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Pollen-based quantitative land-cover reconstruction for northern Asia during the last 40 ka

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ABSTRACT

We collected the available relative pollen productivity (RPP) estimates for 27 major pollen taxa from Eurasia and applied them to estimate plant abundances during the last 40 cal. ka BP (calibrated thousand-year before the present) using pollen counts from 203 fossil pollen records in northern Asia (north of 40°N). These pollen records were organised into 42 site groups; and regional mean plant abundances were calculated using the REVEALS (Regional Estimates of Vegetation Abundance from Large Sites) model. Time-series clustering, constrained hierarchical clustering, and detrended canonical correspondence analysis were performed to investigate the regional pattern, time, and strength of vegetation changes, respectively. Reconstructed regional land cover for each site group is generally consistent with *in situ* modern vegetation in that vegetation changes within the regions are characterized by minor changes in the abundance of major taxa rather than by

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invasions of new taxa, particularly during the Holocene. We argue that pollen-based REVEALS estimates of plant abundances should be a more reliable reflection of the vegetation as pollen may overestimate the turnover, particularly when a high pollen producer invades areas dominated by low pollen producers. Comparisons with vegetation-independent climate records show that climate change is the primary factor driving land-cover changes at broad spatial and temporal scales. Vegetation changes in certain regions or periods, however, could not be explained by direct climate change, for example inland Siberia, where a sharp increase in evergreen conifer tree abundance occurred at ca. 7~8 cal. ka BP despite an unchanging climate, potentially reflecting their response to complex climate-permafrost-fire-vegetation interactions and thus a possible lagged climate response.

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

1 Introduction

High northern latitudes such as northern Asia experience above-average temperature increases in times of past and recent global warming (Serreze et al., 2000; IPCC, 2007), known as polar amplification (Miller et al., 2010). Temperature rise is expected to promote vegetation change as the vegetation composition in these areas is assumed to be controlled mainly by temperature (Li J. et al., 2017; Tian et al., 2018). However, a more complex response can occur mainly because vegetation is not linearly related to temperature change (e.g. due to resilience, stable states or time-lagged responses; Soja et al., 2007; Herzschuh et al., 2016) and/or vegetation is only indirectly limited by temperature and other temperature-related environmental drivers such as permafrost conditions are more influential (Tchebakova et al., 2005).

Such complex relationships between temperature and vegetation may help explain several contradictory findings of recent ecological change in northern Asia. For example, simulations of vegetation change in response to a warmer and drier climate indicate that steppe should expand in the present forest–steppe ecotone of south

Siberia (Tchebakova et al., 2009) but, contrarily, pine forest in south Siberia increased during the past 74 years, probably because the warming temperature was mediated by improved local moisture conditions (Shestakova et al., 2017). In another example, evergreen conifers, which are assumed to be more susceptible to frost damage than *Larix*, expanded their distribution by 10% during a period with cooler winters from 2001 to 2012, while the distribution of *Larix* forests decreased by 40% on the West Siberia Plain as revealed by a remote sensing study (He et al., 2017). Additionally, some field studies and dynamic vegetation models infer a rapid response of the treeline to warming in northern Siberia (e.g., Moiseev, 2002; Soja et al., 2007; Kirdyanov et al., 2012), but combined model- and field-based investigations of larch stands in north-central Siberia reveal only a densification of tree-stands, not an areal expansion (Kruse et al., 2016; Wieczorek et al., 2017).

These findings on recent vegetation dynamics that contradict a straightforward vegetation-temperature relationship may be better understood in the context of vegetation change over longer time-scales. Synthesizing multi-record pollen data is the most suitable approach to investigate quantitatively the past vegetation change at broad spatial and long temporal scales. Broad spatial scale pollen-based land-cover reconstructions have been made for Europe (e.g. Mazier et al., 2012; Nielsen et al., 2012; Trondman et al., 2015) and temperate China (Li, 2016) for the Holocene. However, vegetation change studies in northern Asia are restricted to biome reconstructions (Tarasov et al., 1998, 2000; Bigelow et al., 2003; Binney et al. 2017; Tian et al., 2018), which do not reflect compositional change. Syntheses of pure pollen percentage data are not appropriate due to differences in pollen productivity, which may result in an overestimation of the strength of vegetation changes (Wang and Herzschuh, 2011). This might be particularly severe when strong pollen producers such as pine (Mazier et al., 2012) invade areas dominated by low pollen producers such as larch (Niemeyer et al, 2015). Marquer et al. (2014, 2017) also demonstrated the strength of pollen-based REVEALS estimates of plant abundance in studies of Holocene vegetation change and plant diversity indexes in Europe.

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Accordingly, syntheses of quantitative plant cover derived from the application of RPP to multiple pollen records (Trondman et al., 2015; Li, 2016) should be a better way to investigate Late Glacial and Holocene vegetation change in northern Asia.

In this study, we employ the taxonomically harmonized and temporally standardized fossil pollen datasets available from eastern continental Asia (Cao et al., 2013, 2015) and Siberia (Tian et al., 2018) covering the last 40 cal. ka BP (henceforth abbreviated ka). We compile all the available RPP estimates from Eurasia and use the mean of estimates for each taxon. Finally, we quantitatively reconstruct plant cover using the REVEALS model (Sugita, 2007) for 27 major taxa at 18 key time slices. Our aims are to (1) reveal the nature, strength, and timing of vegetation change in northern Asia and its regional peculiarities; and 2) discuss the driving factors of vegetation change.

2 Data and methods

2.1. Fossil pollen data process

The fossil pollen records were obtained from the extended version of the fossil pollen dataset for eastern continental Asia containing 297 records (Cao et al., 2013, 2015) and the fossil pollen dataset for Siberia with 171 records (Tian et al., 2017). For the 468 pollen records, pollen names were harmonized and age-depth models were re-established using the same procedures (further details are described in Cao et al., 2013). We selected 203 pollen records from lacustrine sediments (110 sites) and peat (93 sites) north of 40°N, with chronologies based on ≥3 dates and <500 year/sample temporal resolution generally, following previous studies (Mazier et al., 2012; Nielsen et al., 2012; Fyfe et al., 2013; Trondman et al., 2015). Out of the 203 pollen records, 170 sites (83 from lakes, 87 from bogs) have original pollen counts, while in the other 33 sites only pollen percentages are available. Due to overall low site density, we decided to include these data. The original pollen counts were back calculated from percentages using the terrestrial pollen sum indicated in the original publications. Detailed information (including data quality, chronology reliability and data source) of the selected sites is presented in Appendix 1.

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

We selected 18 key time slices for reconstruction (Table 1) to capture the general temporal patterns of vegetation change during the last 40 ka, i.e. 40, 25, 21, 18, 14, and 12 ka during the late Pleistocene and 1000-year resolution (i.e. 500-year time windows around each millennium, e.g. 0.7-1.2 ka, 1.7-2 ka, etc.) during the Holocene. For the 0 ka time slice, the ca. 150-year time window (<0.1 ka) was set to represent the modern vegetation. Since few pollen records have available samples at the 0 ka time slice, the 0.2 and 0.5 ka time slices were added with 250-year or 350-year time windows (0.1~0.35 ka and 0.35~0. ka, respectively) to represent the recent vegetation pattern, following the strategy and time windows implemented in Europe (Mazier et al., 2012; Trondman et al., 2015). For the last glacial period, even broader time windows were chosen to offset the sparsely available samples (Table 1). Pollen counts of all available samples within one time window were summed up to

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represent the total pollen count for each time slice. In this study, we selected 27 major pollen taxa that form dominant components in both modern vegetation communities and the fossil pollen spectra with available PPE values and reconstruct their abundances in the past vegetation (Table 2).

Table 2 Fall speed of pollen grains (FS) and the means of the relative pollen productivity (RPP) estimates with their standard error (SE). Plant-functional type (PFT) assignment according to previous biome reconstructions (Tarasov et al., 1998, 2000; Bigelow et al., 2003; Ni et al., 2010).

PFT	PFT description	pollen type	FS (m/s)	PPE (SE)
I	evergreen conifer tree	*Pinus*	0.031 [1]	9.629 (0.075)
I	evergreen conifer tree	*Picea*	0.056 [1]	2.546 (0.041)
I	evergreen conifer tree	*Abies*	0.120 [1]	6.875 (1.442)
II	deciduous conifer tree	*Larix*	0.126 [1]	3.642 (0.125)
III	boreal deciduous tree	*Betula*_tree	0.024 [1]	8.106 (0.125)
III	boreal deciduous tree	*Alnus*_tree	0.021 [1]	9.856 (0.092)
III	boreal deciduous tree	*Corylus*	0.025 [2]	1.637 (0.065)
IV	temperature deciduous tree	*Quercus*	0.035 [1]	6.119 (0.050)
IV	temperature deciduous tree	*Fraxinus*	0.022 [1]	2.046 (0.105)
IV	temperature deciduous tree	*Juglans*	0.037 [3]	4.893 (0.221)
IV	temperature deciduous tree	*Carpinus*	0.042 [1]	5.908 (0.285)
IV	temperature deciduous tree	*Tilia*	0.032 [2]	1.055 (0.066)
IV	temperature deciduous tree	*Ulmus*	0.032 [2]	6.449 (0.684)
V	boreal shrub	*Betula*_shrub	0.024 [1]	1.600 (0.132)
V	boreal shrub	*Alnus*_shrub	0.021 [1]	6.420 (0.420)
V	boreal shrub	*Salix*	0.034 [2]	1.209 (0.039)
V	boreal shrub	Ericaceae	0.034 [4]	0.200 (0.029)
VI	arid-tolerant shrub and herb	*Ephedra*	0.015 [8]	0.960 (0.140)
VI	arid-tolerant shrub and herb	*Artemisia*	0.014 [6]	9.072 (0.176)
VI	arid-tolerant shrub and herb	Chenopodiaceae	0.019 [6]	5.440 (0.460)
VII	steppe and forb tundra	Poaceae	0.035 [4]	1.000 (0.000)
VII	steppe and forb tundra	Cyperaceae	0.035 [5]	0.757 (0.044)
VII	steppe and forb tundra	Asteraceae	0.051 [7]	0.465 (0.066)
VII	steppe and forb tundra	*Thalictrum*	0.007 [8]	3.855 (0.258)
VII	steppe and forb tundra	Ranunculaceae	0.014 [9]	2.900 (0.363)
VII	steppe and forb tundra	Caryophyllaceae	0.028 [9]	0.600 (0.050)
VII	steppe and forb tundra	Brassicaceae	0.002 [3]	4.185 (0.188)

[1] Eisenhut (1961); [2] Gregory (1973); [3] Li et al. (2017); [4] Broström et al. (2004); [5] Sugita et al. (1999); [6] Abraham and Kozáková (2012); [7] Broström et al. (2002); [8] Xu et al. (2014); [9] Bunting et al. (2013).

2.2 The REVEALS model setting

The REVEALS model requires parameter inputs including sediment basin radius (m), fall speed of pollen grain (FS, m/s), and PPE with standard error (SE; Sugita, 2007). The areas of the 110 lakes were obtained from descriptions in original publications and validated by measurements on Google Earth. Their basin radii were back-calculated from their areas assuming a circular shape. There are 83 large lakes (radius >390 m; following Sugita, 2007) in our dataset with a fairly even distribution across the study area (Fig. 1), which helps ensure the reliability of the regional vegetation estimations (Sugita, 2007; Mazier et al., 2012). Only 18 bogs have published descriptions about their size and it is infeasible to measure them on Google Earth because of indefinite boundaries, hence an identical radius of 100 m was set for all bogs.

We collected available RPP estimates for the 27 selected pollen taxa from 20 studies in Eurasia (Appendix 2). We calculated the mean PPE from all available PPE values, but excluded records with PPE ≤ SE (Mazier et al., 2012). For simplification, we did not evaluate the values and further selected RPP values following consistent criteria as was done in Europe (Mazier et al., 2012). We used instead the original values from the studies included in Mazier et al. (2012) and added new RPP values from Europe published since the synthesis of Mazier et al. (2012). SE of the mean PPE was estimated using the delta method (Stuart and Ord, 1994). Fall speeds for each of the 27 pollen taxa were retrieved from previous studies (see Table 2).

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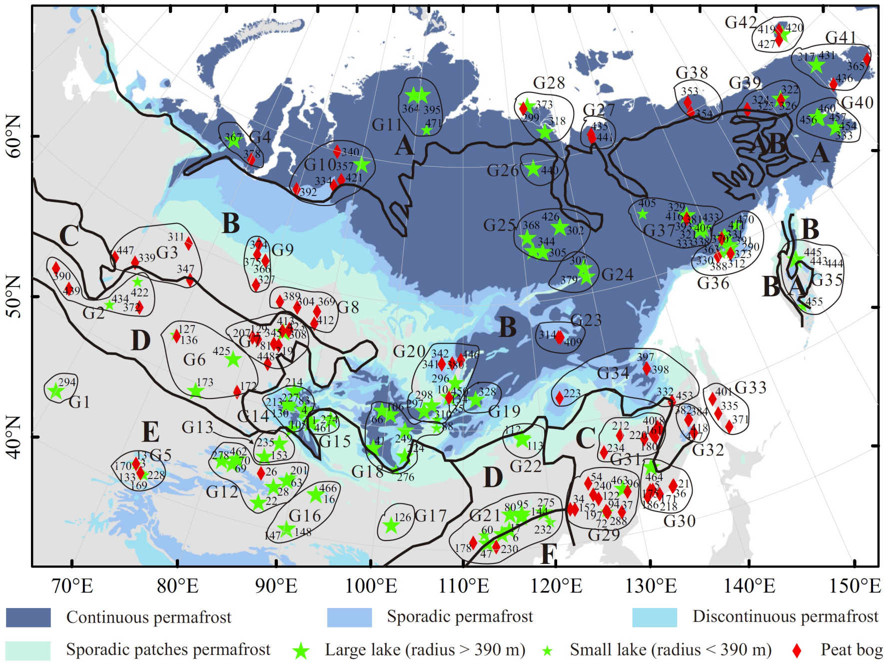

Fig. 1. Distribution of the 203 fossil pollen sites and the 42 site groups together with the modern vegetation zones and permafrost extent in northern Asia. The vegetation-zone map modified from Tseplyayev (1961), Dulamsuren et al. (2005), and Hou (2001) includes: A: tundra, B: taiga forest, C: temperate mixed conifer-deciduous broadleaved forest, D: temperate steppe, E: semi-desert and desert; F: warm-temperate deciduous forest.

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

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

2.2 Numerical analyses of reconstruction

The abundance variations of the seven PFTs during the Holocene (time slices between 12 and 1 ka) from 34 site-groups were used in a clustering analysis. Eight site groups had to be excluded from the analysis due to poor coverage of time slices (G1, G5, G17, G19, G27, G42). For site-groups with <3 missing time slices during the Holocene (G3, G16, G26, G32, G33, G35, G38, G39, G41), linear interpolation was employed to estimate the PFT abundances for the missing time slices. Time-series clustering for the three-way dataset was performed to generate a distance matrix among the site-groups using the *tsclust* function in the *dtwclust* package (Sarda-Espinosa, 2018) in R 3.4.1 (R Core Team, 2017). The distance matrix was employed in hierarchical clustering (using the *hclust* function in R) to cluster the site-groups. Constrained hierarchical clustering (using *chclust* function in *rioja* package version 0.9-15.1; Juggins, 2018) together with the broken-stick model were used to determine the timing of primary vegetation changes in each site-group. The amount of PFT compositional change (turnover) through time during the Holocene was estimated by detrended canonical correspondence analysis (DCCA)

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for each site-group (ter Braak, 1986) using CANOCO 4.5 (ter Braak and Šmilauer, 2002).

3. Results

Large-scale pattern

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

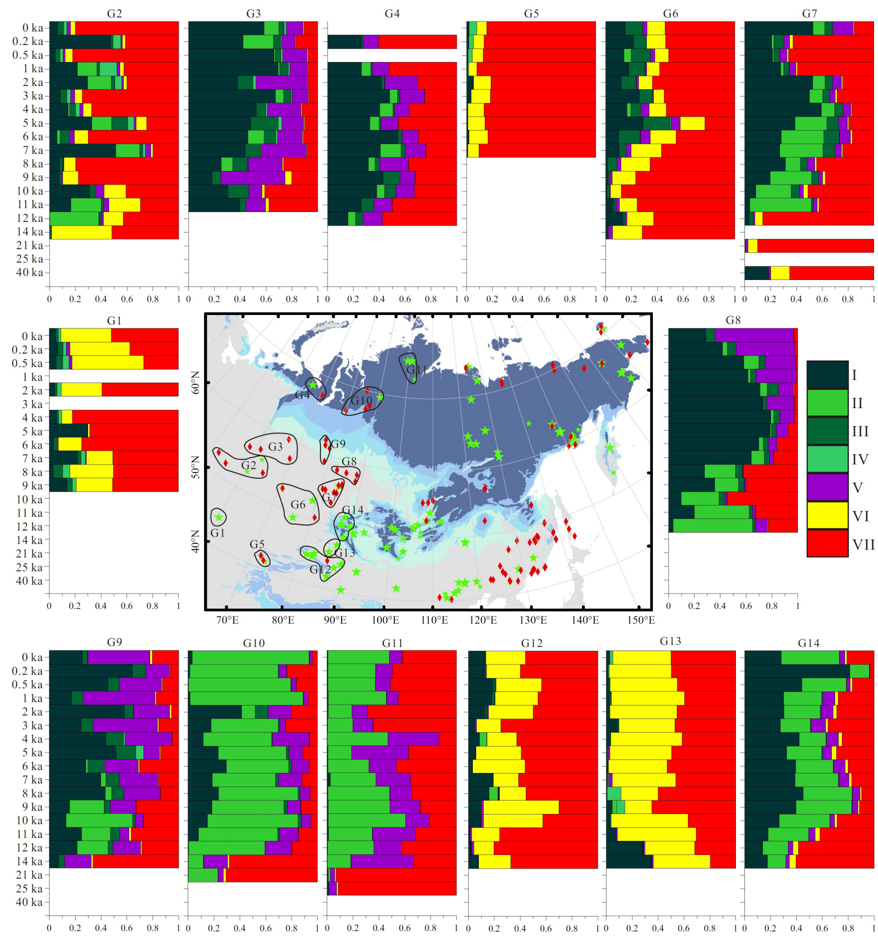

Fig. 2. Temporal changes of plant functional type (PFT) cover in proportion for 42 site groups. PFT I: evergreen conifer tree; PFT II: deciduous conifer tree; PFT III: boreal deciduous tree; PFT IV: temperate deciduous tree; PFT V: boreal shrub; PFT VI: arid-tolerant shrub and herb; and PFT VII: steppe and tundra forb.

The turnover in PFT composition is <0.7 SD units in almost all site-groups, except G8 (0.88 SD), G9 (0.73 SD), and G24 (0.76 SD), indicating only slight vegetation change during the Holocene. The three site-groups with higher turnover show a distinct transition from light taiga to dark taiga in the middle Holocene (at ca. 8 ka). This result is consistent with the finding that PFT abundance from 16 site groups show no significant temporal clusters. The primary vegetation changes (i.e. all significant splits or, if no significant split occurs in a record, the first insignificant split) occur during different intervals in each site-group. Overall, the early Holocene (including 11.5, 10.5, and 9.5 ka time-slices) has the highest frequency of primary vegetation changes. Records from the south-eastern coastal part of the study area are characterized by relatively many early-Holocene splits (e.g. G29, G30, G32, G33, G34, G36, G37). There are 16 site groups whose primary vegetation changes during the middle Holocene (including 8.5, 7.5, 6.5, and 5.5 ka time-slices), and most of them are from inland areas such as the West Siberian Plain, central Yakutia, and northern Mongolia. Only seven site groups have late-Holocene primary vegetation changes (Fig. 3).

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

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

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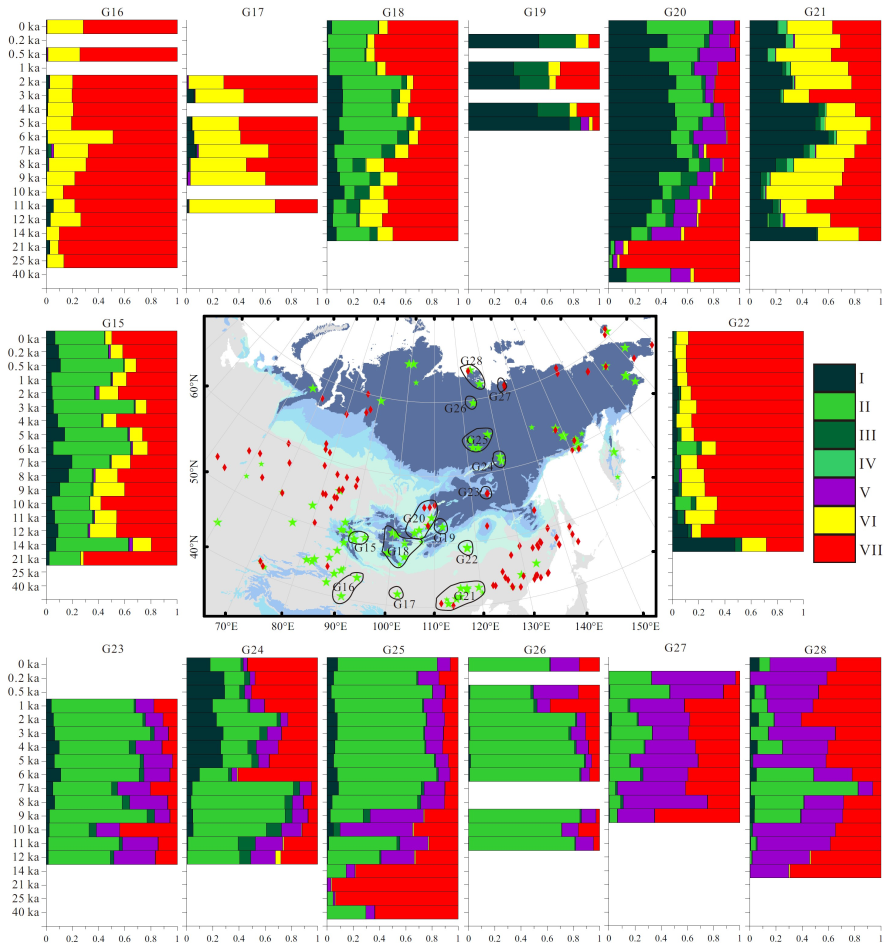

Fig. 2. Continued.

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

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

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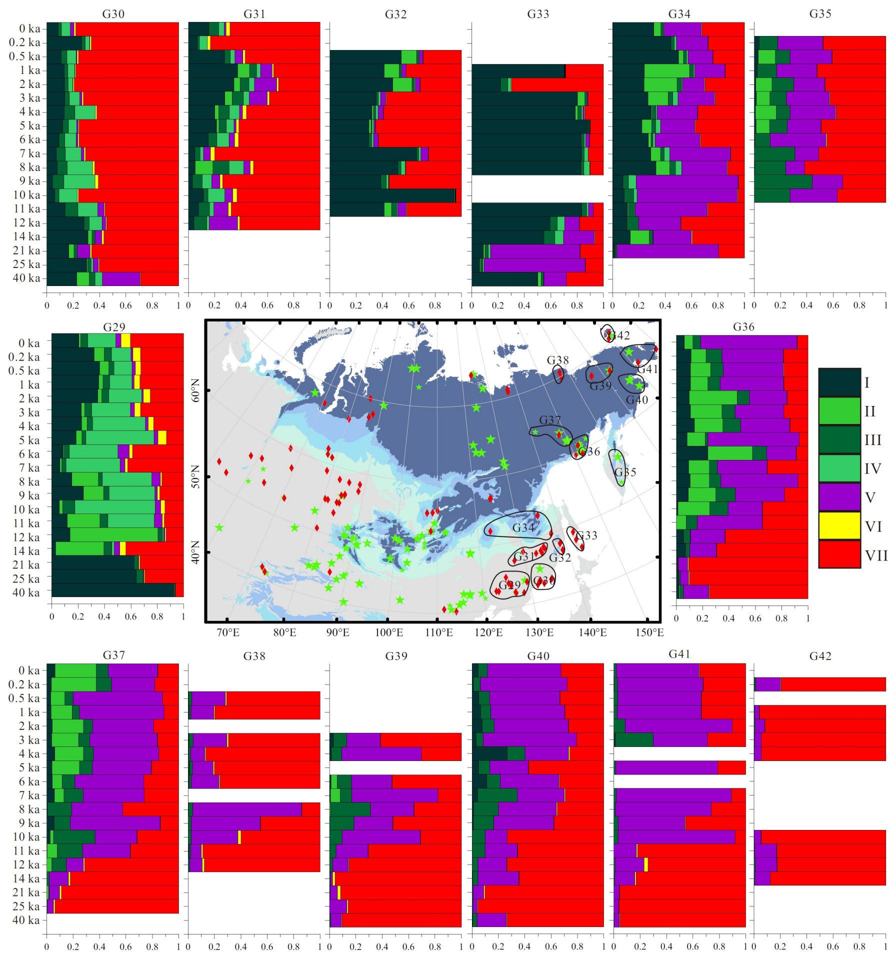

Fig. 2. Continued.

Evergreen conifer tree is the dominant PFT at 40, 25, and 21 ka in the southern part of north-eastern China (G29), *Larix* then becomes the dominant taxa at 14 and 12 ka, and temperate deciduous trees increase thereafter and maintain high cover between 11 and 3 ka. After 2 ka, evergreen conifer trees increase to 32% on average while temperate deciduous trees decrease to 18% on average. While arboreal abundance is lower in the northern part of northeastern China (G30, G31) than in the southern part (G29), it shows a similar temporal pattern.

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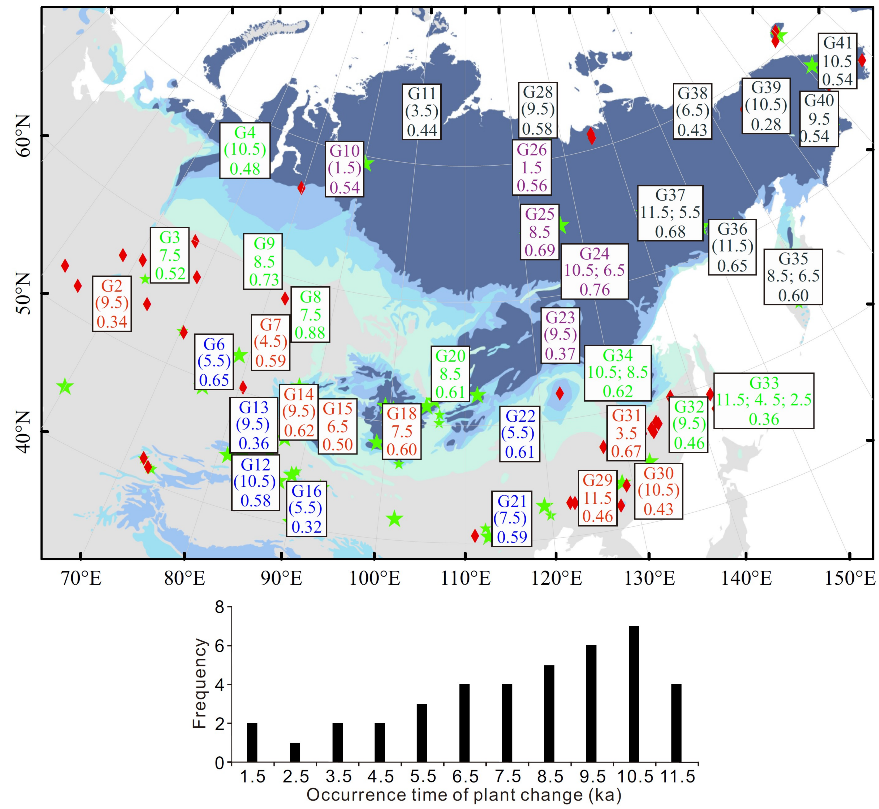

Fig. 3. Clustering results of the 34 site groups represented by the colour of the boxes, with the age of primary vegetation changes (middle row of each box; data in brackets means the hierarchical clustering failed the broken-stick testing) and the compositional change (turnover; lower row) during the Holocene. A summary of the frequency of when the changes occurred is provided below the map.

Open landscape is revealed for the southern Ural region (G2) with high abundances of herbaceous species at 14 ka. The cover of *Larix* and evergreen conifer trees increases after 12 ka and maintains high values thereafter with no notable temporal trend.

In the taiga-steppe transition zone, *Larix* is the dominant arboreal taxon, particularly in the northern Altai Mts. and northern Mongolia (G15, G18). Open landscapes are inferred at 40, 21, and 12 ka on the southern West Siberian Plain (G7); cover of

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Larix increases at 11 ka, and evergreen conifer trees increase from 9 ka and become the dominant forest taxon after 4 ka. The temporal pattern of evergreen conifer trees in the Altai Mts. (G14) is similar to the southern West Siberian Plain, although *Larix* maintains high abundances into the late Holocene. Relative to the Altai Mts., the abundance of evergreen conifer trees for all time windows are lower in the area north of the Altai Mts. and in northern Mongolia (G15, G18), but their temporal change patterns are consistent with those of the Altai Mts. (G14).

Dark taiga forest in western and southeastern Siberia (G3, G4, G8, G9, G20, G32, G33, G34)

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

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

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

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

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

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

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

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

In north-eastern Siberia, arboreal cover shows a decreasing trend from southerly site groups (G35, G36, G37) to northerly ones (G40, G38, G39, G41) following the increasing latitude. In the Olsky District, temporal patterns of vegetation changes in G37 are consistent with G36, with stable vegetation during the Holocene and increases in evergreen conifer tree abundance from ca. 9 ka. Arboreal composition on the southern Kamchatka Peninsula (G35) is dominated by boreal deciduous trees during the first stage of the Holocene, followed by rising abundances of *Larix* and evergreen conifer trees from 5 ka.

In northeastern Siberia (G40, G38, G39, G41), the landscape is dominated by forb

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tundra with sparse shrubs between 40 and 21 ka; the cover of shrubs increases at 14 ka and arboreal cover (dominated by boreal deciduous trees) increases in the early Holocene (11 or 10 ka). Shrubs maintain a high abundance throughout the Holocene, while trees peak between 10 and 2 ka generally.

Fig. 2

Fig. 3

4. Discussion

4.1 Land-cover changes and potential biases

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

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

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

Pollen-based turnover estimates from southern Norway range between 0.84 to 1.3 SD (mean 1.02 SD) for ten Holocene pollen spectra (Birks, 2007), and from northern Europe between 0.01 (recent) to 0.99 (start of the Holocene) SD for three sites (N Sweden, NW and SE Finland) (Marquer et al., 2014). Moreover, the REVEALS-based turnover estimates (0.3-1) for northern Europe are significantly higher than the pollen-based one (0.2-08) from 11 ka to 5.5 ka BP. The same is true for all other regions studied by Marquer et al. (2014) in northwestern Europe, and the turnover estimates (pollen- and REVEALS-based) are generally higher at lower latitudes from southern Sweden down to Switzerland and eastwards to Britain and Ireland. These European values are higher than our REVEALS-based turnover estimates (from 0.37 to 0.88 SD, mean 0.66 SD; G3, G8, G9, G23, G24, G25, G36,

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G37) from a similar latitudinal range (Fig. 3). Aside from the methodological aspects, the lower turnover in northern Asia may, at least partly, originate from differences in the environmental history between northern Europe compared with northern Asia, i.e. glaciation followed by postglacial invasion vs. non-glaciated areas with trees in refugia, respectively, and a maritime climate with temperature-limited vegetation distribution vs. a continental climate with temperature- and moisture-limited vegetation.

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

(1) Twenty RPP sets were used which mostly originate from Europe and temperate northern China (the typical steppe in north-central China, Xilinhaote, Xu et al., 2014; and the temperate coniferous and broadleaved mixed forest in north-eastern China, Changbai Mt.; Li et al., 2015), but also included RPP records from the taiga-tundra ecotone in arctic Siberia (Niemeyer et al., 2015). We assume that the compiled RPP sets can be used to extract major broad-scale and long-term vegetation patterns because the regional differences among RPP estimates within one taxon are small compared to the large between-taxa differences in RPP estimates. Also, the mean values of available RPPs that were used in the REVEALS modelling (Table 2) and the calculated PPEs are broadly consistent with those obtained from Europe (Mazier et al., 2012). In addition, although there is no PPE

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records from the core of the Siberia taiga forest, available studies on modern pollen composition confirm the trends in the applied RPP for major taxa in terms of pollen under- or over-representation of vegetation abundance. For example, modern pollen investigation in north-eastern Siberia revealed that pollen records from northern *Larix* forest often have less than 13% *Larix* pollen confirming the low pollen productivity of *Larix* relative to over-represented pollen taxa such as *Betula* and *Alnus* (Pisaric et al., 2001, Klemm et al., 2016). Similarly, a study on modern pollen in southern Siberia (transitional area of steppe and taiga) finds that *Artemisia*, *Betula,* and *Pinus* are high pollen producers compared to *Larix* (Pelánková et al., 2008). Also, despite *Larix* being the most common tree in taiga forest in north-central Mongolia, the pollen abundance of *Larix* is generally lower than 3% (Ma et al., 2008), implying its low pollen productivity.

(2) In this study, we attempt to reconstruct past landscape changes at a regional scale. Pollen signals from large lakes are assumed to reflect regional vegetation patterns (e.g. Sugita et al., 2010; Trondman et al., 2015). If large lakes are absent in a region, multiple small-sized sites can also be used, although error estimates are usually large (Sugita, 2007; Mazier et al., 2012; Trondman et al., 2016). In our study, 70% of the time slices for the 42 site groups include pollen data from large lakes (i.e. radii >390m), which supports the reliability of REVEALS estimates (Table 3). However, sites are unevenly distributed and occasionally sites from different areas were combined into one group (G2, G6, G34), which might produce a different vegetation-change signal because of the broad distribution of these sites. Finally, pollen signals from certain sites and during certain periods may be of riverine rather than aerial origin violating the assumption of the REVEALS-model that pollen is transported by wind.

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Table 3 Number of pollen records from large lakes (with ⩾390 m radius; represented by L), small lakes (with <390 m radius; represented by S), and bogs (B) for each 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 (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	-	-
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	-	-	-

4.2 Driving factors of vegetation changes

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

A sensitivity analysis of model-based biome estimation reveals that precipitation plays an important or even dominant role in controlling vegetation changes in arid central Asia (e.g. Tian et al., 2018). The climate of central Asia during the early Holocene is inferred to be quite dry and the end of moisture increase occurs at ca. 8 ka by a series of multi-proxy syntheses (Chen et al., 2008, 2016; Xie et al., 2018) and model-based estimations (Jin et al., 2012). In the taiga-steppe transition zone (south-eastern Siberia and north-central Asia; e.g. G6, G12, G14, G18), relatively open landscape is reconstructed for the early Holocene and abundances of forest taxa increase after ca. 8 ka, which are consistent with the moisture evolution, and imply the importance of moisture in controlling vegetation changes. Our results support the prediction of an expansion of steppe in the present forest–steppe ecotone of southern Siberia in response to a warmer and drier climate in the future (Tchebakova et al., 2009).

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

Our results indicate that climate change is the major factor driving land-cover change in northern Asia on a long temporal scale. However, climate change cannot fully explain the changes in arboreal taxa abundance for the West Siberian Plain (G8, G9) and sandy places in central Yakutia (G23, G24, G25). In addition to climate, changes in permafrost condition (Vandenberghe et al., 2014) and fire regime may have played a central role in vegetation change. *Larix* is the dominant arboreal taxon during the early Holocene (ca. between 12 and 8 ka), which is replaced by evergreen conifer trees, mostly pine and spruce at 8 or 7 ka. *Larix* can survive on permafrost with an active-layer depth of <40 cm (Osawa et al., 2010) and a high fire frequency, while pine trees can only grow on soil with >1.5m active-layer (Tzedakis and Bennett, 1995) and spruce is a fire-avoider. Probably the compositional change of boreal trees was not in equilibrium with climate but rather driven by changes in the permafrost and fire characteristics that were themselves affected by forest composition, resulting in complex feedbacks. This explanation would be in agreement with the finding of Herzschuh et al. (2016) that the boreal forest composition of nearby refugia during the glacial influences the initial interglacial forest composition that is then only slowly replaced by a forest composition that is in equilibrium with climate.

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

5. Conclusions

Regional vegetation based on pollen data has been estimated using the REVEALS model for northern Asia during the last 40 ka. Relatively closed land cover was replaced by open landscapes in northern Asia during the transition from MIS 3 to the last glacial maximum. Abundances of woody components increase again from the early Holocene or last deglaciation. Our numerical analyses indicate that the vegetation was quite stable during the Holocene, i.e. only slight changes in the abundances of taxa were recorded rather than mass expansion of new taxa. From comparisons of our results with other data we infer that climate change is likely the primary driving factor for vegetation changes on a glacial-interglacial scale. However, the extension of evergreen conifer trees since ca. 8~7 ka throughout Siberia could reflect a vegetation-climate disequilibrium caused by the interaction of climate, vegetation, fire, and permafrost.

Data availability. The used fossil pollen dataset with the re-established age-depth model for each pollen record, and its full description will be made publicly available in journal Earth System Science Data (ESSD).

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Appendixes

Appendix 1 Metadata for all pollen records used in this study.

Group	Site	Lat.	Long.	Alt. (m)	Basin type	Pollen count	Area (ha)	Radius (m)	Dating method	Num. of dating	Time spa (cal k BP)
G1	Aral Lake	44.42	59.98	53	Lake	Yes	330000	32410	^{14}C	4U	8.7-0
G2	Mokhovoye	53.77	64.25	178	Bog	Yes	20	252	^{14}C	4C+1E	6.0-0
G2	Novienky peat bog	52.24	54.75	197	Bog	Yes	-	-	^{14}C	1U	4.5-0
G2	Zaboinoe Lake	55.53	62.37	275	Lake	Yes	6	138	^{14}C	1U	12.3-0.1
G2	Lake Fernsehsee	52.83	60.50	290	Lake	Yes	0	38	^{14}C	10A	9.1-0.4
G2	Pobochnoye	53.03	51.84	81	Bog	No	79	500	^{14}C	10C+6E	14.4-0
G3	Chesnok Peat	60.00	66.50	42	Bog	Yes	-	-	^{14}C	7C	10.6-0.5
G3	Komaritsa Peat	57.50	69.00	42	Bog	Yes	-	-	^{14}C	10C	10.5-0.5
G3	UstMashevskoe	56.32	57.88	220	Bog	Yes	30	309	^{14}C	5C	7.8-0
G3	Karasieozerskoe	56.77	60.75	230	Bog	Yes	914	1706	^{14}C	3A	5.9-0.1
G4	Nulsaveito	67.53	70.17	57	Bog	Yes	-	-	^{14}C	4A+1C	8.4-6.4
G4	Lyadhej-To Lake	68.25	65.75	150	Lake	Yes	197	792	^{14}C	14A+6E	12.5-0.3
G5	Nizhnee Lake	41.30	72.95	1371	Lake	No	-	70	^{14}C	4E	1.5-0
G5	Verkhnee Lake	41.30	72.95	1440	Lake	No	1	60	^{14}C	5E	1.5-0
G5	Ak Terk Lake	41.28	72.83	1748	Bog	No	-	-	^{14}C	2A	7.5-0
G5	Kosh Sas	41.85	71.97	1786	Bog	No	-	-	^{14}C	1A	3.5-0
G5	Ortok Lake	41.23	73.25	1786	Lake	No	-	60	^{14}C	5A	1-0
G5	Bakaly Lake	41.87	71.97	1879	Lake	No	1	50	^{14}C	4A	7-0
G6	Big Yarovoe Lake	52.85	78.63	79	Lake	Yes	6362	4500	inclination with	-	4.3-0

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									Lake Biwa				
G6	Ozerki	50.40	80.47	210	Bog	Yes	-	-	^{14}C	3A+13C	14.5-0	300	Tarasov et al., 1997
G6	Karas'e Lake	53.03	70.22	435	Lake	Yes	17	235	^{14}C	6U	5.5-0	170	Tarasov and Kremenetskii. 1995
G6	Kotyrkol	52.97	70.42	439	Bog	Yes	-	-	^{14}C	8U	4.5-0.5	180	Tarasov and Kremenetskii. 1995
G6	Pashennoe Lake	49.37	75.40	871	Lake	Yes	64	451	^{14}C	5D+5E	9.5-0	280	Tarasov and Kremenetskii. 1995
G7	Gladkoye Bog	55.00	83.33	80	Bog	Yes	-	-	^{14}C	13C	11-0.5	170	Firsov et al., 1982
G7	Chaginskoe Mire	56.45	84.88	80	Bog	Yes	10	175	^{14}C	2C	8.8-0	320	Blyakharchuk, 2003.
G7	Kirek Lake	56.10	84.22	90	Lake	Yes	52	407	^{14}C	3G	10.5-1.5	190	Blyakharchuk, 2003
G7	Tom' River Peat	56.17	84.00	100	Bog	Yes	-	-	^{14}C	6C	10.1-0.2	390	Arkhipov and Votakh, 1980
G7	Zhukovskoye mire	56.33	84.83	106	Bog	Yes	-	-	^{14}C	9C+6H	11.2-0	130	Borisova et al., 2011
G7	Tolmachevsko	55.00	84.00	110	Bog	Yes	-	-	^{14}C	1A+3C	13-1.5	400	Volkov and Arkhipov, 1978
G7	Suminskoye	55.00	80.25	135	Bog	Yes	-	-	^{14}C	8A	3-0	200	Klimanov, 1976
G7	Kayakskoye	55.00	81.00	150	Bog	Yes	-	-	^{14}C	5C	6.5-0	210	Levina et al., 1987
G7	Kalistratikha	53.33	83.25	190	Bog	Yes	-	-	^{14}C	4A	39.0-12.7	1870	Zudin and Votakh, 1977
G8	Petropavlovka	58.33	82.50	100	Bog	Yes	-	-	^{14}C	4C+1E	10.5-0.1	160	Blyakharchuk, 1989
G8	Bugristoe	58.25	85.17	130	Bog	Yes	-	-	LSC	4C+1E	11.5-5.0	100	Blyakharchuk, 1989
G8	Maksimkin Yar	58.33	88.17	150	Bog	Yes	-	-	^{14}C	4C	8.3-0.2	170	Blyakharchuk, 1989
G8	Teguldet	57.33	88.17	150	Bog	Yes	-	-	LSC	3C	7.3-2.4	90	Blyakharchuk, 1989
G9	Nizhnevartovsk	62.00	76.67	54	Bog	Yes	-	-	^{14}C	3A+7C	11.1-0	300	Neustadt and Zelikson, 1985
G9	Nizhnevartovskoye	61.25	77.00	55	Bog	Yes	-	-	^{14}C	1A+12C+1 E	12.6-0	380	Neishtadt, 1976
G9	Entarnoye Peat	59.00	78.33	65	Bog	Yes	-	-	^{14}C	5C	14.9-0.9	460	Neishtadt, 1976
G9	Lukaschin Yar	61.00	78.50	65	Bog	Yes	-	-	^{14}C	13C	10.9-0.3	430	Neishtadt, 1976
G10	Igarka Peat	67.67	86.00	45	Bog	Yes	244	881	^{14}C	1A+2C	10.9-5.9	230	Kats, 1953
G10	Pur-Taz Peatland	66.70	79.73	50	Bog	Yes	5	126	^{14}C	5A	10.3-4.7	80	Peteet et al., 1998
G10	Karginskii Cape	70.00	85.00	60	Bog	Yes	-	-	^{14}C	13C	8.9-3.5	290	Firsov et al., 1972

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G10	Yenisei	68.17	87.15	68	Bog	No	-	-	^{14}C	7C	6.5-1.6	110	Andreev and Klimanov 2000
G10	Lake Lama	69.53	90.20	77	Lake	Yes	64245	14300	^{14}C	26A+4D+4E	19.5-0	170	Andreev et al., 2004
G11	11-CH-12A Lake	72.40	102.29	60	Lake	Yes	3	100	^{14}C+Pb/Cs	8A+7E	7.0-0.1	110	Klemm et al., 2015
G11	Levinson-Lessing Lake	74.47	98.64	26	Lake	Yes	2145	2613	^{14}C	29A+1B+19E	35.3-0	390	Andreev et al., 2003
G11	SAO1	74.55	100.53	32	Lake	Yes	456000	38098	^{14}C	6A+5C	57.9-0	1320	Andreev et al., 2003
G12	Aibi Lake	45.02	82.83	200	Lake	Yes	100885	17920	^{14}C	8E	12.6-0	65	Wang et al., 2013
G12	Ebinur Lake	44.55	82.45	212	Lake	Yes	46421	12156	^{14}C	7U	13-0	900	Wen and Qiao, 1990
G12	Ebinur Lake_SW	45.00	82.80	212	Lake	Yes	46421	12156	^{14}C	6U	8.5-1.5	780	Lin, 1994
G12	Caotanhu Lake	44.42	86.02	380	Bog	Yes	2760	2964	^{14}C	5C	8.5-0	150	Zhang Y. et al., 2008
G12	Dongdaohaizi Lake	44.70	89.56	430	Lake	Yes	20	252	^{14}C	8U	5.5-0	85	Yan et al., 2004
G12	Sichanghu Lake	44.31	89.14	589	Lake	Yes	2000	2523	^{14}C	4U	1-0	50	Zhang Y. et al., 2004b
G12	Bosten Lake	41.97	86.55	1050	Lake	No	96608	17536	^{14}C	5U	13-0	420	Xu, 1998
G12	Chaiwopu Lake	43.55	87.78	1100	Lake	No	3101	3142	^{14}C	2U	10-0	845	Li and Yan, 1990
G12	Sayram Lake	44.57	81.15	2072	Lake	Yes	45800	12074	^{14}C	12E	13.8-0.1	90	Jiang et al., 2013
G13	Manas Lake	45.83	85.92	251	Lake	Yes	55000	13231	^{14}C	7C	13.5-1	210	Sun et al., 1994
G13	Wulungu Lake	47.22	87.30	479	Lake	Yes	67019	430	^{14}C+Pb/Cs	1C	9-0	80	Liu X.Q. et al., 2008
G14	Teletskoye Lake	51.72	87.65	1900	Lake	Yes	16610	7271	^{14}C+Pb/Cs	6E	1-0	20	Andreev et al., 2007
G14	Uzunkol Lake	50.48	87.11	1985	Lake	No	123	625	^{14}C	2A	17.5-0	210	Blyakharchuk et al., 2004
G14	Kendegelukol Lake	50.51	87.64	2050	Lake	No	5	130	^{14}C	7E	16-1	260	Blyakharchuk et al., 2004
G14	Hoton Nur Lake	48.62	88.35	2083	Lake	Yes	5021	3998	^{14}C	4A	6-0	60	Rudaya et al., 2009
G14	Tashkol Lake	50.45	87.67	2150	Lake	No	-	150	^{14}C	3C	16-3	250	Blyakharchuk et al., 2004
G14	Akkol Lake	50.25	89.63	2204	Lake	No	388	1111	^{14}C	12E	13.5-0	250	Blyakharchuk et al., 2007
G14	Grusha Lake	50.38	89.42	2413	Lake	No	130	644	^{14}C	3A+13E	14-1.5	250	Blyakharchuk et al., 2007
G15	Bayan Nuur	50.00	93.00	932	Lake	No	2968	3073	^{14}C	7E	15.7-0.2	210	Krengel, 2000

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G15	Achit Nur Lake	49.50	90.60	1435	Lake	No	29700	9723	^{14}C	4E	14-0.5	700	Gunin et al., 1999
G15	Achit Nuur	49.42	90.52	1444	Lake	No	29700	9723	^{14}C	10E	20.2-0	250	Sun et al., 2013
G16	Lop Nur_1998	40.28	90.25	780	Lake	No	535000	41267	^{14}C	3U	22-2	2000	Yan et al., 1998
G16	Lop Nur_1983	40.33	90.25	800	Lake	Yes	535000	41267	^{14}C	3U	22-0.5	1600	Yan et al., 1983
G16	Barkol Lake	43.62	92.80	1575	Lake	Yes	11300	5997	^{14}C	1A+10E	10-0	115	Tao et al., 2009
G16	Balikun Lake	43.68	92.80	1575	Lake	Yes	7897	5014	^{14}C	1D+5E	30.5-9	250	An et al., 2013
G17	Juyan Lake	41.89	101.85	892	Lake	Yes	72000	15139	^{14}C	5E	10.5-1.5	140	Herzschuh et al., 2004
G18	Gun Nur Lake	50.25	106.60	600	Lake	No	33	325	^{14}C	7E	11-0	320	Gunin et al., 1999
G18	Yamant Nur Lake	49.90	102.60	1000	Lake	No	58	430	^{14}C	4E	15.5-0.5	360	Gunin et al., 1999
G18	Ugii Nuur Lake	47.77	102.77	1330	Lake	No	2456	2796	^{14}C	2C	9-0	85	Wang et al., 2011
G18	Dood Nur Lake	51.33	99.38	1538	Lake	No	6400	4514	^{14}C	2E	14-0	740	Gunin et al., 1999
G18	Hovsgol Lake	51.10	100.50	1645	Lake	Yes	276000	29640	^{14}C	5E	12-2.5	190	Prokopenko et al., 2007
G18	Khuisiin Lake	46.60	101.80	2270	Lake	Yes	4	118	^{14}C+Pb/Cs	6E	1.2-0	17	Tian et al., 2013
G18	Daba Nur Lake	48.20	98.79	2465	Lake	No	157	707	^{14}C	5E	13-0	520	Gunin et al., 1999
G19	Bolshoe Eravnoe Lake	52.58	111.67	947	Lake	Yes	9503	5500	^{14}C	3E	7.3-0.2	710	Vipper, 2010
G20	Baikel Lake	52.08	105.87	130	Lake	No	3150000	100134	^{14}C	12A	22-0	370	Demske et al., 2005
G20	Baikal Lake-CON01-603-5	53.95	108.91	446	Lake	Yes	3150000	100134	^{14}C	10D	15.8-0	270	Demske et al., 2005
G20	Lake Kotokel_2010	52.78	108.12	458	Lake	Yes	6900	4687	^{14}C	11E	47-0	220	Bezrukova et al., 2010
G20	Lake Kotokel_2009	52.78	108.12	458	Lake	Yes	6900	4687	^{14}C	3E	15-0	500	Tarasov et al., 2009
G20	Chernoe Lake	50.95	106.63	500	Lake	Yes	-	250	^{14}C	4E	7-0.7	620	Vipper, 2010
G20	Baikal Lake-CON01-605-3	51.59	104.85	675	Lake	Yes	3150000	100134	^{14}C	5D	17.7-0	200	Demske et al., 2005
G20	Okunayka	55.52	108.47	802	Bog	Yes	-	-	^{14}C	6C	8.3-2.0	120	Bezrukova et al., 2011
G20	Ukta Creek mouth	55.80	109.70	906	Bog	Yes	-	-	^{14}C	3U	5.1-0	160	Bezrukova et al., 2006
G20	Cheremushka Bog	52.75	108.08	1500	Bog	Yes	-	-	^{14}C	6C	33.5-0	460	Shichi et al., 2009

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G20	Baikal Lake-CON01-605-5	51.58	104.85	492	Lake	Yes	3150000	100134	^{14}C	12D	11.5-0	130	Demske et al., 2005
G20	Khanda-1	55.44	107.00	867	Bog	Yes	-	-	^{14}C	3C	3.1-0.3	50	Bezrukova et al., 2011
G20	Khanda	55.44	107.00	867	Bog	Yes	-	-	^{14}C	6C	5.8-0	140	Bezrukova et al., 2011
G21	Qiganhu Lake	42.90	119.30	600	Lake	Yes	190	778	^{14}C	5E	12.1-6.7	35	Hu et al., 2016
G21	Wangyanggou	42.07	119.92	751	Lake	No	13	200	^{14}C	1A+3E	5-0	85	Li et al., 2006
G21	Wangguantun	40.27	113.67	800	Bog	Yes	-	-	^{14}C	1A+4F	8-3	310	Kong and Du, 1996
G21	Anguli Nur Lake	41.33	114.37	1000	Lake	Yes	4264	3684	^{14}C	2U	14-10.5	520	Li et al., 1990
G21	Qasq	40.67	111.13	1000	Bog	Yes	-	-	^{14}C	2E	10-0	90	Wang et al., 1997
G21	Daihai Lake_2004	40.58	112.67	1220	Lake	Yes	16000	7136	^{14}C	8E	11.5-0	215	Xiao et al., 2004
G21	Gaoximage Lake	42.95	115.37	1253	Lake	No	100000	17841	^{14}C	4E	6-0	150	Li C.Y. et al., 2003
G21	Haoluku Lake	42.96	116.76	1295	Lake	No	1384	2099	^{14}C	4E	11.5-0	250	Wang et al., 2001
G21	Bayanchagan Lake	41.65	115.21	1355	Lake	Yes	636	1423	^{14}C	2B+7E	11.5-0	250	Jiang et al., 2006
G21	Liuzhouwan Lake	42.71	116.68	1365	Lake	No	288	957	^{14}C	3E	13-0.5	470	Wang et al., 2001
G21	Diaojiaohaizi Lake	41.30	112.35	1800	Lake	Yes	30	309	^{14}C	4U	11.5-2.5	95	Song et al., 1996
G22	Hulun Nur Lake_1995	49.28	117.40	544	Lake	No	233900	27286	^{14}C	7U	19-0.5	190	Yang et al., 1995
G22	Hulun Nur Lake_2006	49.13	117.51	545	Lake	Yes	233900	27286	^{14}C	13E	11-0	65	Wen et al., 2010
G23	Derput	57.03	124.12	700	Bog	Yes	1	56	^{14}C	1A+4C	11.7-0.8	210	Andreev and Klimanov, 1991
G23	Suollakh	57.05	123.85	811	Bog	Yes	-	-	^{14}C	8C	12.8-3.7	180	Andreev et al., 1991
G24	Nuochaga Lake	61.30	129.55	260	Lake	Yes	120	618	^{14}C	4E	6.5-0	140	Andreev and Klimanov, 1989
G24	Chabada Lake	61.98	129.37	290	Lake	Yes	210	818	^{14}C	15U	13-0	110	Andreev and Klimanov, 1989
G25	Boguda Lake	63.67	123.25	120	Lake	Yes	2500	2821	^{14}C	7E	10.9-0.4	180	Andreev et al., 1989
G25	Khomustakh Lake	63.82	121.62	120	Lake	Yes	440	1183	^{14}C	9E	12.3-0.1	170	Andreev et al., 1989
G25	Madjaga Lake	64.83	120.97	160	Lake	Yes	1440	2141	LSC	7E	8.2-0.2	120	Andreev and Klimanov, 1989
G25	Billyakh Lake	65.30	126.78	340	Lake	Yes	1678	2311	^{14}C	7A	14.1-0	180	Müller et al., 2009

G25	Lake Billyakh_PG1755	65.27	126.75	340	Lake	Yes	1634	2281	^{14}C	1A+10E	50.6-0.2	470	Müller et al., 2010
G26	Lake Kyutyunda_PG2022	69.63	123.65	66	Lake	Yes	468	1220	^{14}C	10E	10.8-0.3	360	Biskaborn et al., 2015
G27	Khocho	71.05	136.23	6	Bog	Yes	10	178	^{14}C	1C	10.4-0.4	300	Velichko et al., 1994
G27	Samandon	70.77	136.25	10	Bog	Yes	100	564	^{14}C	3A+8C+4E	7.9-0.2	280	Velichko et al., 1994
G28	Barbarina Tumsa	73.57	123.35	10	Bog	Yes	-	-	^{14}C	4C	4.9-0.3	240	Andreev et al., 2004
G28	Lake Nikolay	73.67	124.25	35	Lake	Yes	1500	2185	^{14}C	6A	12.5-0	600	Andreev et al., 2004
G28	Dolgoe Ozero	71.87	127.07	12	Lake	Yes	84	517	^{14}C	1A+9B	15.3-0	210	Pisaric et al., 2001
G29	Maili	42.87	122.88	155	Bog	No	-	-	^{14}C	5A	3-0	115	Ren and Zhang, 1997
G29	Dashan	44.88	124.85	200	Bog	Yes	-	-	^{14}C	5U	7.5-1	160	Xia et al., 1993
G29	Xiaonan	43.88	125.22	209	Bog	Yes	-	-	^{14}C	5U	5.5-0	290	Wang and Xia, 1988
G29	Shuangyang	43.45	125.75	215	Bog	Yes	-	-	^{14}C	12E	2.5-0	30	Qiu et al., 1981
G29	Charisu	42.95	122.35	249	Bog	Yes	-	-	^{14}C	10A	5.5-0	170	Li Y.H. et al., 2003b
G29	Jingbo Lake	43.91	128.75	350	Lake	Yes	9500	5499	^{14}C+LSC	3E+4	8.8-0	40	Li et al., 2011
G29	Harbaling	43.63	129.20	600	Bog	Yes	-	-	^{14}C	3U	3-0	150	Xia, 1988b
G29	Jinchuan	42.35	126.38	620	Bog	Yes	-	-	^{14}C	7A	5.5-0	105	Li Y.H. et al., 2003a
G29	Erhailongwan Lake	42.30	126.37	724	Lake	Yes	30	309	^{14}C	2A+14E	22-0	760	Liu Y.Y. et al., 2008
G29	Sihailongwan Lake	42.28	126.60	797	Lake	Yes	41	360	^{14}C+varve	40A	16.9-0.2	47	Stebich et al., 2015
G29	Hani	42.21	126.52	899	Bog	Yes	1800	2394	^{14}C	1C	9.5-0	455	Qiao, 1993
G29	Chichi Lake	42.03	128.13	1800	Bog	Yes	0	40	^{14}C	1C	1-0	140	Xu et al., 1994
G30	Belaya Skala	43.25	134.57	4	Bog	Yes	-	-	^{14}C	2A+1C	6.5-3	250	Korotky et al., 1980
G30	Chernyii Yar	43.18	134.43	4	Bog	Yes	-	-	^{14}C	4C	10-0.5	260	Korotky et al., 1980
G30	Tikhangou	42.83	132.78	4	Bog	Yes	-	-	^{14}C	5U	12-0	500	Korotky et al., 1980
G30	Amba River	43.32	131.82	5	Bog	Yes	-	-	^{14}C	1A+1C+1U	5-2.5	300	Korotky et al., 1980
G30	Ryazanovka	42.83	131.37	6	Bog	Yes	-	-	^{14}C	7A	6-0.5	540	Shilo, 1987

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G30	Ovrazhnyii	43.25	134.57	8	Bog	Yes	-	-	^{14}C	3A	7-1	200	Shilo, 1987
G30	Peschanka	43.30	132.12	12	Bog	Yes	-	-	^{14}C	3U	22-11	965	Anderson et al., 2002
G30	Xingkai Lake	45.21	132.51	69	Lake	Yes	419000	36520	^{14}C+Pb/Cs	3E	28.5-0	150	Ji et al., 2015
G31	Tongjiang	47.65	132.50	49	Bog	Yes	-	-	^{14}C	5C	6-0	130	Zhang and Yang, 2002
G31	Chuangye	48.33	134.47	50	Bog	Yes	-	-	^{14}C	3U	12-1	400	Xia, 1988a
G31	Minzhuqiao	47.53	133.87	52	Bog	Yes	-	-	^{14}C	4U	6.5-0.5	420	Xia, 1988a
G31	Qindeli	47.88	133.67	52	Bog	Yes	-	-	^{14}C	1F+7U	13.5-0.5	380	Xia, 1988a
G31	Beidawan	48.13	134.70	60	Bog	Yes	8	157	^{14}C	3U	5.5-0.5	350	Xia, 1988a
G31	Wuchanghai	47.22	127.33	200	Bog	Yes	-	-	^{14}C	9E	7-0	250	Xia, 1988b
G31	Tangbei	48.35	129.67	486	Bog	Yes	-	-	^{14}C	2A	5.5-1	160	Xia, 1996
G32	Venyukovka-3	47.12	138.58	5	Bog	Yes	-	-	^{14}C	1A+2C	5.8-3.2	140	Korotky et al., 1980
G32	Venyukovka-2	47.03	138.58	6	Bog	Yes	-	-	^{14}C	1A+1C	3.6-0.4	140	Korotky et al., 1980
G32	Oumi	48.22	138.40	990	Bog	Yes	-	-	^{14}C	5C	2.6-0.4	80	Anderson et al., 2002
G32	Opasnaya River	48.23	138.48	1320	Bog	Yes	-	-	^{14}C	7C	13.3-6.7	360	Korotky et al., 1988
G33	Il'inka Terrace	47.97	142.17	3	Bog	Yes	-	-	^{14}C	2C+1F	2.6-1.1	360	Korotky et al., 1997
G33	Mereya River	46.62	142.92	4	Bog	Yes	-	-	^{14}C	2C+2F	42.0-0.8	1530	Anderson et al., 2002
G33	Sergeevskii	49.23	142.08	6	Bog	Yes	-	-	^{14}C	8A+1C	8.4-2.2	110	Korotky et al., 1997
G34	Gurskii Peat	50.07	137.08	15	Bog	Yes	-	-	^{14}C	7C	13.1-1.5	380	Korotky, 1982
G34	Gur Bog	50.00	137.05	35	Bog	No	-	-	^{14}C	13C	22.1-0	340	Mokhova et al., 2009
G34	Tuqiang	52.23	122.80	400	Bog	Yes	-	-	^{14}C	10A+14E+8F	3-1	125	Xia, 1996
G34	Selitkan-2	53.22	135.03	1300	Bog	Yes	-	-	^{14}C	4C	6.4-1.9	260	Volkov and Arkhipov, 1978
G34	Selitkan-1	53.22	135.05	1320	Bog	Yes	-	-	^{14}C	6C	7.9-0	140	Korotky et al., 1985
G35	Two-Yurts Lake_PG1856-3	56.82	160.04	275	Lake	Yes	1168	1928	^{14}C	5A	6.0-2.8	140	Hoff et al., 2015
G35	Two-Yurts Lake_PG1857-2	56.82	160.07	275	Lake	Yes	1168	1928	^{14}C	5A	2.5-0.1	130	Hoff et al., 2015

G35	Two-Yurts Lake_PG1857-5	56.82	160.07	275	Lake	Yes	1168	1928	^{14}C	5A	4.4-2.5	120	Hoff et al., 2015
G35	Lake Sokoch	53.25	157.75	495	Lake	Yes	41	363	^{14}C	8E	9.7-0.3	250	Dirksen et al., 2012.
G36	Glukhoye Lake	59.75	149.92	10	Bog	Yes	-	-	^{14}C	5C	9.4-3.4	1000	Lozhkin et al., 1990
G36	Chistoye Lake	59.55	151.83	91	Bog	Yes	-	-	^{14}C	5C	7.0-0	540	Anderson ey al., 1997
G36	Lesnoye Lake	59.58	151.87	95	Lake	Yes	13	200	^{14}C	8A	15.5-0	400	Anderson et al., 1997
G36	Pepel'noye Lake	59.85	150.62	115	Lake	Yes	0	18	^{14}C	2A	4.3-0	180	Lozhkin et al., 2000
G36	Alut Lake	60.14	152.31	480	Lake	Yes	63	448	^{14}C	16A+9B	50.4-0	430	Anderson et al., 1998
G36	Podkova Lake	59.96	152.10	660	Lake	Yes	114	602	^{14}C	5A	6.0-0	220	Anderson et al., 1997
G36	Maltan River	60.88	151.62	735	Bog	Yes	-	-	^{14}C	4A+7C	12.0-9.4	120	Lozhkin and Glushkova, 1997
G36	Taloye Lake	61.02	152.33	750	Lake	Yes	16	227	^{14}C	7A	10.3-0	290	Lozhkin et al., 2000
G36	Elikchan 4 Lake	60.75	151.88	810	Lake	Yes	329	1023	^{14}C	16U	55.5-0	440	Lozhkin and Anderson, 1995
G36	Goluboye Lake	61.12	152.27	810	Lake	Yes	12	192	^{14}C	11A+2B	9.7-0	240	Lozhkin et al., 2000
G36	Julietta Lake	61.34	154.56	880	Lake	Yes	11	189	^{14}C	2A+4E+1I	36.1-1.4	270	Anderson et al., 2010
G36	Elgennya Lake	62.08	149.00	1040	Lake	Yes	455	1204	^{14}C	6A	16.0-0	310	Lozhkin et al., 1996
G37	Smorodinovoye Lake	64.77	141.12	800	Lake	Yes	27	293	^{14}C	6A+5F	27.1-0	360	Anderson et al., 1998
G37	Vechernii River	63.28	147.75	800	Bog	Yes	-	-	^{14}C	1F	14.4-0.1	380	Anderson et al., 2002
G37	Jack London Lake	62.17	149.50	820	Lake	Yes	1213	1965	^{14}C	7F	19.5-0.2	320	Lozhkin et al., 1993
G37	Sosednee Lake	62.17	149.50	822	Lake	Yes	82	510	^{14}C	4E+1F	26.3-0	640	Lozhkin et al., 1993
G37	Rock Island Lake	62.03	149.59	849	Lake	Yes	5	124	^{14}C	2E	6.6-0	470	Lozhkin et al., 1993
G37	Oldcamp Lake	62.04	149.59	853	Lake	Yes	7	150	^{14}C	2E	3.7-0	370	Anderson, unpublished
G37	Gek Lake	63.52	147.93	969	Lake	Yes	2392	2759	^{14}C	8A+1B	9.6-0	440	Stetsenko, 1998
G37	Figurnoye Lake	62.10	149.00	1053	Lake	Yes	439	1182	^{14}C	4A	1.3-0	30	Lozhkin et al., 1996
G38	Kuropatoch'ya_Kurop7	70.67	156.75	7	Bog	Yes	-	-	^{14}C	3C	5.7-0.4	760	Anderson et al., 2002
G38	Kuropatoch'ya_Kurpeat	69.97	156.38	47	Bog	Yes	-	-	^{14}C	1A+4C	11.7-7.5	430	Lozhkin and Vazhenina, 1987

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G39	Elgygytgyn Lake	67.50	172.10	496	Lake	No	9503	5500	polarity	-	20.2-1.5	650	Melles et al., 2012
G39	Enmynveem_mammoth	68.17	165.93	400	Bog	Yes	50	399	^{14}C	2C+2F	36.4-9.3	2470	Lozhkin et al., 1988
G39	Enmyvaam River	67.42	172.08	490	Bog	Yes	18	239	^{14}C	1A+4C	10.6-4.3	630	Lozhkin and Vazhenina, 1987
G39	Enmynveem River	68.25	166.00	500	Bog	Yes	-	-	^{14}C	4C	10.7-4.0	420	Anderson et al., 2002
G40	Malyi Krechet Lake	64.80	175.53	32	Lake	Yes	125	630	^{14}C	12A	9.6-0	400	Lozhkin and Anderson, 2013
G40	Melkoye Lake	64.86	175.23	36	Lake	Yes	1870	2440	^{14}C	21E	39.1-0	1260	Lozhkin and Anderson, 2013
G40	Sunset Lake	64.84	175.30	36	Lake	Yes	240	874	^{14}C	7A	14.0-0	260	Lozhkin and Anderson, 2013
G40	Gytgykai Lake	63.42	176.57	102	Lake	Yes	99	561	^{14}C	1A+8E	32.3-0	470	Lozhkin et al., 1998
G40	Patricia Lake	63.33	176.50	121	Lake	Yes	40	357	^{14}C	3A+7E	19.1-0	290	Anderson and Lozhkin, 2015
G41	Konergino	65.90	-178.90	10	Bog	Yes	-	-	^{14}C	1C	9.8-0	900	Ivanov et al., 1984
G41	Lorino	65.50	-171.70	12	Bog	Yes	-	-	^{14}C	3C	17.9-5.1	850	Ivanov, 1986
G41	Dlinnoye Lake	67.75	-178.83	280	Lake	Yes	71	476	^{14}C	3A	1.3-0	130	Anderson et al., 2002
G41	Dikikh Olyenyeii Lake	67.75	-178.83	300	Lake	Yes	64	450	^{14}C	1A+4C	50.3-0	1050	Anderson et al., 2002
G42	Blossom Cape	70.68	178.95	6	Bog	Yes	-	-	^{14}C	1C	13.8-0.2	3400	Oganesyan et al., 1993
G42	Jack London Lake	70.83	-179.75	7	Lake	Yes	69	469	^{14}C	5A+1E	16.1-0.3	790	Lozhkin et al., 2001
G42	Wrangel Island	71.17	-179.75	200	Bog	Yes	-	-	^{14}C	17A+3C	13.7-10.2	110	Lozhkin et al., 2001

LSC: liquid-scintillation counting; A: terrestrial plant macrofossil; B: non-terrestrial plant macrofossil; C: peat; D: pollen; U: unknown; E: total organic matter from silt; F: animal remains or shell; G: charcoal; H: $CaCO_3$; I: tephra.

Appendix 2 RPP estimates (with their standard errors; SEs) of 27 pollen taxa from 20 study areas. The excluded PPE (SE ≥ PPE) are 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)
Abies					9.92 (2.86)		3.83 (0.37)			
Pinus	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)
Picea				1.76 (0.00)	0.57 (0.16)	0.5 (0.00)	7.1 (0.2)	2.78 (0.21)		4.73 (0.13)
Larix		*0.00009 (0.1)*				1.4 (0.00)				
*Alnus*_tree	15.95 (0.66)			4.2 (0.14)		20 (0.00)				13.93 (0.15)
*Betula*_tree	13.94 (0.23)			8.87 (0.13)	2.42 (0.39)			2.24 (0.2)	4.6 (0.7)	1.81 (0.02)
Juglans										
Fraxinus				0.67 (0.03)	1.39 (0.21)					
Quercus	18.47 (0.10)			7.53 (0.08)	2.56 (0.39)					7.39 (0.2)
Tilia	0.98 (0.03)			0.8 (0.03)						
Ulmus										
*Alnus*_shrub		6.42 (0.42)								
*Betula*_shrub		1.8 (0.26)								
Carpinus	4.48 (0.03)				4.56 (0.85)					
Corylus	1.35 (0.05)			1.4 (0.04)	2.58 (0.25)					
Salix		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)		
Ephedra										
Cyperaceae		0.53 (0.06)	1 (0.16)				0.68 (0.01)	0.89 (0.03)	0.002 (0.0022)	1.23 (0.09)

Artemisia										3.48 (0.19)
Chenopodiaceae										
Asteraceae			0.24 (0.06)		0.17 (0.03)					
Thalictrum										
Ranunculaceae			3.85 (0.72)							
Caryophyllaceae										
Brassicaceae										

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 Herzschuh, 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)	
Abies										
Pinus	6.17 (0.41)	5.73 (0.07)				5.2 (0.00)			8.96 (0.23)	15.2079 (0.489)
Picea		1.2 (0.04)				1.456 (0.05)				
Larix						8.06 (0.32)				1.47 (0.19)
*Alnus*_tree	2.56 (0.32)	3.22 (0.22)		10.564 (0.00)	4.028 (0.00)	14.248 (0.22)				
*Betula*_tree			3.7 (0.4)	9.804 (0.00)		8.84 (0.34)				24.65 (0.73)
Juglans									0.3 (0.05)	9.49 (0.44)
Fraxinus	1.11 (0.09)			1.14 (0.00)	0.076 (0.00)	6.188 (0.12)				3.72 (0.68)
Quercus	1.76 (0.2)	1.3 (0.1)		7.6 (0.00)	7.6 (0.00)	1.976 (0.03)			4.89 (0.16)	
Tilia	1.36 (0.26)					1.352 (0.04)				0.78 (0.19)
Ulmus								11.5 (1.09)	1 (0.31)	6.85 (1.71)
*Alnus*_shrub										
*Betula*_shrub			1.4 (0.05)							

Carpinus						8.684 (0.09)			
Corylus					1.216 (0.00)				
Salix	1.19 (0.12)	0.62 (0.11)	0.8 (0.002)	1.748 (0.00)	2.736 (0.00)				
Ericaceae									
Ephedra								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)
Artemisia	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)
Thalictrum			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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Appendix 3 Map of the study area showing the geographic locations mentioned in the text.