundra forb	<i>Thalictrum</i>	0.007 <sup>8</sup>	3.855 (0.258)
VII	grassland and tundra forb	Ranunculaceae	0.014 <sup>9</sup>	2.900 (0.363)
VII	grassland and tundra forb	Caryophyllaceae	0.028 <sup>9</sup>	0.600 (0.050)
VII	grassland and tundra forb	Brassicaceae	0.002 <sup>3</sup>	4.185 (0.188)

135 <sup>1</sup> Eisenhut (1961); <sup>2</sup> Gregory (1973); <sup>3</sup> Li et al. (2017); <sup>4</sup> Broström et al. (2004); <sup>5</sup> Sugita et al.  
 136 (1999); <sup>6</sup> Abraham and Kozáková (2012); <sup>7</sup> Broström et al. (2002); <sup>8</sup> Xu et al. (2014); <sup>9</sup> Bunting et  
 137 al. (2013).

## 138 2.2 The REVEALS model setting

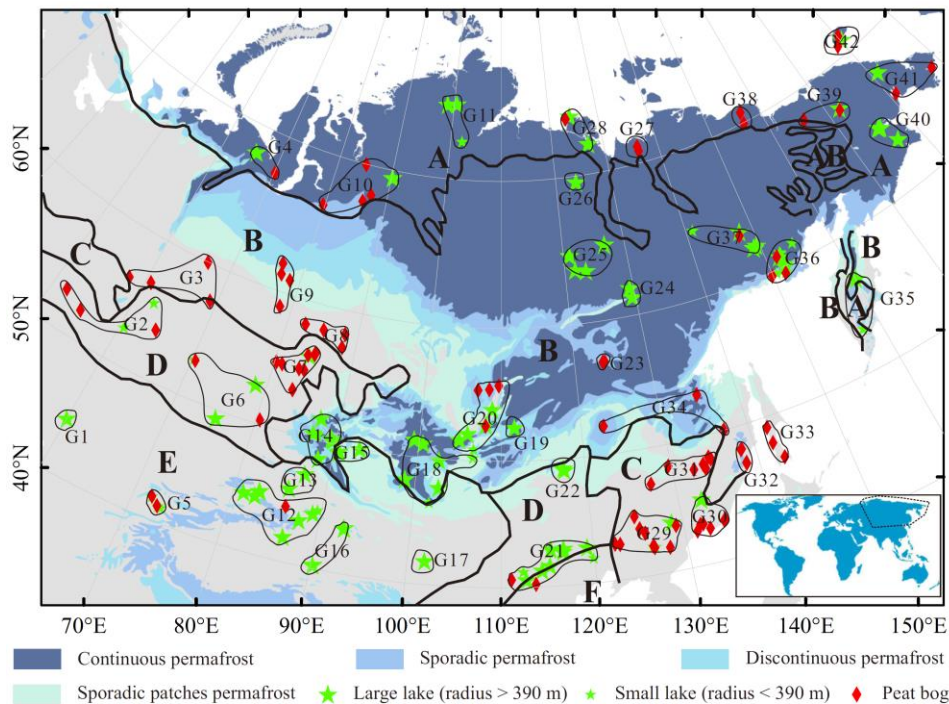
139 The REVEALS model assumes the PPEs of pollen taxa are constant variables over the  
 140 target period, and requires parameter inputs including sediment basin radius (m), fall  
 141 speed of pollen grain (FS, m/s), and PPE with standard error (SE; Sugita, 2007). The  
 142 areas of the 110 lakes were obtained from descriptions in original publications and  
 143 validated by measurements on Google Earth. Their basin radii were back-calculated  
 144 from their areas assuming a circular shape. There are 83 large lakes (radius >390 m;  
 145 following Sugita, 2007) in our dataset with a fairly even distribution across the study  
 146 area (Fig. 1; Appendix 1), which helps ensure the reliability of the regional vegetation  
 147 estimations (Sugita, 2007; Mazier et al., 2012). Only 18 bogs have published  
 148 descriptions about their size and it is infeasible to measure them on Google Earth  
 149 because of indefiniteunclear boundaries. A test-run showed that using different bog  
 150 radii (i.e. 5 m, 10 m, 20 m, 50 m, 100 m, 200 m and 500 m) did not significantly  
 151 affect the REVEALS estimates (Appendix 3), hence a standard (moderate size) radius  
 152 of 100 m was set for all bogs.

153 We collected available PPEs for the 27 selected pollen taxa from 20 studies in Eurasia  
 154 (Appendix 4). We calculated the mean PPE from all available PPE values, but  
 155 excluded records with  $PPE \leq SE$  (Mazier et al., 2012). We included these PPEs for  
 156 various species in the mean PPE calculation for their family or genus. For  
 157 simplification, we did not evaluate the values or select PPE values following  
 158 consistent criteria as was done in Europe (Mazier et al., 2012). Instead, we used the  
 159 original values from the studies included in Mazier et al. (2012) and added new PPE



160 values from Europe published since the synthesis of Mazier et al. (2012). SE of the  
 161 mean PPE was estimated using the delta method (Stuart and Ord, 1994). Fall speeds  
 162 for each of the 27 pollen taxa were retrieved from previous studies (Table 2).

163 The REVEALS model generally performs best with pollen records from large lakes,  
 164 although multiple pollen records from small lakes and bogs (at least two sites) can  
 165 also produce reliable results where large lakes are absent (Sugita, 2007; Trondman et  
 166 al., 2016). Here, due to the sparse distribution of available sites, we divided the 203  
 167 sites into 42 site-groups, based on criteria of geographic location, vegetation type  
 168 (vegetation zone map modified from Tseplyayev, 1961; Dulamsuren et al., 2005; Hou,  
 169 2001), climate (based on modern precipitation and temperature contours), and  
 170 permafrost (Brown, 1997) following the strategy of Li (2016), and the pollen data  
 171 within one site-group should be of similar components and temporal patterns. To  
 172 ensure the reliability of REVEALS estimates of plant cover, each group includes at  
 173 least one large lake or two small sites (small lakes or bogs; Fig. 1; Appendix 5).



174 **Fig. 1.** Distribution of the 42 site-groups together with the modern vegetation zones and  
 175 permafrost extent in northern Asia. The vegetation-zone map modified from Tseplyayev (1961),  
 176

177 Dulamsuren et al. (2005), and Hou (2001) includes: A: tundra, B: taiga forest, C: temperate mixed  
178 conifer-deciduous broadleaved forest, D: temperate steppe, E: semi-desert and desert; F:  
179 warm-temperate deciduous forest.

180 The REVEALS model was run with a mean wind speed set to 3 m/s and neutral  
181 atmospheric conditions following Trondman et al. (2015), and the maximum distance  
182 of regional vegetation  $Z_{max}$  was set to 100 km. The lake and bog sites were  
183 reconstructed using the models of pollen dispersal and deposition for lakes (Sugita,  
184 1993) and bogs (Prentice, 1985), respectively in REVEALS version 5.0 (Sugita,  
185 unpublished). The mean estimate of plant abundances from lakes and bogs was  
186 calculated for each of the 42 site-groups, which includes both sediment types (using  
187 the computer program bog.lake.data.fusion, Sugita, unpublished). Finally, the 27 taxa  
188 were assigned to seven plant functional types (PFT; Table 1) following the PFT  
189 definitions for China and Siberia (Tarasov et al. 1998, 2000; Bigelow et al. 2003; Ni  
190 et al., 2010; Tian et al., 2017), with the restriction that each pollen taxon is attributed  
191 to only one PFT according to the strategy of Li (2016) (Table 2).

## 192 2.2 Numerical analyses of reconstruction

193 The abundance variations of the seven PFTs during the Holocene (time slices between  
194 12 and 1 ka) from 34 site-groups were used in a clustering analysis. Eight site-groups  
195 had to be excluded from the analysis due to poor coverage of time slices (G1, G5,  
196 G17, G19, G27, G42). For site-groups with <3 missing time slices during the  
197 Holocene (G3, G16, G26, G32, G33, G35, G38, G39, G41), linear interpolation was  
198 employed to estimate the PFT abundances for the missing time slices. Time-series  
199 clustering for the three-way dataset was performed to generate a distance matrix  
200 among the site-groups using the *tsclust* function in the *dtwclust* package  
201 (Sarda-Espinosa, 2018) in R 3.4.1 (R Core Team, 2017). The distance matrix was  
202 employed in hierarchical clustering (using the *hclust* function in R) to cluster the  
203 site-groups. Constrained hierarchical clustering (using *chclust* function in *rioja*  
204 package version 0.9-15.1; Juggins, 2018) was used to determine the timing of primary

205 vegetation changes (i.e. the first split) in each site-group. A change was considered to  
206 be significant when the split passed the broken-stick test. The amount of PFT  
207 compositional change (turnover) through time during the period between 12 and 1 ka  
208 for the 34 site-groups (their time slices or interpolated ones can cover entire period)  
209 was estimated by detrended canonical correspondence analysis (DCCA) for each  
210 site-group (ter Braak, 1986) using CANOCO 4.5 (ter Braak and Šmilauer, 2002).

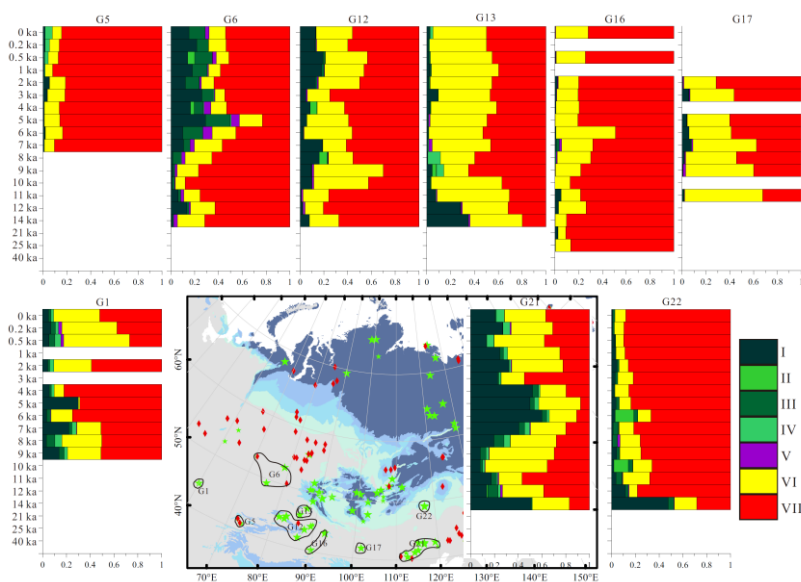
### 211 **3. Results**

#### 212 *Large-scale pattern*

213 On a glacial-interglacial scale, marked temporal changes in the occurrence and  
214 abundance of PFTs are revealed, in particular the high cover of tree PFTs during the  
215 Holocene as opposed to the widespread open landscape during the glacial period. In  
216 contrast, vegetation changes in northern Asia within the Holocene are rather minor  
217 with only slight changes in PFT abundances. Cluster analyses of grouped vegetation  
218 records from the Holocene find five clusters (Appendix 6). Their spatial distribution is  
219 largely consistent with the distribution of modern vegetation types as characterized by  
220 certain PFTs. (1) Records from the forest-steppe ecotone (e.g. G12, G21; Fig. 2A) in  
221 north-central China and the Tianshan Mts. (the mentioned geographic locations are  
222 indicated in Appendix 7) have high tree PFTs during the middle Holocene. (2) Areas  
223 in southern and south-western Siberia and north-eastern China were covered by  
224 cool-temperate mixed forest or light taiga with a high diversity of trees throughout the  
225 Holocene (e.g. G2, G7, G14, G29; Fig. 2B). (3) The West Siberian Plain and  
226 south-eastern Siberia that are presently covered by open dark taiga forests (e.g. G8,  
227 G9, G33; Fig. 2C) had an even higher abundance of evergreen conifer trees during the  
228 middle Holocene than at present. (4) *Larix* formed light taiga forests in central Yakutia  
229 throughout the Holocene (e.g. G25, G26; Fig. 2D). (5) Northern Siberia, which is  
230 currently covered by tundra formed by boreal shrubs and herbs, had a higher share of  
231 tree PFTs during the middle Holocene (e.g. G28, G39; Fig. 2E).

232 The turnover in PFT composition is  $<0.7$  SD units in almost all site-groups, except G8

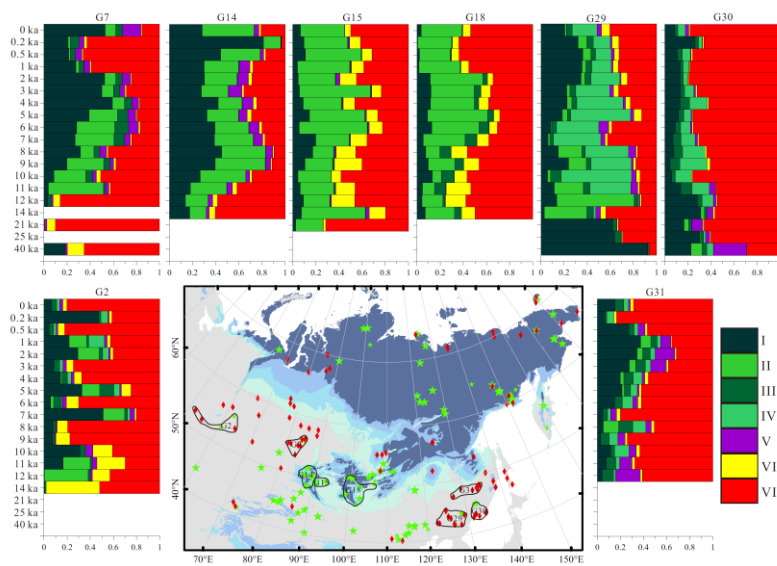
233 (0.88 SD), G9 (0.73 SD), and G24 (0.76 SD), indicating only slight vegetation change  
 234 during the Holocene (Fig. 3). The three site-groups with higher turnover show a  
 235 distinct transition from light taiga to dark taiga in the middle Holocene (at ca. 8 ka).  
 236 This result is consistent with the finding that PFT abundance from 16 site-groups  
 237 shows no significant temporal clusters. The primary vegetation changes (i.e. all  
 238 significant splits or, if no significant split occurs in a record, the first insignificant split)  
 239 occur during different intervals in each site-group. Overall, the early Holocene  
 240 (including 11.5, 10.5, and 9.5 ka time-slices) has the highest frequency of primary  
 241 vegetation changes. Records from the south-eastern coastal part of the study area are  
 242 characterized by relatively many early-Holocene splits (e.g. G29, G30, G32, G33,  
 243 G34, G36, G37). There are 16 site-groups whose primary vegetation changes during  
 244 the middle Holocene (including 8.5, 7.5, 6.5, and 5.5 ka time-slices), and most of  
 245 them are from inland areas such as the West Siberian Plain, central Yakutia, and  
 246 northern Mongolia. Only seven site-groups have late-Holocene primary vegetation  
 247 changes (Fig. 3).



248  
 249 Fig. 2A. Temporal changes of plant functional type (PFT) cover, as proportions, for the site-groups  
 250 from the warm temperate forest margin zone. PFT I: evergreen conifer tree; PFT II: deciduous  
 251 conifer tree; PFT III: boreal deciduous tree; PFT IV: temperate deciduous tree; PFT V: boreal  
 252 shrub; PFT VI: arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

253 Warm temperate forest margin zone in vicinity of Tianshan Mts. and north-central  
254 China (G6, G12, G13, G16, G21, G22)

255 Six site-groups from the warm temperate forest-steppe transition zone (G6, G21, G22)  
256 and from the lowlands adjacent to mountainous forest in arid central Asia (G12, G13,  
257 G16) are clustered together (Fig. 3). Our results indicate that these areas, which are  
258 now dominated by arid-tolerant shrub and steppe species, had more arboreal species,  
259 mainly evergreen conifer tree taxa, in the middle Holocene (Fig. 2A). For example,  
260 north-central China (G21) has a marked mid-Holocene maximum in forest cover (7–4  
261 ka; mean 51%). However, certain peculiarities are noted: open landscape is  
262 reconstructed between 14 and 7 ka in northern Kazakhstan (G6), followed by an  
263 abundance of evergreen conifer trees and an increase in boreal deciduous trees that  
264 maintain high values (mean 30%) after 7 ka. In the eastern branch of the Tianshan Mts.  
265 (G12), evergreen conifer trees are highly abundant from 10 to 7 ka and after 2 ka,  
266 while low abundance occurs from 14 to 11 ka and from 6 to 3 ka. In the Gobi desert  
267 near the Tianshan Mts. (G16) there was an even higher abundance of arid-tolerant  
268 species with no notable temporal trend in abundance of arboreal species. We assume  
269 that the high arboreal cover at site-groups G13 and G22 at 14 and 12 ka originates  
270 from riverine transport and therefore exclude them from further analyses.

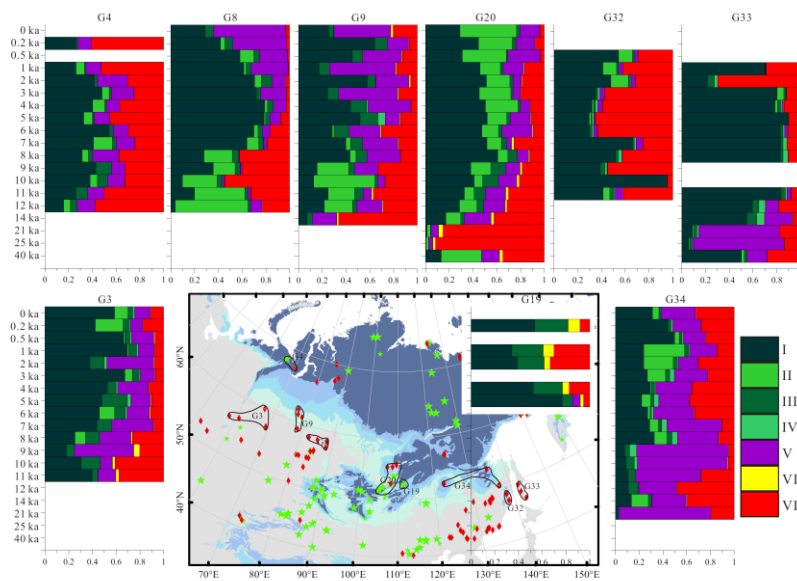


271

272 Fig. 2B. Temporal changes of plant functional type (PFT) cover, as proportions, for the site-groups  
 273 from cool-temperate mixed forest and taiga forest. PFT I: evergreen conifer tree; PFT II:  
 274 deciduous conifer tree; PFT III: boreal deciduous tree; PFT IV: temperate deciduous tree; PFT V:  
 275 boreal shrub; PFT VI: arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

276 *Cool-temperate mixed forest and taiga forest in southern and south-western Siberia*  
 277 *and north-eastern China (G2, G7, G14, G15, G18, G29, G30, G31)*

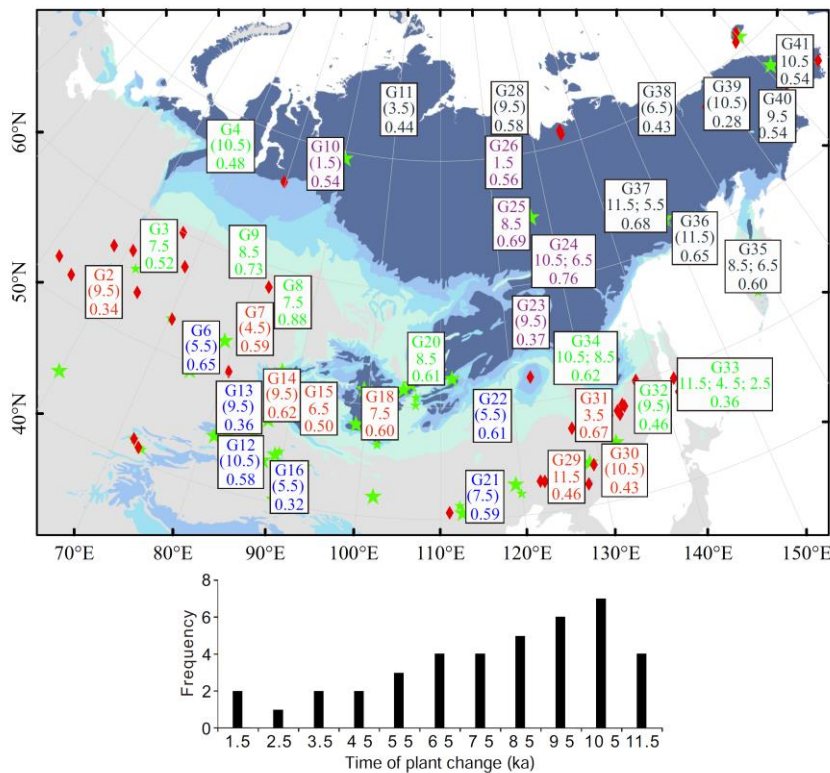
278 Eight site-groups located in (or near) the temperate mixed conifer-deciduous  
 279 broadleaved forest zone (G2, G29, G30, G31) and taiga-steppe transition zone (G7,  
 280 G14, G15, G18) show similar PFT compositions and temporal evolutions. At these  
 281 sites, evergreen conifer tree is the dominant PFT intermixed with other arboreal PFTs,  
 282 such as deciduous conifers (*Larix*) in the Altai Mts. and northern Mongolia, and/or  
 283 temperate deciduous trees in north-eastern China (Fig. 2B).



284  
 285 Fig. 2C. Temporal changes of plant functional type (PFT) cover, as proportions, for the site-groups  
 286 from dark taiga forest. PFT I: evergreen conifer tree; PFT II: deciduous conifer tree; PFT III:  
 287 boreal deciduous tree; PFT IV: temperate deciduous tree; PFT V: boreal shrub; PFT VI:  
 288 arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

289 Evergreen conifer tree is the dominant PFT at 40, 25, and 21 ka in the southern part of

290 north-eastern China (G29), *Larix* then becomes the dominant taxa at 14 and 12 ka,  
 291 and temperate deciduous trees increase thereafter and maintain high cover between 11  
 292 and 3 ka. After 2 ka, evergreen conifer trees increase to 32% on average while  
 293 temperate deciduous trees decrease to 18% on average. While arboreal abundance is  
 294 lower in the northern part of north-eastern China (G30, G31) than in the southern part  
 295 (G29), it shows a similar temporal pattern (Fig. 2B).



296  
 297 Fig. 3. Clustering results of the 34 site-groups represented by the colour of the boxes, with the age  
 298 of primary vegetation changes (middle row of each box; data in brackets means the hierarchical  
 299 clustering failed the broken-stick test) and the compositional change (turnover; lower row) during  
 300 the Holocene. A summary of the frequency of when the primary vegetation changes (revealed by  
 301 constrained hierarchical clustering, including significant and insignificant once) occurred is  
 302 provided below the map.

303 Open landscape is revealed for the southern Ural region (G2) with high abundances of  
 304 herbaceous species at 14 ka. The cover of *Larix* and evergreen conifer trees increases

305 after 12 ka and maintains high values thereafter with no notable temporal trend (Fig.  
306 2B).

307 In the taiga-steppe transition zone, *Larix* is the dominant arboreal taxon, particularly  
308 in the northern Altai Mts. and northern Mongolia (G15, G18). Open landscapes are  
309 inferred at 40, 21, and 12 ka on the southern West Siberian Plain (G7); cover of *Larix*  
310 increases at 11 ka, and evergreen conifer trees increase from 9 ka and become the  
311 dominant forest taxon after 4 ka. The temporal pattern of evergreen conifer trees in  
312 the Altai Mts. (G14) is similar to the southern West Siberian Plain, although *Larix*  
313 maintains high abundances into the late Holocene. Relative to the Altai Mts., the  
314 abundance of evergreen conifer trees for all time windows are lower in the area north  
315 of the Altai Mts. and in northern Mongolia (G15, G18), but their temporal change  
316 patterns are consistent with those of the Altai Mts. (G14; Fig. 2B).

317 *Dark taiga forest in western and south-eastern Siberia (G3, G4, G8, G9, G20, G32,*  
318 *G33, G34)*

319 Site-groups with dark taiga forest from western Siberia (G3, G4, G8, G9), the Baikal  
320 region (G20), and south-eastern Siberia (G32, G33, G34) form one cluster sharing  
321 similar PFT compositions dominated by evergreen conifer trees, with *Larix* and boreal  
322 broadleaved shrubs as the common woody taxa during the Holocene (Fig. 2C).

323 On the West Siberian Plain (G8, G9), high cover of *Larix* is reconstructed during the  
324 early Holocene as well as high woody cover since the middle Holocene formed by  
325 evergreen conifer trees and boreal shrubs. In the Ural region (G3, G4), evergreen  
326 conifer trees dominate the arboreal species throughout the Holocene. The absence of  
327 *Larix* in the early Holocene in this Ural region is a notable difference to the West  
328 Siberian Plain (Fig. 2C).

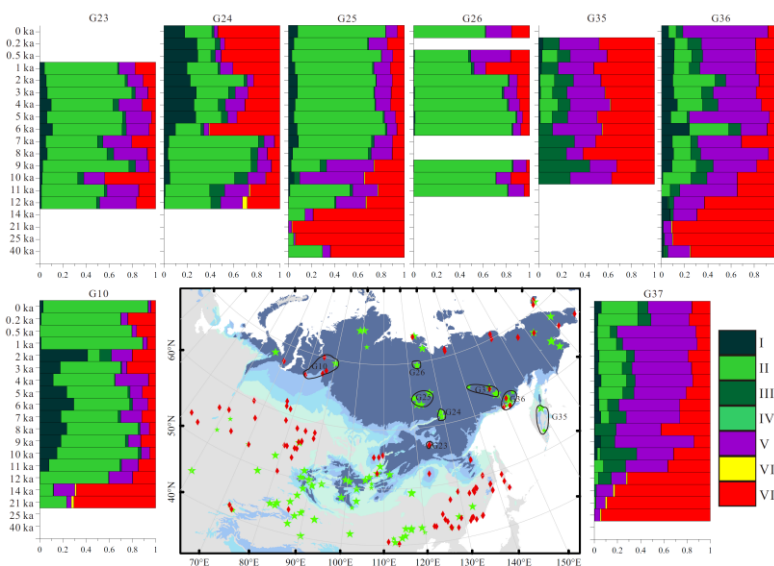
329 In the Baikal region (G20), relatively closed landscape is revealed at 40 ka; openness  
330 then increases to >95% at 25 and 21 ka. Since 14 ka, woody cover increases as shown  
331 by a notable rise in evergreen conifer trees from 14 to 8 ka and by increases of *Larix*  
332 after 7 ka (Fig. 2C).



333 In south-eastern Siberia (G32, G34), arboreal abundance is high in the early and late  
 334 Holocene, but low in the middle Holocene. South of Sakhalin Island (G33), closed  
 335 landscape is revealed between 40 and 1 ka with >80% woody cover. Evergreen  
 336 conifer tree PFT has lower cover than boreal shrub PFT at 25 and 21 ka, but increases  
 337 in abundance around 14 ka rising to 83% on average between 11 and 3 ka, and  
 338 reduces thereafter (Fig. 2C).

339 *Light taiga forest in north-western Siberia and central Yakutia (G10, G23, G24, G25,*  
 340 *G26)*

341 Plant composition of this cluster is dominated by *Larix* with high arboreal cover  
 342 during the Holocene. Evergreen conifer trees are present at ca. 15% cover between 11  
 343 and 2 ka, with high arboreal values (mean 73%) during the Holocene in north-western  
 344 Siberia (G10). In central Yakutia (G23, G24, G25), evergreen conifer trees increase  
 345 markedly from ca. 8 ka, 6 ka, and 7 ka, respectively and maintain high cover  
 346 thereafter, with ca. 60% arboreal cover throughout the Holocene. Evergreen conifer  
 347 trees are almost absent in the taiga-tundra ecotone (G26; Fig. 2D).

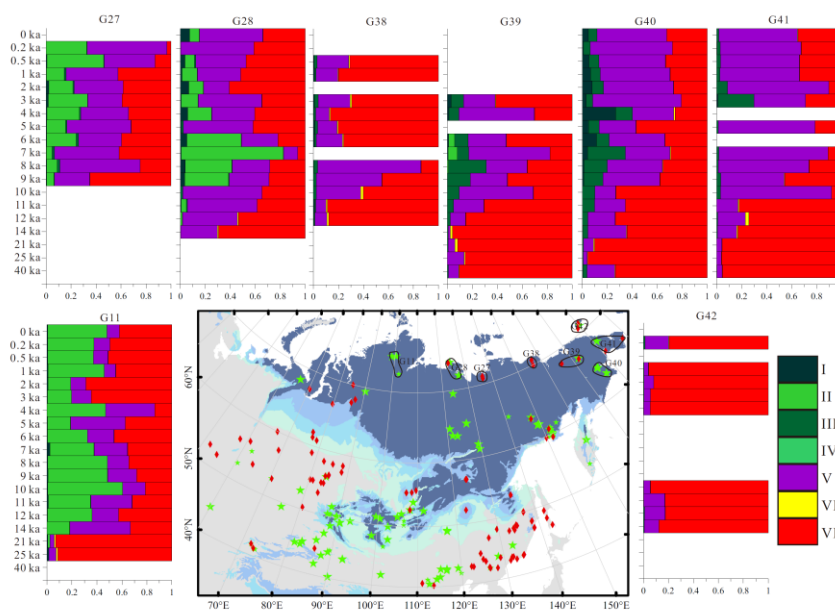


348  
 349 Fig. 2D. Temporal changes of plant functional type (PFT) cover, as proportions, for the site-groups  
 350 from light taiga forest and taiga-tundra ecotone (G35, G36, G37). PFT I: evergreen conifer tree;  
 351 PFT II: deciduous conifer tree; PFT III: boreal deciduous tree; PFT IV: temperate deciduous tree;

352 PFT V: boreal shrub; PFT VI: arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

353 *Tundra on the Taymyr Peninsula and taiga-tundra ecotone in north-eastern Siberia*  
354 (G11, G28, G35, G36, G37, G38, G39, G40, G41)

355 Plant compositions of this cluster are characterized by high abundances of boreal  
356 shrubs and tundra forbs. *Larix* is the only tree species on the Taymyr Peninsula (G11)  
357 and its abundance increases from 18% at 14 ka to 60% at 10 ka, and then decreases to  
358 18% at 5 ka. The landscape of the north Siberian coast (G28) is dominated by shrub  
359 tundra from 14 ka to 10 ka, then *Larix* increases sharply and maintains high values  
360 between 9 and 6 ka. After 5 ka, *Larix* reduces, and shrub tundra becomes the  
361 dominant landscape again (Fig. 2E).



362

363 Fig. 2E. Temporal changes of plant functional type (PFT) cover, as proportions, for the site-groups  
364 from tundra and taiga-tundra ecotone. PFT I: evergreen conifer tree; PFT II: deciduous conifer tree;  
365 PFT III: boreal deciduous tree; PFT IV: temperate deciduous tree; PFT V: boreal shrub; PFT VI:  
366 arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

367 In north-eastern Siberia, arboreal cover shows a decreasing trend from southerly  
368 site-groups (G35, G36, G37; Fig. 2D) to northerly ones (G40, G38, G39, G41)  
369 following the increasing latitude. In the Olsky District, temporal patterns of vegetation

370 changes in G37 are consistent with G36, with stable vegetation during the Holocene  
371 and increases in evergreen conifer tree abundance from ca. 9 ka. Arboreal composition  
372 on the southern Kamchatka Peninsula (G35) is dominated by boreal deciduous trees  
373 during the first stage of the Holocene, followed by rising abundances of *Larix* and  
374 evergreen conifer trees from 5 ka.

375 In north-eastern Siberia (G40, G38, G39, G41), the landscape is dominated by forb  
376 tundra with sparse shrubs between 40 and 21 ka; the cover of shrubs increases at 14  
377 ka and arboreal cover (dominated by boreal deciduous trees) increases in the early  
378 Holocene (11 or 10 ka). Shrubs maintain a high abundance throughout the Holocene,  
379 while trees peak between 10 and 2 ka generally (Fig. 2E).

#### 380 **4. Discussion**

##### 381 ***4.1 Land-cover changes and potential biases***

382 The overall patterns of pollen-based REVEALS estimates of land cover are generally  
383 consistent with previous vegetation reconstructions. Although only a few site-groups  
384 cover the period from 40 to 21 ka, a consistent vegetation signal indicates that  
385 relatively closed landscapes occurred in south-eastern Siberia, north-eastern China,  
386 and the Baikal region (Fig. 2), while most of Siberia was rather open, particularly  
387 around 21 ka (Fig. 2). These findings are consistent with previous pollen-based  
388 (Tarasov et al., 1998, 2000; Bigelow et al., 2003; Binney et al. 2017; Tian et al., 2018)  
389 and model-estimated biome reconstructions (Tian et al., 2018). During the late  
390 Pleistocene (40, 25, 21, 14 ka), steppe PFT abundance was high in central Yakutia and  
391 north-eastern Siberia (e.g. G25, G36, G37, G39, G40, G41), which may reflect the  
392 expansion of tundra-steppe, consistent with results from ancient sediment DNA which  
393 reveal abundant forb species during the period between 46 and 12.5 ka on the Taymyr  
394 Peninsula (Jørgensen et al., 2012). The tundra-steppe was replaced by light taiga in  
395 southern Siberia and by tundra in northern Siberia at the beginning of Holocene or the  
396 last deglaciation, which is consistent with ancient DNA results (forbs-dominated  
397 steppe-tundra; Willerslev et al., 2014).

398 During the Holocene, reconstructed land cover for each site-group is generally  
399 consistent with their modern vegetation. The slight vegetation changes are represented  
400 by changes in PFT abundances rather than by changes in PFT presence/absence.  
401 Minor changes are also indicated in the cluster analysis, which shows that plant  
402 compositions and their temporal patterns are consistent among the site-groups within  
403 the same modern vegetation zone (Fig. 3). PFT datasets from 16 site-groups fail the  
404 broken-stick test for clustering analysis, and most of the remaining site-groups have  
405 only one significant vegetation change, further supporting the case that only slight  
406 changes occurred during the Holocene in northern Asia. In addition, the low total  
407 amount of PFT change (turnover) over the Holocene for most site-groups supports the  
408 view of slight temporal changes in land cover.

409 Vegetation turnover on the Tibetan Plateau inferred from pollen percentages is  
410 documented to overestimate the strength of vegetation changes (Wang and Herzschuh,  
411 2011). This matches with our results. In central Yakutia, the pollen percentage data  
412 indicate a strong vegetation change during the middle Holocene, represented by a  
413 sharp increase of *Pinus* pollen, but the strength of the vegetation change is  
414 overestimated because of the high PPE of *Pinus*. The PPE-corrected arboreal  
415 abundances in central Yakutia after ca. 7 ka with ca. 70% *Larix* and ca. 10% *Pinus* are  
416 consistent with modern light taiga (Katamura et al., 2009). Furthermore, the absence  
417 of *Pinus* macrofossils in central Yakutia throughout the Holocene (Binney et al., 2009)  
418 also suggests a restricted distribution of *Pinus*, possibly to sandy places such as river  
419 banks (Isaev et al., 2010).

420 Pollen-based turnover estimates from southern Norway range between 0.84 to 1.3 SD  
421 (mean 1.02 SD) for ten Holocene pollen spectra (Birks, 2007), and from northern  
422 Europe between 0.01 (recent) to 0.99 (start of the Holocene) SD for three sites (N  
423 Sweden, NW and SE Finland) (Marquer et al., 2014). Moreover, the REVEALS-based  
424 turnover estimates (0.3–1) for northern Europe are significantly higher than the  
425 pollen-based one (0.2–0.8) from 11 ka to 5.5 ka BP. The same is true for all other  
426 regions studied by Marquer et al. (2014) in north-western Europe, and the turnover

427 estimates (pollen- and REVEALS-based) are generally higher at lower latitudes from  
428 southern Sweden down to Switzerland and eastwards to Britain and Ireland. These  
429 European values are higher than our REVEALS-based turnover estimates (from 0.37  
430 to 0.88 SD, mean 0.66 SD; G3, G8, G9, G23, G24, G25, G36, G37) from a similar  
431 latitudinal range (Fig. 3). The fewer parameters used in the turnover calculations for  
432 northern Asia (PFTs) compared to Europe (pollen taxa) is a potential reason for the  
433 lower turnover obtained in this study. In addition, the PPE-based transformation from  
434 pollen percentages to plant abundances may reduce the strength of vegetation changes  
435 (Wang and Herzschuh, 2011). Aside from the methodological aspects, the lower  
436 turnover in northern Asia may, at least partly, originate from differences in the  
437 environmental history between northern Europe compared with northern Asia, that is  
438 | glaciation followed by postglacial invasione-vegetation vs. non-glaciated areas with  
439 trees in refugia, respectively, and a maritime climate with temperature-limited  
440 vegetation distribution vs. a continental climate with temperature- and  
441 moisture-limited vegetation.

442 We consider the REVEALS-based regional vegetation-cover estimations in this study  
443 as generally reliable with reasonable standard errors (Appendix 8) thanks to the  
444 thorough selection of records with high quality pollen data and reliable chronologies.  
445 In addition, the landscape reconstructions are generally consistent with previous  
446 syntheses of past vegetation change (e.g. Tian et al., 2018) and known global climate  
447 trends (Marcott et al., 2013), plus the clustering results of PFT abundance are  
448 consistent with modern spatial vegetation patterns. That said, this study faced two  
449 major methodological challenges, discussed below, that may reduce the reliability of  
450 the obtained quantitative land-cover reconstructions; 1) the low number of PPEs and  
451 their origin and 2) restrictions with respect to the number, distribution, and type of  
452 available sites.

453 (1) Twenty PPE sets were used which mostly originate from Europe and  
454 temperate northern China. The available PPEs were estimated from various  
455 environmental and ecological settings, which might cause regional differences

456 | in each PPE. ~~Also~~And, PPEs of different species within one family or genus  
457 | were included in our mean PPE calculation for the family or genus, ignoring  
458 | the inter-species differences. ~~Both these~~Also, some taxa behave few available  
459 | PPEs with significant differences (such as *Abies*, *Larix*, *Juglans*, *Brassicaceae*),  
460 | and their mean PPE could fail to represent their real pollen productivities.  
461 | These aspects can cause uncertainty in the mean PPE to some extent. However,  
462 | we believe that the compiled PPE sets can be used to extract major broad-scale  
463 | and long-term vegetation patterns because the regional differences in the PPE  
464 | for ~~each~~most taxon are small compared to the large between-taxa differences.  
465 | The mean PPEs used in this REVEALS modelling (Table 2) are broadly  
466 | consistent with those obtained from Europe (Mazier et al., 2012). In addition,  
467 | although there are no PPEs for the core from the Siberia taiga forest, available  
468 | studies on modern pollen composition support the weightings in the applied  
469 | PPEs for major taxa in terms of pollen under- or over-representation of  
470 | vegetation abundance. For example, modern pollen investigations in  
471 | north-eastern Siberia revealed that pollen records from northern *Larix* forest  
472 | often have less than 13% *Larix* pollen, confirming the low pollen productivity  
473 | of *Larix* relative to over-represented pollen taxa such as *Betula* and *Alnus*  
474 | (Pisaric et al., 2001, Klemm et al., 2016). Similarly, a study on modern pollen  
475 | in southern Siberia (transitional area of steppe and taiga) finds that *Artemisia*,  
476 | *Betula*, and *Pinus* are high pollen producers compared to *Larix* (Pel ánkov á et  
477 | al., 2008). Also, despite *Larix* being the most common tree in taiga forest in  
478 | north-central Mongolia, the pollen abundance of *Larix* is generally lower than  
479 | 3% (Ma et al., 2008), implying its low pollen productivity.

480 | (2) In this study, we attempt to reconstruct past landscape changes at a regional  
481 | scale. Pollen signals from large lakes are assumed to reflect regional  
482 | vegetation patterns (e.g. Sugita et al., 2010; Trondman et al., 2015). If large  
483 | lakes are absent in a region, multiple small-sized sites can be used, although  
484 | error estimates are usually large (Sugita, 2007; Mazier et al., 2012; Trondman

485 et al., 2016). In our study, 70% of the time slices for the 42 site-groups include  
486 pollen data from large lakes (i.e. radii >390m), which supports the reliability  
487 of REVEALS reconstructions (Appendix 5). However, sites are unevenly  
488 distributed and occasionally sites from different areas were combined into one  
489 group (G2, G6, G34), which might produce a different vegetation-change  
490 signal because of the broad distribution of these sites (Fig. 1). In addition, the  
491 linear interpolation of pollen abundances for time windows with few pollen  
492 data might be another source of uncertainty, particularly for the late  
493 Pleistocene and its broad time windows (Table 1). Finally, pollen signals from  
494 certain sites and during certain periods may be of water-runoff origin rather  
495 than aerial origin violating the assumption of the REVEALS-model that pollen  
496 is transported by wind.

#### 497 ***4.2 Driving factors of vegetation changes***

498 On a glacial-interglacial scale, pollen-based reconstructed land-cover changes in  
499 northern Asia are generally consistent with the global climate signal (e.g. sea-surface  
500 temperature: Pailler and Bard, 2002; ice-core: Andersen et al., 2004; solar insolation:  
501 Laskar et al., 2004; cave deposits: Cheng et al., 2016; Appendix 9). For example, the  
502 relatively high arboreal cover at 40 ka (e.g. G20) corresponds with the warm MIS3  
503 record from the Baikal region (Swann et al., 2005). The open landscape at 25 ka and  
504 21 ka (e.g. G25, G36) reflects the cold and dry last glacial maximum (e.g. Swann et  
505 al., 2010). Furthermore, the relatively high arboreal cover during the Holocene is  
506 consistent with the warm and wet climate (occurring in most site-groups). The  
507 primary vegetation change in north-eastern China (G29, G30) occurs in the early  
508 Holocene (11.5 and 10.5 ka), caused by the rapid increase in abundance of temperate  
509 deciduous trees, which may reflect the warmer climate and enhanced summer  
510 monsoon known from that region at the beginning of the Holocene (Hong et al., 2009,  
511 Liu et al., 2014).

512 A sensitivity analysis of model-based biome estimation reveals that precipitation plays  
513 an important or even dominant role in controlling vegetation changes in arid central

514 Asia (e.g. Tian et al., 2018). The climate of central Asia during the early Holocene is  
515 inferred to be quite dry and moisture increase occurs at ca. 8 ka revealed by a series of  
516 multi-proxy syntheses (Chen et al., 2008, 2016; Xie et al., 2018) and model-based  
517 estimations (Jin et al., 2012). In the taiga-steppe transition zone (south-eastern Siberia  
518 and north-central Asia; e.g. G6, G12, G14, G18), relatively open landscape is  
519 reconstructed for the early Holocene and abundances of forest taxa increase after ca. 8  
520 ka, which are consistent with the moisture evolution, and imply the importance of  
521 moisture in controlling vegetation changes. Our results support the prediction of an  
522 expansion of steppe in the present forest–steppe ecotone of southern Siberia in  
523 response to a warmer and drier climate in the future (Tchebakova et al., 2009). During  
524 the late Holocene, the decreases in forest cover in the forest–steppe ecotone of  
525 north-central China and central Asia are ascribed to the drying or cooling climate  
526 respectively by sensitivity analysis (Tian et al., 2018). However, the enhanced human  
527 impacts might be another important factor (e.g. Ren, 2017), while the model fail to  
528 separate its contribution on vegetation.

529 High abundances of *Larix* or boreal deciduous woody taxa (mostly shrubs) pollen  
530 occur in northern Siberia (e.g. G28, G38, G39, G40) during the middle Holocene,  
531 which is now covered by tundra. This is consistent with non-vegetation climate  
532 records of a mid-Holocene temperature maximum (e.g. Biskaborn et al, 2012;  
533 Nazarova et al., 2013). This result indicates that the boreal treeline in northern Siberia  
534 reacts sensitively to warming on millennial time-scales, which contrasts with the  
535 observed lack of response on a decadal time-scale (Wieczoreck et al., 2017). This may  
536 point to a highly non-linear vegetation–climate relationship in northern Siberia.

537 Our results indicate that climate change is the major factor driving land-cover change  
538 in northern Asia on a long temporal scale. However, climate change cannot fully  
539 explain the changes in arboreal taxa abundance for the West Siberian Plain (G8, G9)  
540 and sandy places in central Yakutia (G23, G24, G25). In addition to climate, changes  
541 in permafrost condition (Vandenberghe et al., 2014) and fire regime may have played  
542 a central role in vegetation change. *Larix* is the dominant arboreal taxon during the



543 early Holocene (ca. between 12 and 8 ka), which is replaced by evergreen conifer  
544 trees, mostly pine and spruce at 8 or 7 ka. *Larix* can survive on permafrost with an  
545 active-layer depth of <40 cm (Osawa et al., 2010) and a high fire frequency, while  
546 pine trees can only grow on soil with >1.5m active-layer (Tzedakis and Bennett, 1995)  
547 and spruce is a fire-avoider. Probably the compositional change of boreal trees was  
548 not in equilibrium with climate but rather driven by changes in the permafrost and fire  
549 characteristics that were themselves affected by forest composition, resulting in  
550 complex feedbacks. This explanation would be in agreement with the finding of  
551 Herzschuh et al. (2016) that the boreal forest composition of nearby refugia during a  
552 glacial influences the initial interglacial forest composition that is then only slowly  
553 replaced by a forest composition that is in equilibrium with climate.

554 Population changes of herbivores could also be an important factor for vegetation  
555 change at a regional scale during certain intervals (Zimov et al., 1995; Guthrie, 2006).  
556 As with our pollen-based land-cover reconstruction, a circumpolar ancient DNA  
557 metabarcoding study confirms the replacement of steppe-like tundra by moist tundra  
558 with abundant woody plants at the Pleistocene–Holocene transition (Willerslev et al.,  
559 2014). According to Zimov et al. (1995, 2012), such a change cannot be explained by  
560 climate change alone, and thus a reduced density of herbivores is considered to be a  
561 major driving factor of steppe composition reduction, since a reduced number of  
562 herbivores is insufficient to maintain the open steppe landscapes and so causes a  
563 decrease in steppe area (Zimov et al., 1995; Guthrie, 2006). Our land-cover  
564 reconstruction fails to address the contribution of herbivores to vegetation changes,  
565 but the extinction of herbivorous megafauna would add to the complexity of the  
566 interactions among vegetation, climate and permafrost.

## 567 **5. Conclusions**

568 Regional vegetation based on pollen data has been estimated using the REVEALS  
569 model for northern Asia during the last 40 ka. Relatively closed land cover was  
570 replaced by open landscapes in northern Asia during the transition from MIS 3 to the

571 last glacial maximum. Abundances of woody components increase again from the last  
572 deglaciation or early Holocene. Pollen-based REVEALS estimates of plant  
573 abundances should be a more reliable reflection of the vegetation as pollen may  
574 overestimate the turnover, and indicates that the vegetation was quite stable during the  
575 Holocene as only slight changes in the abundances of PFTs were recorded rather than  
576 mass expansion of new PFTs. From comparisons of our results with other data we  
577 infer that climate change is likely the primary driving factor for vegetation changes on  
578 a glacial-interglacial scale. However, the extension of evergreen conifer trees since ca.  
579 8–7 ka throughout Siberia could reflect vegetation-climate disequilibrium at a  
580 long-term scale caused by the interaction of climate, vegetation, fire, and permafrost,  
581 which could be an palaeo-analogue not only for the recent complex vegetation  
582 response to climate changes but also for the vegetation prediction in future.

583 **Data availability.** The used fossil pollen dataset with the re-established age-depth  
584 model for each pollen record, ~~and its full description will be~~ have been made publicly  
585 available in ~~the journal Earth System Science Data (ESSDPangaea~~  
586 (<https://doi.pangaea.de/10.1594/PANGAEA.898616>).

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595 LandCover6k working group project.

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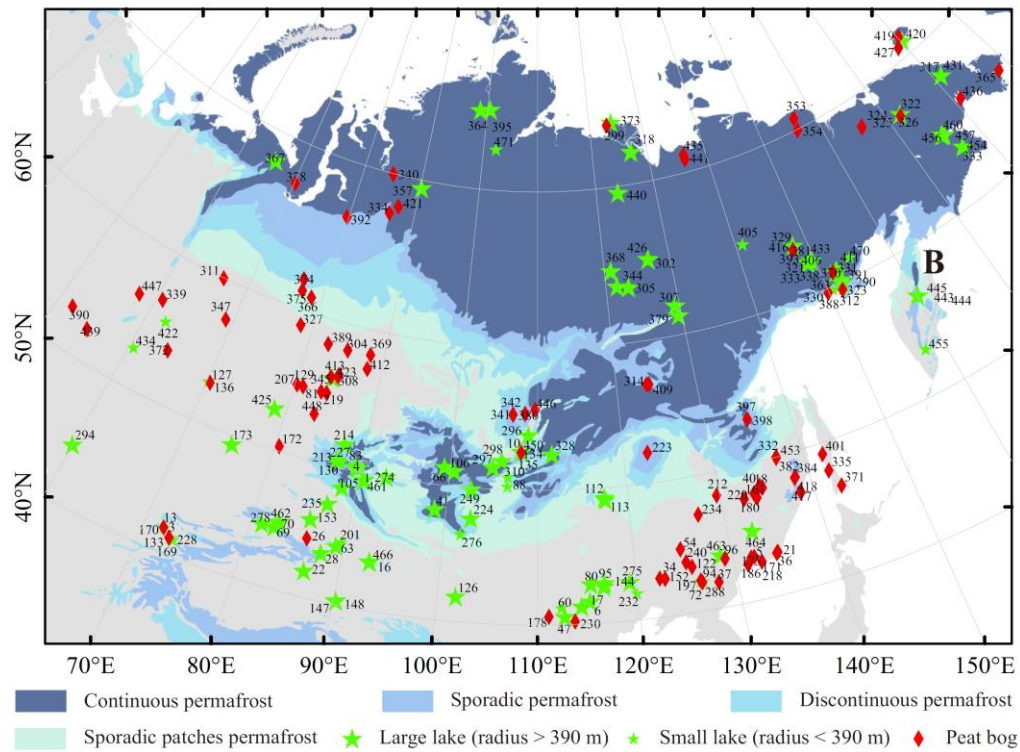
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1001 Appendices

1002 **Appendix 1** Distribution of the 203 fossil pollen sites together with the modern permafrost extent in northern Asia. The number of each site is used as its site ID in

1003 Appendix 2.



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**Appendix 2** Metadata for all pollen records used in this study. [Original publications list see https://doi.pangaea.de/10.1594/PANGAEA.898616](https://doi.pangaea.de/10.1594/PANGAEA.898616).

Group	Site ID	Site	Lat.	Long.	Elev. (m)	Basin type	Pollen count	Area (ha)	Radius (m)	Dating method	Num. of dating	Time span (cal ka BP)	Resol. (year)	Reference
G1	294	Aral Lake	44.42	59.98	53	Lake	Yes	330000	32410	<sup>14</sup> C	4U	8.7-0	260	Aleshinskaya, Z.V. unpublished.
G2	372	Mokhovoye	53.77	64.25	178	Bog	Yes	20	252	<sup>14</sup> C	4C+1E	6.0-0	180	Kremenetskii et al., 1994
G2	439	Novienky peat bog	52.24	54.75	197	Bog	Yes	-	-	<sup>14</sup> C	1U	4.5-0	270	López-García et al., 2003
G2	422	Zaboinoe Lake	55.53	62.37	275	Lake	Yes	6	138	<sup>14</sup> C	1U	12.3-0.1	220	Khomutova and Pushenko, 1995
G2	434	Lake Fernshee	52.83	60.50	290	Lake	Yes	0	38	<sup>14</sup> C	10A	9.1-0.4	220	Stobbe et al., 2015
G2	390	Pobochnoye	53.03	51.84	81	Bog	No	79	500	<sup>14</sup> C	10C+6E	14.4-0	540	Kremenetski et al., 1999
G3	311	Chesnok Peat	60.00	66.50	42	Bog	Yes	-	-	<sup>14</sup> C	7C	10.6-0.5	280	Volkova, 1966
G3	347	Komaritsa Peat	57.50	69.00	42	Bog	Yes	-	-	<sup>14</sup> C	10C	10.5-0.5	350	Volkova, 1966
G3	447	UstMashevskoe	56.32	57.88	220	Bog	Yes	30	309	<sup>14</sup> C	5C	7.8-0	150	Panova et al., 1996
G3	339	Karasieozerskoe	56.77	60.75	230	Bog	Yes	914	1706	<sup>14</sup> C	3A	5.9-0.1	190	Panova, 1997
G4	378	Nulsaveito	67.53	70.17	57	Bog	Yes	-	-	<sup>14</sup> C	4A+1C	8.4-6.4	70	Panova, 1990
G4	367	Lyadhej-To Lake	68.25	65.75	150	Lake	Yes	197	792	<sup>14</sup> C	14A+6E	12.5-0.3	170	Andreev et al., 2005
G5	169	Nizhnee Lake	41.30	72.95	1371	Lake	No	-	70	<sup>14</sup> C	4E	1.5-0	100	Beer et al., 2008
G5	228	Verkhnee Lake	41.30	72.95	1440	Lake	No	1	60	<sup>14</sup> C	5E	1.5-0	100	Beer et al., 2008
G5	3	Ak Terk Lake	41.28	72.83	1748	Bog	No	-	-	<sup>14</sup> C	2A	7.5-0	200	Beer et al., 2008
G5	133	Kosh Sas	41.85	71.97	1786	Bog	No	-	-	<sup>14</sup> C	1A	3.5-0	100	Beer et al., 2008
G5	170	Ortok Lake	41.23	73.25	1786	Lake	No	-	60	<sup>14</sup> C	5A	1-0	100	Beer et al., 2008
G5	13	Bakaly Lake	41.87	71.97	1879	Lake	No	1	50	<sup>14</sup> C	4A	7-0	195	Beer et al., 2008
G6	425	Big Yarovoe Lake	52.85	78.63	79	Lake	Yes	6362	4500	inclination	-	4.3-0	190	Rudaya et al., 2012

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G6	172	Ozerki	50.40	80.47	210	Bog	Yes	-	-	<sup>14</sup> C	3A+13C	14.5-0	300	Tarasov et al., 1997
G6	127	Karas'e Lake	53.03	70.22	435	Lake	Yes	17	235	<sup>14</sup> C	6U	5.5-0	170	Tarasov and Kremenetskii, 1995
G6	136	Kotyrkol	52.97	70.42	439	Bog	Yes	-	-	<sup>14</sup> C	8U	4.5-0.5	180	Tarasov and Kremenetskii, 1995
G6	173	Pashennoe Lake	49.37	75.40	871	Lake	Yes	64	451	<sup>14</sup> C	5D+5E	9.5-0	280	Tarasov and Kremenetskii, 1995
G7	81	Gladkoye Bog	55.00	83.33	80	Bog	Yes	-	-	<sup>14</sup> C	13C	11-0.5	170	Firsov et al., 1982
G7	308	Chaginskoe Mire	56.45	84.88	80	Bog	Yes	10	175	<sup>14</sup> C	2C	8.8-0	320	Blyakharchuk, 2003.
G7	345	Kirek Lake	56.10	84.22	90	Lake	Yes	52	407	<sup>14</sup> C	3G	10.5-1.5	190	Blyakharchuk, 2003
G7	413	Tom' River Peat	56.17	84.00	100	Bog	Yes	-	-	<sup>14</sup> C	6C	10.1-0.2	390	Arkhipov and Votakh, 1980
G7	423	Zhukovskoye mire	56.33	84.83	106	Bog	Yes	-	-	<sup>14</sup> C	9C+6H	11.2-0	130	Borisova et al., 2011
G7	219	Tolmachevsko	55.00	84.00	110	Bog	Yes	-	-	<sup>14</sup> C	1A+3C	13-1.5	400	Volkov and Arkhipov, 1978
G7	207	Suminskoye	55.00	80.25	135	Bog	Yes	-	-	<sup>14</sup> C	8A	3-0	200	Klimanov, 1976
G7	129	Kayakskoye	55.00	81.00	150	Bog	Yes	-	-	<sup>14</sup> C	5C	6.5-0	210	Levina et al., 1987
G7	448	Kalistratikha	53.33	83.25	190	Bog	Yes	-	-	<sup>14</sup> C	4A	39.0-12.7	1870	Zudin and Votakh, 1977
G8	389	Petropavlovka	58.33	82.50	100	Bog	Yes	-	-	<sup>14</sup> C	4C+1E	10.5-0.1	160	Blyakharchuk, 1989
G8	304	Bugristoe	58.25	85.17	130	Bog	Yes	-	-	LSC	4C+1E	11.5-5.0	100	Blyakharchuk, 1989
G8	369	Maksimkin Yar	58.33	88.17	150	Bog	Yes	-	-	<sup>14</sup> C	4C	8.3-0.2	170	Blyakharchuk, 1989
G8	412	Teguldet	57.33	88.17	150	Bog	Yes	-	-	LSC	3C	7.3-2.4	90	Blyakharchuk, 1989
G9	374	Nizhnevartovsk	62.00	76.67	54	Bog	Yes	-	-	<sup>14</sup> C	3A+7C	11.1-0	300	Neustadt and Zelikson,

													1985	
G9	375	Nizhnevartovskoye	61.25	77.00	55	Bog	Yes	-	-	<sup>14</sup> C	1A+12C+1E	12.6-0	380	Neishtadt, 1976
G9	327	Entarmoye Peat	59.00	78.33	65	Bog	Yes	-	-	<sup>14</sup> C	5C	14.9-0.9	460	Neishtadt, 1976
G9	366	Lukaschin Yar	61.00	78.50	65	Bog	Yes	-	-	<sup>14</sup> C	13C	10.9-0.3	430	Neishtadt, 1976
G10	334	Igarka Peat	67.67	86.00	45	Bog	Yes	244	881	<sup>14</sup> C	1A+2C	10.9-5.9	230	Kats, 1953
G10	392	Pur-Taz Peatland	66.70	79.73	50	Bog	Yes	5	126	<sup>14</sup> C	5A	10.3-4.7	80	Peteet et al., 1998
G10	340	Karginskii Cape	70.00	85.00	60	Bog	Yes	-	-	<sup>14</sup> C	13C	8.9-3.5	290	Firsov et al., 1972
G10	421	Yenisei	68.17	87.15	68	Bog	No	-	-	<sup>14</sup> C	7C	6.5-1.6	110	Andreev and Klimanov 2000
G10	357	Lake Lama	69.53	90.20	77	Lake	Yes	64245	14300	<sup>14</sup> C	26A+4D+4E	19.5-0	170	Andreev et al., 2004
G11	471	11-CH-12A Lake	72.40	102.29	60	Lake	Yes	3	100	<sup>14</sup> C+Pb/Cs	8A+7E	7.0-0.1	110	Klemm et al., 2015
G11	364	Levinson-Lessing Lake	74.47	98.64	26	Lake	Yes	2145	2613	<sup>14</sup> C	29A+1B+19E	35.3-0	390	Andreev et al., 2003
G11	395	SAO1	74.55	100.53	32	Lake	Yes	456000	38098	<sup>14</sup> C	6A+5C	57.9-0	1320	Andreev et al., 2003
G12	462	Aibi Lake	45.02	82.83	200	Lake	Yes	100885	17920	<sup>14</sup> C	8E	12.6-0	65	Wang et al., 2013
G12	69	Ebinur Lake	44.55	82.45	212	Lake	Yes	46421	12156	<sup>14</sup> C	7U	13-0	900	Wen and Qiao, 1990
G12	70	Ebinur Lake_SW	45.00	82.80	212	Lake	Yes	46421	12156	<sup>14</sup> C	6U	8.5-1.5	780	Lin, 1994
G12	26	Caotanh Lake	44.42	86.02	380	Bog	Yes	2760	2964	<sup>14</sup> C	5C	8.5-0	150	Zhang Y. et al., 2008
G12	63	Dongdaohaizi Lake	44.70	89.56	430	Lake	Yes	20	252	<sup>14</sup> C	8U	5.5-0	85	Yan et al., 2004
G12	201	Sichanghu Lake	44.31	89.14	589	Lake	Yes	2000	2523	<sup>14</sup> C	4U	1-0	50	Zhang Y. et al., 2004b
G12	22	Bosten Lake	41.97	86.55	1050	Lake	No	96608	17536	<sup>14</sup> C	5U	13-0	420	Xu, 1998
G12	28	Chaiwopu Lake	43.55	87.78	1100	Lake	No	3101	3142	<sup>14</sup> C	2U	10-0	845	Li and Yan, 1990
G12	278	Sayram Lake	44.57	81.15	2072	Lake	Yes	45800	12074	<sup>14</sup> C	12E	13.8-0.1	90	Jiang et al., 2013
G13	153	Manas Lake	45.83	85.92	251	Lake	Yes	55000	13231	<sup>14</sup> C	7C	13.5-1	210	Sun et al., 1994
G13	235	Wulungu Lake	47.22	87.30	479	Lake	Yes	67019	430	<sup>14</sup> C+Pb/Cs	1C	9-0	80	Liu X.Q. et al., 2008

G14	214	Teletskoye Lake	51.72	87.65	1900	Lake	Yes	16610	7271	<sup>14</sup> C+Pb/Cs	6E	1-0	20	Andreev et al., 2007
G14	227	Uzunkol Lake	50.48	87.11	1985	Lake	No	123	625	<sup>14</sup> C	2A	17.5-0	210	Blyakharchuk et al., 2004
G14	130	Kendegelukol Lake	50.51	87.64	2050	Lake	No	5	130	<sup>14</sup> C	7E	16-1	260	Blyakharchuk et al., 2004
G14	105	Hoton Nur Lake	48.62	88.35	2083	Lake	Yes	5021	3998	<sup>14</sup> C	4A	6-0	60	Rudaya et al., 2009
G14	213	Tashkol Lake	50.45	87.67	2150	Lake	No	-	150	<sup>14</sup> C	3C	16-3	250	Blyakharchuk et al., 2004
G14	4	Akkol Lake	50.25	89.63	2204	Lake	No	388	1111	<sup>14</sup> C	12E	13.5-0	250	Blyakharchuk et al., 2007
G14	83	Grusha Lake	50.38	89.42	2413	Lake	No	130	644	<sup>14</sup> C	3A+13E	14-1.5	250	Blyakharchuk et al., 2007
G15	274	Bayan Nuur	50.00	93.00	932	Lake	No	2968	3073	<sup>14</sup> C	7E	15.7-0.2	210	Krengel, 2000
G15	1	Achit Nur Lake	49.50	90.60	1435	Lake	No	29700	9723	<sup>14</sup> C	4E	14-0.5	700	Gunin et al., 1999
G15	461	Achit Nuur	49.42	90.52	1444	Lake	No	29700	9723	<sup>14</sup> C	10E	20.2-0	250	Sun et al., 2013
G16	148	Lop Nur_1998	40.28	90.25	780	Lake	No	535000	41267	<sup>14</sup> C	3U	22-2	2000	Yan et al., 1998
G16	147	Lop Nur_1983	40.33	90.25	800	Lake	Yes	535000	41267	<sup>14</sup> C	3U	22-0.5	1600	Yan et al., 1983
G16	16	Barkol Lake	43.62	92.80	1575	Lake	Yes	11300	5997	<sup>14</sup> C	1A+10E	10-0	115	Tao et al., 2009
G16	466	Balikun Lake	43.68	92.80	1575	Lake	Yes	7897	5014	<sup>14</sup> C	1D+5E	30.5-9	250	An et al., 2013
G17	126	Juyan Lake	41.89	101.85	892	Lake	Yes	72000	15139	<sup>14</sup> C	5E	10.5-1.5	140	Herzschuh et al., 2004
G18	88	Gun Nur Lake	50.25	106.60	600	Lake	No	33	325	<sup>14</sup> C	7E	11-0	320	Gunin et al., 1999
G18	249	Yamant Nur Lake	49.90	102.60	1000	Lake	No	58	430	<sup>14</sup> C	4E	15.5-0.5	360	Gunin et al., 1999
G18	224	Ugii Nuur Lake	47.77	102.77	1330	Lake	No	2456	2796	<sup>14</sup> C	2C	9-0	85	Wang et al., 2011
G18	66	Dood Nur Lake	51.33	99.38	1538	Lake	No	6400	4514	<sup>14</sup> C	2E	14-0	740	Gunin et al., 1999
G18	106	Hovsgol Lake	51.10	100.50	1645	Lake	Yes	276000	29640	<sup>14</sup> C	5E	12-2.5	190	Prokopenko et al., 2007
G18	276	Khuisiin Lake	46.60	101.80	2270	Lake	Yes	4	118	<sup>14</sup> C+Pb/Cs	6E	1.2-0	17	Tian et al., 2013
G18	41	Daba Nur Lake	48.20	98.79	2465	Lake	No	157	707	<sup>14</sup> C	5E	13-0	520	Gunin et al., 1999
G19	328	Bolshoe Eravnoe Lake	52.58	111.67	947	Lake	Yes	9503	5500	<sup>14</sup> C	3E	7.3-0.2	710	Vipper, 2010
G20	10	Baikel Lake	52.08	105.87	130	Lake	No	3150000	100134	<sup>14</sup> C	12A	22-0	370	Demske et al., 2005

G20	296	Baikal Lake-CON01-603-5	53.95	108.91	446	Lake	Yes	3150000	100134	<sup>14</sup> C	10D	15.8-0	270	Demske et al., 2005
G20	135	Lake Kotokel_2010	52.78	108.12	458	Lake	Yes	6900	4687	<sup>14</sup> C	11E	47-0	220	Bezrukova et al., 2010
G20	134	Lake Kotokel_2009	52.78	108.12	458	Lake	Yes	6900	4687	<sup>14</sup> C	3E	15-0	500	Tarasov et al., 2009
G20	310	Chernoe Lake	50.95	106.63	500	Lake	Yes	-	250	<sup>14</sup> C	4E	7-0.7	620	Vipper, 2010
G20	297	Baikal Lake-CON01-605-3	51.59	104.85	675	Lake	Yes	3150000	100134	<sup>14</sup> C	5D	17.7-0	200	Demske et al., 2005
G20	380	Okunayka	55.52	108.47	802	Bog	Yes	-	-	<sup>14</sup> C	6C	8.3-2.0	120	Bezrukova et al., 2011
G20	446	Ukta Creek mouth	55.80	109.70	906	Bog	Yes	-	-	<sup>14</sup> C	3U	5.1-0	160	Bezrukova et al., 2006
G20	450	Cheremushka Bog	52.75	108.08	1500	Bog	Yes	-	-	<sup>14</sup> C	6C	33.5-0	460	Shichi et al., 2009
G20	298	Baikal Lake-CON01-605-5	51.58	104.85	492	Lake	Yes	3150000	100134	<sup>14</sup> C	12D	11.5-0	130	Demske et al., 2005
G20	341	Khanda-1	55.44	107.00	867	Bog	Yes	-	-	<sup>14</sup> C	3C	3.1-0.3	50	Bezrukova et al., 2011
G20	342	Khanda	55.44	107.00	867	Bog	Yes	-	-	<sup>14</sup> C	6C	5.8-0	140	Bezrukova et al., 2011
G21	275	Qiganhu Lake	42.90	119.30	600	Lake	Yes	190	778	<sup>14</sup> C	5E	12.1-6.7	35	Hu et al., 2016
G21	232	Wangyanggou	42.07	119.92	751	Lake	No	13	200	<sup>14</sup> C	1A+3E	5-0	85	Li et al., 2006
G21	230	Wangguantun	40.27	113.67	800	Bog	Yes	-	-	<sup>14</sup> C	1A+4F	8-3	310	Kong and Du, 1996
G21	6	Anguli Nur Lake	41.33	114.37	1000	Lake	Yes	4264	3684	<sup>14</sup> C	2U	14-10.5	520	Li et al., 1990
G21	178	Qasq	40.67	111.13	1000	Bog	Yes	-	-	<sup>14</sup> C	2E	10-0	90	Wang et al., 1997
G21	47	Daihai Lake_2004	40.58	112.67	1220	Lake	Yes	16000	7136	<sup>14</sup> C	8E	11.5-0	215	Xiao et al., 2004
G21	80	Gaoximage Lake	42.95	115.37	1253	Lake	No	100000	17841	<sup>14</sup> C	4E	6-0	150	Li C.Y. et al., 2003
G21	95	Haoluku Lake	42.96	116.76	1295	Lake	No	1384	2099	<sup>14</sup> C	4E	11.5-0	250	Wang et al., 2001
G21	17	Bayanchagan Lake	41.65	115.21	1355	Lake	Yes	636	1423	<sup>14</sup> C	2B+7E	11.5-0	250	Jiang et al., 2006
G21	144	Liuzhouwan Lake	42.71	116.68	1365	Lake	No	288	957	<sup>14</sup> C	3E	13-0.5	470	Wang et al., 2001
G21	60	Diaojiaohaizi Lake	41.30	112.35	1800	Lake	Yes	30	309	<sup>14</sup> C	4U	11.5-2.5	95	Song et al., 1996

G22	112	Hulun Nur Lake_1995	49.28	117.40	544	Lake	No	233900	27286	<sup>14</sup> C	7U	19-0.5	190	Yang et al., 1995
G22	113	Hulun Nur Lake_2006	49.13	117.51	545	Lake	Yes	233900	27286	<sup>14</sup> C	13E	11-0	65	Wen et al., 2010
G23	314	Derput	57.03	124.12	700	Bog	Yes	1	56	<sup>14</sup> C	1A+4C	11.7-0.8	210	Andreev and Klimanov, 1991
G23	409	Suollakh	57.05	123.85	811	Bog	Yes	-	-	<sup>14</sup> C	8C	12.8-3.7	180	Andreev et al., 1991
G24	379	Nuochaga Lake	61.30	129.55	260	Lake	Yes	120	618	<sup>14</sup> C	4E	6.5-0	140	Andreev and Klimanov, 1989
G24	307	Chabada Lake	61.98	129.37	290	Lake	Yes	210	818	<sup>14</sup> C	15U	13-0	110	Andreev and Klimanov, 1989
G25	305	Boguda Lake	63.67	123.25	120	Lake	Yes	2500	2821	<sup>14</sup> C	7E	10.9-0.4	180	Andreev et al., 1989
G25	344	Khomustakh Lake	63.82	121.62	120	Lake	Yes	440	1183	<sup>14</sup> C	9E	12.3-0.1	170	Andreev et al., 1989
G25	368	Madjaga Lake	64.83	120.97	160	Lake	Yes	1440	2141	LSC	7E	8.2-0.2	120	Andreev and Klimanov, 1989
G25	302	Billyakh Lake	65.30	126.78	340	Lake	Yes	1678	2311	<sup>14</sup> C	7A	14.1-0	180	Müller et al., 2009
G25	426	Lake Billyakh_PG1755	65.27	126.75	340	Lake	Yes	1634	2281	<sup>14</sup> C	1A+10E	50.6-0.2	470	Müller et al., 2010
G26	440	Lake Kyutyunda_PG2022	69.63	123.65	66	Lake	Yes	468	1220	<sup>14</sup> C	10E	10.8-0.3	360	Biskaborn et al., 2015
G27	435	Khocho	71.05	136.23	6	Bog	Yes	10	178	<sup>14</sup> C	1C	10.4-0.4	300	Velichko et al., 1994
G27	441	Samandon	70.77	136.25	10	Bog	Yes	100	564	<sup>14</sup> C	3A+8C+4E	7.9-0.2	280	Velichko et al., 1994
G28	299	Barbarina Tumsa	73.57	123.35	10	Bog	Yes	-	-	<sup>14</sup> C	4C	4.9-0.3	240	Andreev et al., 2004
G28	373	Lake Nikolay	73.67	124.25	35	Lake	Yes	1500	2185	<sup>14</sup> C	6A	12.5-0	600	Andreev et al., 2004
G28	318	Dolgoe Ozero	71.87	127.07	12	Lake	Yes	84	517	<sup>14</sup> C	1A+9B	15.3-0	210	Pisaric et al., 2001
G29	152	Maili	42.87	122.88	155	Bog	No	-	-	<sup>14</sup> C	5A	3-0	115	Ren and Zhang, 1997
G29	54	Dashan	44.88	124.85	200	Bog	Yes	-	-	<sup>14</sup> C	5U	7.5-1	160	Xia et al., 1993
G29	240	Xiaonan	43.88	125.22	209	Bog	Yes	-	-	<sup>14</sup> C	5U	5.5-0	290	Wang and Xia, 1988

G29	197	Shuangyang	43.45	125.75	215	Bog	Yes	-	-	<sup>14</sup> C	12E	2.5-0	30	Qiu et al., 1981
G29	34	Charisu	42.95	122.35	249	Bog	Yes	-	-	<sup>14</sup> C	10A	5.5-0	170	Li Y.H. et al., 2003b
G29	463	Jingbo Lake	43.91	128.75	350	Lake	Yes	9500	5499	<sup>14</sup> C+LSC	3E+4	8.8-0	40	Li et al., 2011
G29	96	Harbaling	43.63	129.20	600	Bog	Yes	-	-	<sup>14</sup> C	3U	3-0	150	Xia, 1988b
G29	122	Jinchuan	42.35	126.38	620	Bog	Yes	-	-	<sup>14</sup> C	7A	5.5-0	105	Li Y.H. et al., 2003a
G29	72	Erhailongwan Lake	42.30	126.37	724	Lake	Yes	30	309	<sup>14</sup> C	2A+14E	22-0	760	Liu Y.Y. et al., 2008
G29	288	Sihailongwan Lake	42.28	126.60	797	Lake	Yes	41	360	<sup>14</sup> C+varve	40A	16.9-0.2	47	Stebich et al., 2015
G29	94	Hani	42.21	126.52	899	Bog	Yes	1800	2394	<sup>14</sup> C	1C	9.5-0	455	Qiao, 1993
G29	37	Chichi Lake	42.03	128.13	1800	Bog	Yes	0	40	<sup>14</sup> C	1C	1-0	140	Xu et al., 1994
G30	21	Belaya Skala	43.25	134.57	4	Bog	Yes	-	-	<sup>14</sup> C	2A+1C	6.5-3	250	Korotky et al., 1980
G30	36	Chernyii Yar	43.18	134.43	4	Bog	Yes	-	-	<sup>14</sup> C	4C	10-0.5	260	Korotky et al., 1980
G30	218	Tikhanguou	42.83	132.78	4	Bog	Yes	-	-	<sup>14</sup> C	5U	12-0	500	Korotky et al., 1980
G30	5	Amba River	43.32	131.82	5	Bog	Yes	-	-	<sup>14</sup> C	1A+1C+1U	5-2.5	300	Korotky et al., 1980
G30	186	Ryazanovka	42.83	131.37	6	Bog	Yes	-	-	<sup>14</sup> C	7A	6-0.5	540	Shilo, 1987
G30	171	Ovrazhnyii	43.25	134.57	8	Bog	Yes	-	-	<sup>14</sup> C	3A	7-1	200	Shilo, 1987
G30	175	Peschanka	43.30	132.12	12	Bog	Yes	-	-	<sup>14</sup> C	3U	22-11	965	Anderson et al., 2002
G30	464	Xingkai Lake	45.21	132.51	69	Lake	Yes	419000	36520	<sup>14</sup> C+Pb/Cs	3E	28.5-0	150	Ji et al., 2015
G31	220	Tongjiang	47.65	132.50	49	Bog	Yes	-	-	<sup>14</sup> C	5C	6-0	130	Zhang and Yang, 2002
G31	40	Chuanyue	48.33	134.47	50	Bog	Yes	-	-	<sup>14</sup> C	3U	12-1	400	Xia, 1988a
G31	161	Minzhuqiao	47.53	133.87	52	Bog	Yes	-	-	<sup>14</sup> C	4U	6.5-0.5	420	Xia, 1988a
G31	180	Qindeli	47.88	133.67	52	Bog	Yes	-	-	<sup>14</sup> C	1F+7U	13.5-0.5	380	Xia, 1988a
G31	18	Beidawan	48.13	134.70	60	Bog	Yes	8	157	<sup>14</sup> C	3U	5.5-0.5	350	Xia, 1988a
G31	234	Wuchanghai	47.22	127.33	200	Bog	Yes	-	-	<sup>14</sup> C	9E	7-0	250	Xia, 1988b
G31	212	Tangbei	48.35	129.67	486	Bog	Yes	-	-	<sup>14</sup> C	2A	5.5-1	160	Xia, 1996



G32	418	Venyukovka-3	47.12	138.58	5	Bog	Yes	-	-	<sup>14</sup> C	1A+2C	5.8-3.2	140	Korotky et al., 1980
G32	417	Venyukovka-2	47.03	138.58	6	Bog	Yes	-	-	<sup>14</sup> C	1A+1C	3.6-0.4	140	Korotky et al., 1980
G32	384	Oumi	48.22	138.40	990	Bog	Yes	-	-	<sup>14</sup> C	5C	2.6-0.4	80	Anderson et al., 2002
G32	382	Opasnaya River	48.23	138.48	1320	Bog	Yes	-	-	<sup>14</sup> C	7C	13.3-6.7	360	Korotky et al., 1988
G33	335	Il'inka Terrace	47.97	142.17	3	Bog	Yes	-	-	<sup>14</sup> C	2C+1F	2.6-1.1	360	Korotky et al., 1997
G33	371	Mereya River	46.62	142.92	4	Bog	Yes	-	-	<sup>14</sup> C	2C+2F	42.0-0.8	1530	Anderson et al., 2002
G33	401	Sergeevskii	49.23	142.08	6	Bog	Yes	-	-	<sup>14</sup> C	8A+1C	8.4-2.2	110	Korotky et al., 1997
G34	332	Gurskii Peat	50.07	137.08	15	Bog	Yes	-	-	<sup>14</sup> C	7C	13.1-1.5	380	Korotky, 1982
G34	453	Gur Bog	50.00	137.05	35	Bog	No	-	-	<sup>14</sup> C	13C	22.1-0	340	Mokhova et al., 2009
G34	223	Tuqiang	52.23	122.80	400	Bog	Yes	-	-	<sup>14</sup> C	10A+14E+8F	3-1	125	Xia, 1996
G34	398	Selitkan-2	53.22	135.03	1300	Bog	Yes	-	-	<sup>14</sup> C	4C	6.4-1.9	260	Volkov and Arkhipov, 1978
G34	397	Selitkan-1	53.22	135.05	1320	Bog	Yes	-	-	<sup>14</sup> C	6C	7.9-0	140	Korotky et al., 1985
G35	443	Two-Yurts Lake_PG1856-3	56.82	160.04	275	Lake	Yes	1168	1928	<sup>14</sup> C	5A	6.0-2.8	140	Hoff et al., 2015
G35	444	Two-Yurts Lake_PG1857-2	56.82	160.07	275	Lake	Yes	1168	1928	<sup>14</sup> C	5A	2.5-0.1	130	Hoff et al., 2015
G35	445	Two-Yurts Lake_PG1857-5	56.82	160.07	275	Lake	Yes	1168	1928	<sup>14</sup> C	5A	4.4-2.5	120	Hoff et al., 2015
G35	455	Lake Sokoch	53.25	157.75	495	Lake	Yes	41	363	<sup>14</sup> C	8E	9.7-0.3	250	Dirksen et al., 2012.
G36	330	Glukhoye Lake	59.75	149.92	10	Bog	Yes	-	-	<sup>14</sup> C	5C	9.4-3.4	1000	Lozhkin et al., 1990
G36	312	Chistoye Lake	59.55	151.83	91	Bog	Yes	-	-	<sup>14</sup> C	5C	7.0-0	540	Anderson et al., 1997
G36	363	Lesnoye Lake	59.58	151.87	95	Lake	Yes	13	200	<sup>14</sup> C	8A	15.5-0	400	Anderson et al., 1997
G36	388	Pepel'noye Lake	59.85	150.62	115	Lake	Yes	0	18	<sup>14</sup> C	2A	4.3-0	180	Lozhkin et al., 2000
G36	290	Alut Lake	60.14	152.31	480	Lake	Yes	63	448	<sup>14</sup> C	16A+9B	50.4-0	430	Anderson et al., 1998

G36	391	Podkova Lake	59.96	152.10	660	Lake	Yes	114	602	<sup>14</sup> C	5A	6.0-0	220	Anderson et al., 1997
G36	370	Maltan River	60.88	151.62	735	Bog	Yes	-	-	<sup>14</sup> C	4A+7C	12.0-9.4	120	Lozhkin and Glushkova, 1997
G36	411	Taloye Lake	61.02	152.33	750	Lake	Yes	16	227	<sup>14</sup> C	7A	10.3-0	290	Lozhkin et al., 2000
G36	323	Elikchan 4 Lake	60.75	151.88	810	Lake	Yes	329	1023	<sup>14</sup> C	16U	55.5-0	440	Lozhkin and Anderson, 1995
G36	331	Goluboye Lake	61.12	152.27	810	Lake	Yes	12	192	<sup>14</sup> C	11A+2B	9.7-0	240	Lozhkin et al., 2000
G36	470	Julietta Lake	61.34	154.56	880	Lake	Yes	11	189	<sup>14</sup> C	2A+4E+II	36.1-1.4	270	Anderson et al., 2010
G36	321	Elgennya Lake	62.08	149.00	1040	Lake	Yes	455	1204	<sup>14</sup> C	6A	16.0-0	310	Lozhkin et al., 1996
G37	405	Smorodinovoye Lake	64.77	141.12	800	Lake	Yes	27	293	<sup>14</sup> C	6A+5F	27.1-0	360	Anderson et al., 1998
G37	416	Vechernii River	63.28	147.75	800	Bog	Yes	-	-	<sup>14</sup> C	1F	14.4-0.1	380	Anderson et al., 2002
G37	338	Jack London Lake	62.17	149.50	820	Lake	Yes	1213	1965	<sup>14</sup> C	7F	19.5-0.2	320	Lozhkin et al., 1993
G37	406	Sosednee Lake	62.17	149.50	822	Lake	Yes	82	510	<sup>14</sup> C	4E+1F	26.3-0	640	Lozhkin et al., 1993
G37	393	Rock Island Lake	62.03	149.59	849	Lake	Yes	5	124	<sup>14</sup> C	2E	6.6-0	470	Lozhkin et al., 1993
G37	381	Oldcamp Lake	62.04	149.59	853	Lake	Yes	7	150	<sup>14</sup> C	2E	3.7-0	370	Anderson, unpublished
G37	329	Gek Lake	63.52	147.93	969	Lake	Yes	2392	2759	<sup>14</sup> C	8A+1B	9.6-0	440	Stetsenko, 1998
G37	433	Figurnoye Lake	62.10	149.00	1053	Lake	Yes	439	1182	<sup>14</sup> C	4A	1.3-0	30	Lozhkin et al., 1996
G38	353	Kuropatoch'ya_Kurop7	70.67	156.75	7	Bog	Yes	-	-	<sup>14</sup> C	3C	5.7-0.4	760	Anderson et al., 2002
G38	354	Kuropatoch'ya_Kurpeat	69.97	156.38	47	Bog	Yes	-	-	<sup>14</sup> C	1A+4C	11.7-7.5	430	Lozhkin and Vazhenina, 1987
G39	322	Elgygytgyn Lake	67.50	172.10	496	Lake	No	9503	5500	polarity	-	20.2-1.5	650	Melles et al., 2012
G39	325	Enmyneem_mammoth	68.17	165.93	400	Bog	Yes	50	399	<sup>14</sup> C	2C+2F	36.4-9.3	2470	Lozhkin et al., 1988
G39	326	Enmyvaam River	67.42	172.08	490	Bog	Yes	18	239	<sup>14</sup> C	1A+4C	10.6-4.3	630	Lozhkin and Vazhenina, 1987
G39	324	Enmyneem River	68.25	166.00	500	Bog	Yes	-	-	<sup>14</sup> C	4C	10.7-4.0	420	Anderson et al., 2002

G40	454	Malyi Krechet Lake	64.80	175.53	32	Lake	Yes	125	630	<sup>14</sup> C	12A	9.6-0	400	Lozhkin and Anderson, 2013
G40	456	Melkoye Lake	64.86	175.23	36	Lake	Yes	1870	2440	<sup>14</sup> C	21E	39.1-0	1260	Lozhkin and Anderson, 2013
G40	460	Sunset Lake	64.84	175.30	36	Lake	Yes	240	874	<sup>14</sup> C	7A	14.0-0	260	Lozhkin and Anderson, 2013
G40	333	Gytgykai Lake	63.42	176.57	102	Lake	Yes	99	561	<sup>14</sup> C	1A+8E	32.3-0	470	Lozhkin et al., 1998
G40	457	Patricia Lake	63.33	176.50	121	Lake	Yes	40	357	<sup>14</sup> C	3A+7E	19.1-0	290	Anderson and Lozhkin, 2015
G41	436	Konergino	65.90	-178.90	10	Bog	Yes	-	-	<sup>14</sup> C	1C	9.8-0	900	Ivanov et al., 1984
G41	365	Lorino	65.50	-171.70	12	Bog	Yes	-	-	<sup>14</sup> C	3C	17.9-5.1	850	Ivanov, 1986
G41	317	Dlinnoye Lake	67.75	-178.83	280	Lake	Yes	71	476	<sup>14</sup> C	3A	1.3-0	130	Anderson et al., 2002
G41	431	Dikikh Olyenyeyii Lake	67.75	-178.83	300	Lake	Yes	64	450	<sup>14</sup> C	1A+4C	50.3-0	1050	Anderson et al., 2002
G42	427	Blossom Cape	70.68	178.95	6	Bog	Yes	-	-	<sup>14</sup> C	1C	13.8-0.2	3400	Oganesyan et al., 1993
G42	420	Wrangle Island_Jack London Lake	70.83	-179.75	7	Lake	Yes	69	469	<sup>14</sup> C	5A+1E	16.1-0.3	790	Lozhkin et al., 2001
G42	419	Wrangel Island	71.17	-179.75	200	Bog	Yes	-	-	<sup>14</sup> C	17A+3C	13.7-10.2	110	Lozhkin et al., 2001

1006 LSC: liquid-scintillation counting; A: terrestrial plant macrofossil; B: non-terrestrial plant macrofossil; C: peat; D: pollen; U: unknown; E: total organic matter from  
1007 silt; F: animal remains or shell; G: charcoal; H: CaCO<sub>3</sub>; I: tephra.

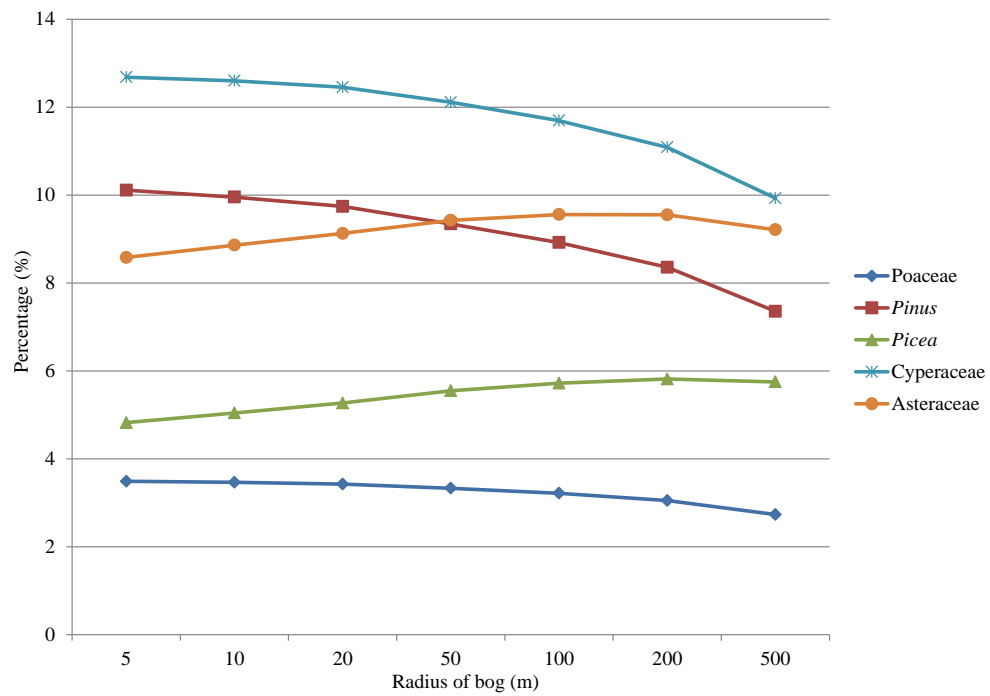
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1012 **Appendix 3** Slight percentage changes for five major plant taxa reconstructed by REVEALS model with different bog radii (5 m, 10 m, 20 m, 50 m, 100 m, 200 m  
1013 and 500 m).



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1017 **Appendix 4** Pollen Productivity Estimates (PPEs) with their standard errors (SEs) for 27 pollen taxa from 20 study areas. Estimates where  $SE \geq PPE$  were  
 1018 excluded from the calculation of mean PPE and are shown in italics.

Country	Poland	Russia	Sweden	Sweden	Swiss	Swiss	Switzerland	Sweden	Finland	Estonia
Region	Białowieża Forest	Khatanga region	Southern Sweden	Southern Sweden	Swiss Plateau	Alps	Jura Mountains	west-central	Fennoscandia	Southeast
sample type	Moss	Moss	Moss	Moss	Lake	Trap	Moss	Moss	Moss	Lake
Reference	Baker et al., 2016	Niemeyer et al., 2015	Broström et al., 2004	Sugita et al., 1999	Soepboer et al., 2007	Sjögren et al., 2008	Mazier et al., 2008	von Stedingk et al., 2008	Räsänen et al., 2007	Poska et al., 2011
Model	ERV-3	ERV-2	ERV-3	ERV-3	ERV-3	-	ERV-1	ERV-3	ERV-3	ERV-1
Poaceae	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)
<i>Abies</i>					9.92 (2.86)		3.83 (0.37)			
<i>Pinus</i>	23.12 (0.24)			5.66 (0.00)	1.35 (0.45)	9 (0.00)		21.58 (2.87)	8.4 (1.34)	5.07 (0.06)
<i>Picea</i>				1.76 (0.00)	0.57 (0.16)	0.5 (0.00)	7.1 (0.2)	2.78 (0.21)		4.73 (0.13)
<i>Larix</i>		<i>0.00009 (0.1)</i>				1.4 (0.00)				
<i>Alnus_tree</i>	15.95 (0.66)			4.2 (0.14)		20 (0.00)				13.93 (0.15)
<i>Betula_tree</i>	13.94 (0.23)			8.87 (0.13)	2.42 (0.39)			2.24 (0.2)	4.6 (0.7)	1.81 (0.02)
<i>Juglans</i>										
<i>Fraxinus</i>				0.67 (0.03)	1.39 (0.21)					
<i>Quercus</i>	18.47 (0.10)			7.53 (0.08)	2.56 (0.39)					7.39 (0.2)
<i>Tilia</i>	0.98 (0.03)			0.8 (0.03)						
<i>Ulmus</i>										
<i>Alnus_shrub</i>		6.42 (0.42)								
<i>Betula_shrub</i>		1.8 (0.26)								
<i>Carpinus</i>	4.48 (0.03)				4.56 (0.85)					
<i>Corylus</i>	1.35 (0.05)			1.4 (0.04)	2.58 (0.25)					

<i>Salix</i>	0.03 (0.03)		1.27 (0.31)			0.09 (0.03)		2.31 (0.08)
Ericaceae	0.33 (0.03)					0.07 (0.04)		
<i>Ephedra</i>								
Cyperaceae	0.53 (0.06)	1 (0.16)				0.68 (0.01)	0.89 (0.03)	0.002 (0.0022) 1.23 (0.09)
<i>Artemisia</i>								3.48 (0.19)
Chenopodiaceae								
Asteraceae		0.24 (0.06)		0.17 (0.03)				
<i>Thalictrum</i>								
Ranunculaceae		3.85 (0.72)						
Caryophyllaceae								
Brassicaceae								

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Country	Czech	Norway	Greenland	England	England	Germany	China	China	China	China
Region	Central Bohemia	South	Southern	Calthorpe	Wheatfen	Brandenburg	Tibetan Plateau	Xilinhaote	Shandong	Changbai Mt.
sample type	Moss	Lake	Moss	Moss	Moss	Lake	Lake	Soil	moss	Moss
Reference	Abraham and Kozáková 2012	Hjelle and Sugita, 2012	Bunting et al., 2013	Bunting et al., 2005	Bunting et al., 2005	Matthias et al., 2012	Wang and Herzsuh, 2011	Xu et al., 2014	Li et al., 2017	Li et al., 2015
Model	ERV-1	ERV-3	ERV-1	Average	Average	allFIDage_ERV3	ERV-2	ERV2	ERV-3	-
Poaceae	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	
<i>Abies</i>										
<i>Pinus</i>	6.17 (0.41)	5.73 (0.07)				5.2 (0.00)		8.96 (0.23)		15.2079 (0.489)
<i>Picea</i>		1.2 (0.04)				1.456 (0.05)				
<i>Larix</i>						8.06 (0.32)				1.47 (0.19)

<i>Alnus_tree</i>	2.56 (0.32)	3.22 (0.22)		10.564 (0.00)	4.028 (0.00)	14.248 (0.22)			
<i>Betula_tree</i>			3.7 (0.4)	9.804 (0.00)		8.84 (0.34)			24.65 (0.73)
<i>Juglans</i>							0.3 (0.05)		9.49 (0.44)
<i>Fraxinus</i>	1.11 (0.09)			1.14 (0.00)	0.076 (0.00)	6.188 (0.12)			3.72 (0.68)
<i>Quercus</i>	1.76 (0.2)	1.3 (0.1)		7.6 (0.00)	7.6 (0.00)	1.976 (0.03)		4.89 (0.16)	
<i>Tilia</i>	1.36 (0.26)					1.352 (0.04)			0.78 (0.19)
<i>Ulmus</i>							11.5 (1.09)	1 (0.31)	6.85 (1.71)
<i>Alnus_shrub</i>									
<i>Betula_shrub</i>			1.4 (0.05)						
<i>Carpinus</i>						8.684 (0.09)			
<i>Corylus</i>					1.216 (0.00)				
<i>Salix</i>	1.19 (0.12)	0.62 (0.11)	0.8 (0.002)	1.748 (0.00)	2.736 (0.00)				
Ericaceae									
<i>Ephedra</i>							0.96 (0.14)		
Cyperaceae		1.37 (0.21)	0.95 (0.05)			0.65 (0.4)	0.94 (0.079)	0.21 (0.07)	
<i>Artemisia</i>	2.77 (0.39)					3.2 (0.6)	11.21 (0.31)	24.7 (0.36)	
Chenopodiaceae	4.28 (0.27)					5.3 (1.1)	6.74 (0.79)		
Asteraceae							0.39 (0.16)	1.06 (0.21)	
<i>Thalictrum</i>			4.65 (0.3)				3.06 (0.42)		
Ranunculaceae			1.95 (0.1)						
Caryophyllaceae			0.6 (0.05)						
Brassicaceae							7.48 (0.33)	0.89 (0.18)	

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- 1023 [Reference list of Appendix 4:](#)
- 1024 [Abraham, V. and Kozáková R.: Relative pollen productivity estimates in the modern agricultural landscape of Central Bohemia \(Czech Republic\). Review of](#)
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1042 [Mazier, F., Broström, A., Gaillard, M.-J., Sugita, S., Vittoz, P. and Buttler, A.: Pollen productivity estimates and relevant source area of pollen for selected plant taxa](#)

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1045 [Palaeobotany and Palynology, 221: 71–82, 2015.](#)

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 1060 [their potential in past vegetation reconstruction. Science China: Earth Sciences, 57: 1254–1266, 2014.](#)

1061 **Appendix 5** Number of pollen records from large lakes ( $\geq 390$  m radius; represented by L), small lakes ( $< 390$  m radius; represented by S), and bogs (B) for each  
 1062 site-group used to run REVEALS for each time slice. For example, site-group G6 has 2 large lake records, 1 small lake record, and 2 bog records at 4 ka  
 1063 (represented by 2L1S2B).

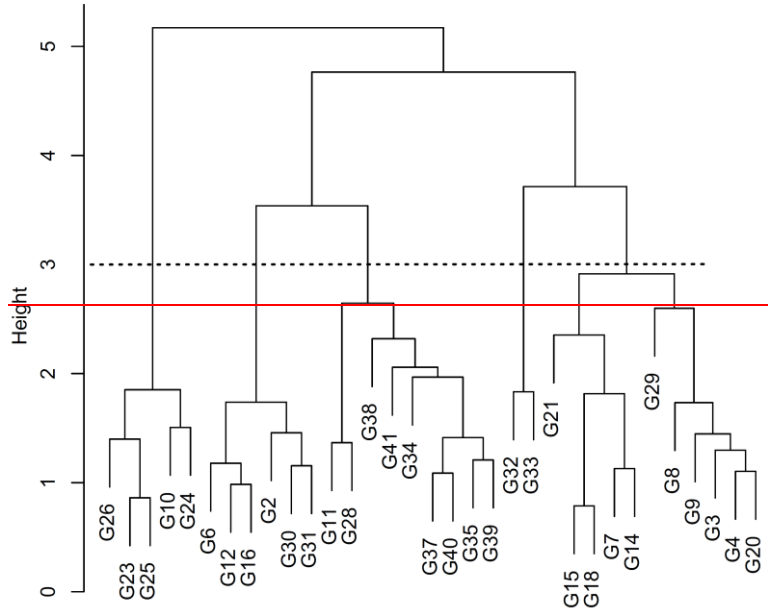
Grou	0 ka	0.2 ka	0.5 ka	1 ka	2 ka	3 ka	4 ka	5 ka	6 ka	7 ka	8 ka	9 ka	10 ka	11 ka	12 ka	14 ka	21 ka	25 ka	40 ka
G1	1L	1L	1L	-	1L	-	1L	1L	1L	1L	1L	1L	-	-	-	-	-	-	-
G2	6B	1S6B	1S6B	1S6B	1S4B	2S6B	2S6B	1S4B	2S2B	1S	2S	2S	1S2B	1S2B	1S2B	2B	-	-	-
G3	4B	4B	8B	8B	6B	8B	8B	8B	8B	6B	6B	4B	4B	4B	-	-	-	-	-
G4	-	1L	-	1L	1L	1L	1L	1L	1L	1L2B	1L2B	1L	1L	1L	1L	-	-	-	-
G5	4S4B	4S4B	4S4B	4S4B	1S4B	1S4B	1S4B	1S2B	1S2B	1S2B	-	-	-	-	-	-	-	-	-
G6	2L1S2B	1L1S2B	2L1S4B	2L1S4B	2L1S4B	1L1S2B	2L1S2B	1S	1L1S	1L2B	1L2B	1L2B	2B	2B	2B	2B	-	-	-
G7	4B	10B	12B	12B	1L12B	1L12B	1L10B	1L10B	1L10B	1L10B	6B	8B	8B	1L6B	2B	-	2B	-	2B
G8	2B	2B	4B	4B	2B	4B	6B	8B	8B	8B	6B	4B	4B	4B	2B	-	-	-	-
G9	4B	4B	6B	6B	4B	6B	6B	2B	6B	4B	8B	8B	8B	8B	4B	2B	-	-	-
G10	1L	1L	1L	1L	2B	1L2B	1L4B	1L6B	1L8B	1L6B	1L6B	1L6B	1L4B	1L2B	1L	1L	1L	-	-
G11	2L1S	2L1S	2L1S	2L1S	1L1S	2L1S	1L1S	1L1S	2L1S	2L1S	2L	2L	1L	1L	2L	1L	1L	1L	-
G12	6L1S2B	5L1S2B	5L1S2B	6L1S2B	5L1S2B	3L1S2B	5L1S2B	4L1S2B	4L2B	4L2B	5L2B	4L	4L	3L	4L	1L	-	-	-
G13	1L	1L	1L	2L	2L	2L	2L	2L	2L	2L	2L	2L	1L	1L	1L	1L	-	-	-
G14	4L	1L	4L	4L1S	5L1S	5L2S	5L1S	4L1S	3L1S	4L2S	4L2S	4L2S	3L1S	4L2S	4L1S	3L2S	-	-	-
G15	1L	2L	2L	2L	2L	3L	3L	3L	3L	2L	2L	3L	1L	3L	3L	2L	1L	1L	-
G16	1L	-	2L	-	2L	2L	2L	1L	1L	2L	2L	2L	2L	2L	3L	1L	2L	3L	-
G17	-	-	-	-	1L	1L	-	1L	1L	1L	1L	1L	-	1L	-	-	-	-	-
G18	2L2S	3L1S	2L2S	4L2S	2L1S	4L1S	5L1S	4L1S	4L1S	4L	5L	4L1S	2L1S	3L1S	4L	2L	-	-	-
G19	-	1L	-	1L	1L	-	1L	1L	-	-	-	-	-	-	-	-	-	-	-
G20	6L6B	4L4B	6L8B	5L1S6B	6L1S8B	5L8B	5L6B	5L1S6B	5L1S6B	5L1S4B	4L4B	4L2B	5L2B	5L2B	6L2B	5L2B	2L2B	2L2B	1L
G21	4L1S2B	2L1S2B	4L1S2B	4L1S2B	3L1S2B	4L2S4B	4L2S4B	3L2S4B	3L1S4B	4L1S2B	5L1S4B	4L1S2B	5L1S2B	6L1S	5L1S	1L	-	-	-
G22	1L	1L	2L	2L	2L	2L	2L	2L	2L	2L	2L	2L	2L	2L	1L	1L	-	-	-

G23	-	-	-	2B	2B	2B	4B	4B	4B	4B	4B	4B	4B	4B	4B	-	-	-	-
G24	2L	2L	2L	2L	2L	2L	2L	2L	2L	1L	1L	1L	1L	1L	1L	-	-	-	-
G25	1L	4L	4L	4L	5L	5L	5L	5L	5L	4L	4L	3L	3L	4L	2L	2L	1L	1L	1L
G26	1L	-	1L	1L	1L	1L	1L	1L	1L	-	-	1L	1L	1L	-	-	-	-	-
G27	-	2B	4B	4B	4B	2B	4B	4B	4B	4B	4B	2B	-	-	-	-	-	-	-
G28	2L	2B	2L2B	1L2B	2L2B	1L2B	2L2B	2B	2L	1L	2L	2L	2L	2L	1L	1L	-	-	-
G29	1L1S10B	1L1S14B	1L2S14B	1L1S16B	1L1S16B	1L2S16B	1L1S10B	1L2S10B	1L1S4B	1L2S4B	1L2S2B	1L1S2B	2S	2S	1S	1S	1S	1S	1S
G30	1L	1L2B	1L6B	1L4B	1L8B	1L8B	1L6B	1L10B	1L8B	1L8B	1L4B	1L4B	1L2B	1L4B	1L4B	1L2B	1L4B	1L4B	4B
G31	2B	2B	10B	14B	12B	14B	10B	12B	10B	4B	2B	4B	2B	4B	4B	-	-	-	-
G32	-	-	4B	4B	4B	2B	2B	2B	2B	2B	2B	2B	2B	2B	-	-	-	-	-
G33	-	-	-	4B	2B	2B	4B	2B	4B	2B	2B	-	-	2B	2B	2B	2B	2B	2B
G34	4B	4B	4B	6B	10B	8B	8B	6B	6B	6B	6B	4B	4B	4B	4B	2B	2B	-	-
G35	-	1L1S	1L1S	1L1S	1L1S	2L1S	1L	1L1S	1L	1S	1S	1S	1S	-	-	-	-	-	-
G36	4L4S2B	2L2S	4L3S	4L4S	4L4S	4L5S	4L4S	3L2S2B	4L2S	2L4S4B	3L4S2B	3L4S	2L4S2B	3L2S2B	2L2S2B	2L2S	2L1S	2L1S	2L1S
G37	3L3S	2L1S2B	3L1S2B	1L3S2B	1L3S2B	2L3S2B	1L3S2B	2L2S2B	3L2S2B	3L1S	1L1S	2L	2L1S	2L1S	1L1S	2L1S	2L1S	1L1S	-
G38	-	-	2B	2B	-	2B	2B	2B	2B	-	2B	2B	2B	2B	2B	-	-	-	-
G39	-	-	-	-	-	1L	1L2B	-	1L4B	2B	1L4B	1L4B	2B	1L4B	1L	1L	1L2B	2B	2B
G40	4L1S	1L	2L1S	3L1S	3L1S	2L	1S	2L	2L1S	1S	1L1S	3L1S	2L	2L	3L	2L	2L1S	1L	1L
G41	2L2B	1L	1L	1L	2B	2B	-	4B	-	4B	4B	4B	2B	1L2B	2B	1L2B	1L	1L	1L
G42	-	1L2B	-	1L	1L	1L	1L	-	-	-	-	-	1L	1L2B	1L4B	1L4B	-	-	-

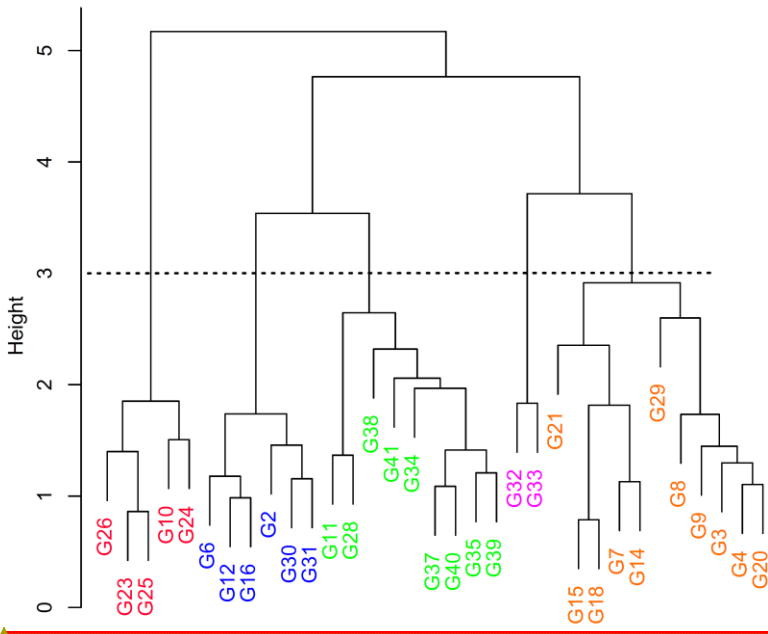
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1071 **Appendix 6** Cluster diagram of the site-groups based on the plant functional type  
 1072 dataset

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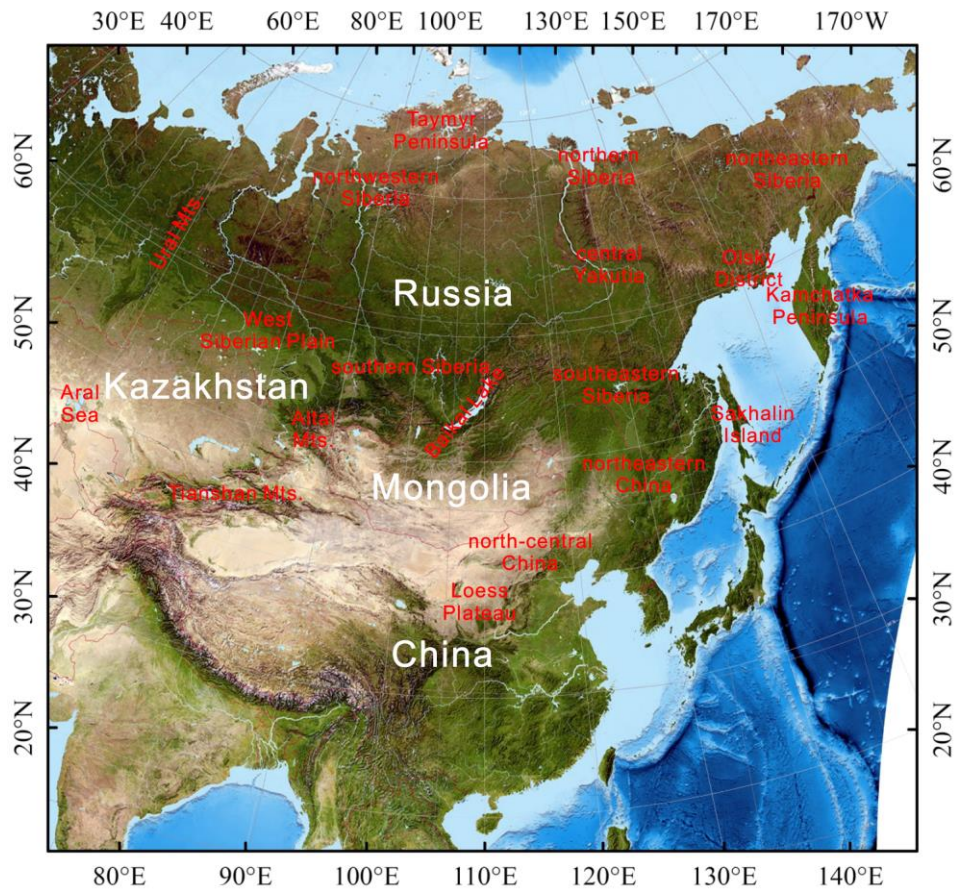
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**Appendix 7** Map of the study area showing the geographic locations mentioned in the text.



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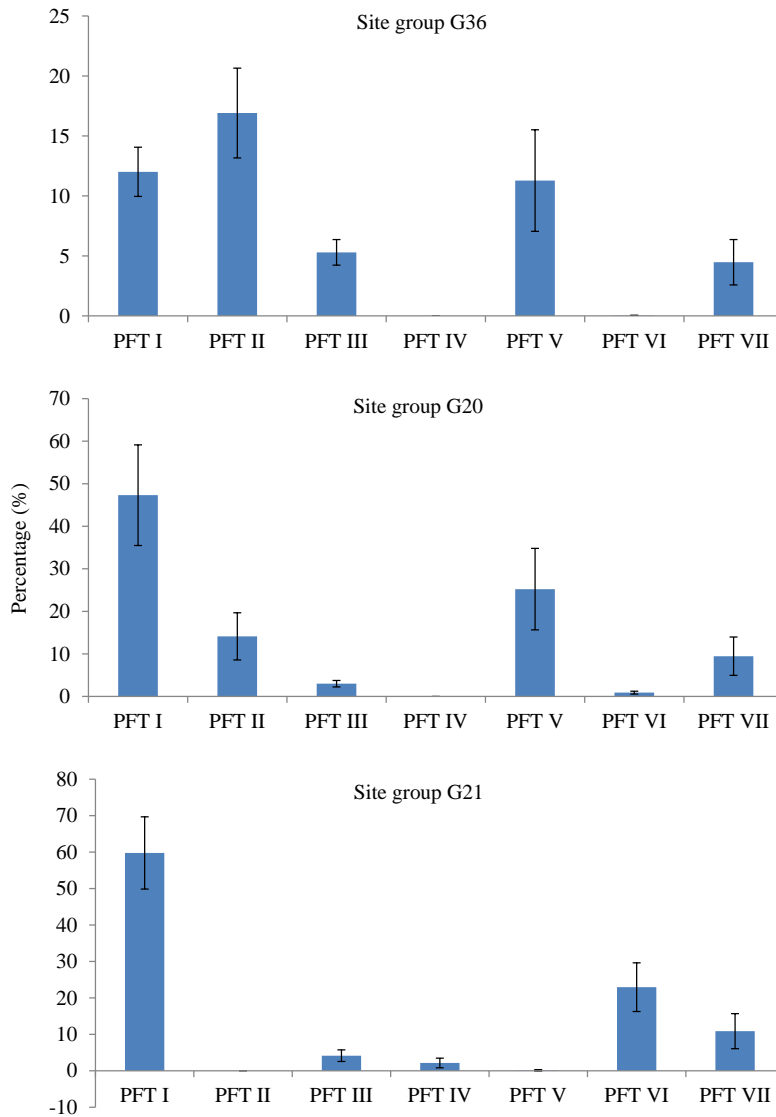
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1113 | **Appendix 8** Selected examples of standard errors for seven plant functional type (PFT)

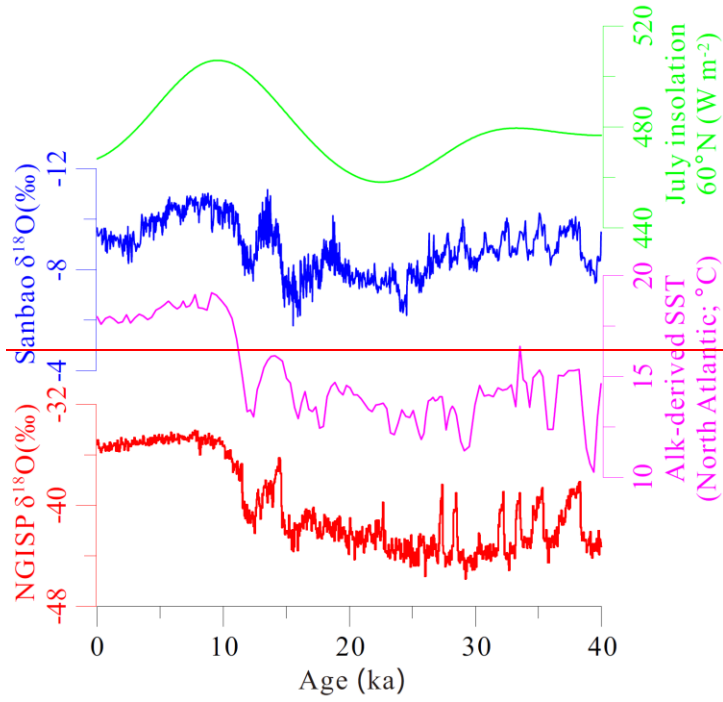
1114 reconstructions at site-groups G21, G20, and G36 at 6 ka.



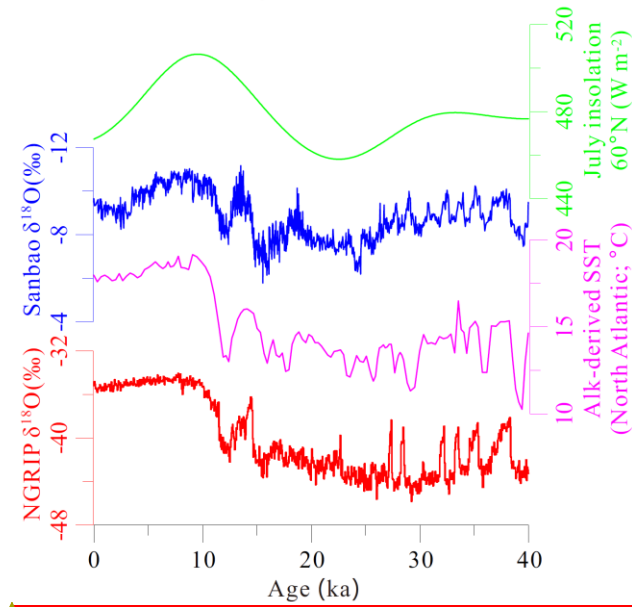
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1124 **Appendix 9** Proxy-based climate reconstructions from the Northern Hemisphere and insolation  
 1125 variations during the last 40 cal ka BP discussed in the paper. [NGISPNGRIP](#): the North Greenland

1126 Ice-Core Project (Andersen et al. 2004); Sanbao cave (Cheng et al. 2016); Alkenone-derived  
1127 sea-surface temperatures (SST) from deep-sea cores SU8118 and MD952042 (Pailler and Bard  
1128 2002); solar insolation in July at 60° N (Laskar et al. 2004).



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