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Vegetation dynamics around Lake Baikal since the middle Holocene reconstructed from the pollen and botanical composition analyses of peat sediments: Implications for paleoclimatic and archeological research

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ABSTRACT

The present paper summarizes the current evidence of natural changes in the forest and forest-steppe areas of the Lake Baikal Region (LBR) since ca. 7 cal ka BP, covering the period from the late Neolithic to the present time. To reconstruct local to small-regional scale vegetation changes and their probable causes during this period, pollen content and peat botanical composition were analyzed from three radiocarbon-dated peat sections, located near Lake Baikal. For better understanding of the local and regional environmental history and climate variability during the middle and late Holocene, the results are compared with published environmental records from lacustrine and mire sediments from the LBR and from elsewhere. The comparison confirms the earlier interpretations that the middle and late Holocene vegetation dynamics in the LBR was primarily driven by natural forcing and likely was associated with large-scale circulation processes controlling the regional water balance rather than with human activities. Some synchronous changes in environmental and archeological data likely point to a possible causal link between past climate changes and the cultural history of the region. The Kuchelga (53°00′57″N, 106°44′49″E), Ochkovoe (51°26′05″N, 104°38′57″E) and Cheremushka (52°45′09″N, 108°05′50″E) peat records represent three different climatic regions around Lake Baikal and demonstrate that the environments and vegetation of the drier western coast were more sensitive to the climate oscillations of the middle and late Holocene in comparison to the more humid areas east, and particularly south of Baikal. Therefore, it could be expected that environmental impact on early human societies was strongest in the arid region to the west of Lake Baikal. To test this hypothesis, however, accurately dated multi-proxy records of the Holocene climate and environments from this so far poorly studied region are absolutely necessary.

1. Introduction

Since the introduction of pollen analysis by Lennart von Post in 1916 pollen data became an important proxy frequently used for reconstruction of the late Quaternary vegetation, climate change and human activities. A better understanding of the regional climate and vegetation dynamics and their driving mechanisms is important for improving climate predictability and properly attributing ongoing climate changes to human-induced and/or natural forcing (e.g. Ruddiman, 2003; Wanner et al., 2008; Kleinen et al., 2011). So far, most studies on climate and vegetation dynamics in the Lake Baikal Region (LBR) have been focused on the late Pleistocene and Holocene intervals with special attention to the late glacial–early Holocene transition and early–mid-Holocene climatic optimum (Takahara et al., 2000; Bezrukova et al., 2005a, 2010; Demske et al., 2005; Tarasov et al., 2005, 2007, 2009; Shichi et al., 2007, 2009). The majority of pollen and other proxy records used to interpret past climate and environments have been obtained from lake sedimentary archives. However, the LBR is also rich in peatlands, which are considered as high potential natural archives providing sensitive records of vegetation and climate changes with decadal to centennial precision (e.g. Barber et al.,

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2004 and references therein; Bezrukova et al., 2005b; Tarasov et al., 2006; Shichi et al., 2009). To date, however, the potential of peat sediments as environmental and climate archives has been poorly exploited in the LBR.

Available studies on the regional peat sediments demonstrate that peat records may cover the whole Holocene (e.g. Shichi et al., 2009), but mainly represent the last 7000 years (Bezrukova et al., 2005c, 2006, 2008; Danko et al., 2009), the time interval which reveals prominent changes in climate and in archeological records at both regional and global scales. Multidisciplinary research conducted under the framework of the Baikal Archaeology Project (BAP) provide rich material on archeological and cultural changes among the middle and late Holocene hunter–gatherers of the LBR (Weber et al., 2002, 2010, 2013). Available paleoenvironmental data and climate modeling results demonstrate that climatic conditions during the Holocene varied significantly in the LBR and likely affected subsistence strategies and lifestyle of the local populations (White and Bush, 2010). However, despite the relatively few study sites and resolution of data available, the results from climate and environmental studies have been largely neglected by archeologists of the LBR. To generate records of the Holocene climate and environments with better spatio-temporal resolution and to bring together archeological data and environmental reconstructions supported by mathematical modeling is an important task of the Baikal-Hokkaido Archaeology Project (BHAP) (see Weber et al., 2013).

The current paper presents results of the pollen and botanical composition analyses of peat sediments from three locations representing different climatic conditions and environments within the LBR during the ca. last 7000 years. The paper aims to reconstruct local and regional changes in vegetation and their causal mechanisms. The following discussion focuses on the sensitivity of different areas to environmental changes, comparison of the vegetation and environmental history of the study sites with other records, and possible influence of climate dynamics on early societies.

2. Background to the study sites

2.1. Kuchelga

Sediment samples for pollen and botanical composition analysis were obtained from three peat bogs. Kuchelga peat bog (53°00′57″N, 106°44′49″E) is located in the central part of the Lake Baikal western coast (Fig. 1). The peat bog occupies the low terrace of the Kuchelga River, 1.5 km upstream of its discharge into Lake Baikal (Bezrukova et al., 2005b). The central part of the western coast of Lake Baikal close to the Ol'khon Island, called *Priol'khon'e* in the Russian geographical sources, remains poorly investigated in comparison to the southern and eastern coasts of Lake Baikal (Takahara et al., 2000; Bezrukova et al., 2005a). The Holocene vegetation records of this area are rare and discontinuous (Sklyarov et al., 2010). However, Priol'khon'e has a particular interest for paleoenvironmental research due to its several distinctive features and richness of the archeological data (Goriunova, 2003; Katzenberg et al., 2009; Weber and Bettinger, 2010; Weber et al., 2010).

The area is characterized by the most arid and continental climate within the whole LBR. This feature can be explained by the influence of the Primorsky Mountain Range (1000–1500 m a.s.l.), which stretches along the Lake Baikal western coast and blocks the moisture carried by the Atlantic westerlies, thus leaving Priol'khon'e in the rain shadow (Gustokashina and Bufal, 2003). The modern climate registered at the Sarma and Khuzhir meteorological stations (Fig. 1) is characterized by lowest annual precipitation (ca. 200 mm) and number of days with snow cover (72) within the LBR (Table 1). The area reveals the most continental climatic conditions among the three sites presented here, with mean temperatures of January and July reaching −19.7 °C and 15.4 °C, respectively (Table 1) (Galaziy, 1993; Bufal et al., 2005). The low precipitation, particularly during the winter, and frequent strong winds (wind-speeds up to 144 km/h) called *sarma* may explain the deep penetration of the dry steppe vegetation of northern central Asia into the boreal coniferous forest zone here (Danko et al., 2009). The forest vegetation is represented mostly by Scots pine (*Pinus sylvestris*), growing on slopes of different gradient and exposure, and by Siberian larch (*Larix sibirica*), occupying the middle and low parts of the slopes. Steppe vegetation occurs locally in dry and stony habitats. Local vegetation at and around Kuchelga bog is represented by a swampy sedge meadow with scattered willow shrubs and larch trees.

Table 1
Modern climate variables in the study sites areas (after Galaziy, 1993). See Fig. 1 for location of sites (diamonds with names) and meteorological stations (circles with numbers).

Study site	Nearest meteorological stations	Mean January temperature [°C]	Mean April temperature [°C]	Mean July temperature [°C]	Mean October temperature [°C]	Number of days with snow cover	Mean annual precipitation [mm]
Kuchelga	(1) Sarma	−18.3	−0.8	15.4	1.1	72	200
	(2) Khuzhir	−19.7	1.4	14.7	1.3	No data	187
Ochkovoe	(3) Vydrino	−18.7	−0.7	15.4	1.8	203	900
	(4) Tankhoy	−17.7	−0.9	14.1	1.8	No data	800
Cheremushka	(5) Goryachinsk	−19.3	−2.3	14.0	0.9	170	350
	(6) Cheremukhovo	−19.5	−3.1	15.4	−0.2	181	400

2.2. Ochkovoe

Ochkovoe peat bog (51°26′05″N, 104°38′57″E) lies in the Tankhoy Plain and is situated in the piedmont area of the Khamar-Daban Range at an elevation of about 470 m a.s.l., in the most humid area within the Lake Baikal coastal zone (Fig. 1). During the Holocene the Tankhoy Plain experienced intensive swamp development and peat accumulation (Takahara et al., 2000). *Sphagnum* bogs in this area provide very helpful archives for the reconstruction of Holocene environments at local and regional scales. Modern climate of the Tankhoy Plain is wet and moderately continental (Galaziy, 1993) with mean July temperature about 14.1–15.4 °C, mean January temperature about −18 °C, number of days with snow cover about 200, and mean annual precipitation of 800–900 mm (Table 1), increasing up to 1200 mm in the high-mountain belt of the Khamar-Daban Range (Galaziy, 1993). Relatively high precipitation supports growth of the species-rich boreal evergreen conifer forest (taiga) which consists mainly of Siberian pine (*Pinus sibirica*), fir (*Abies sibirica*), and spruce (*Picea obovata*). Scots pine and larch are present in the forests growing on the piedmont plains, but do not play a dominant role. *P. obovata* grows mainly along the floodplains and in the shady moist mountain valleys. *P. sibirica* along with *A. sibirica* are the main constituents of the forest on the Tankhoy

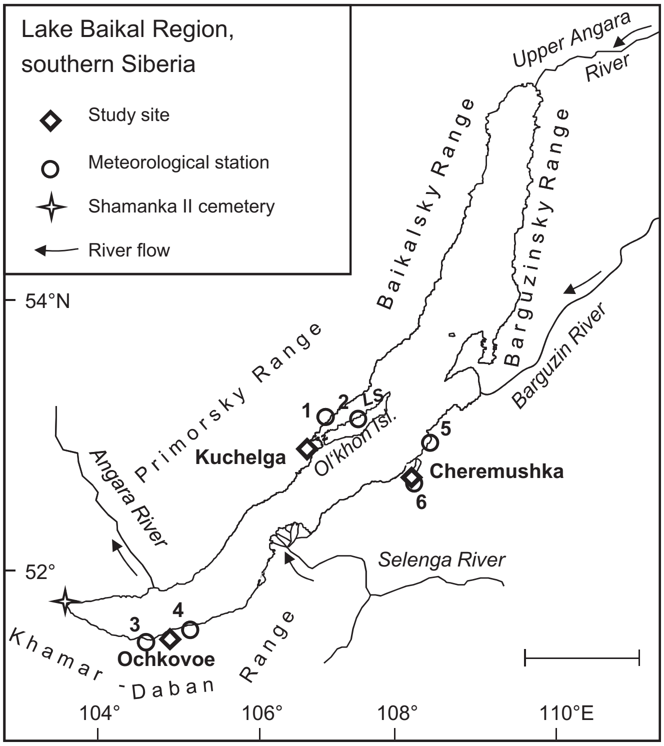

Fig. 1. Schematic map of the Lake Baikal Region indicating sites discussed in this study. Locations of the studied peat sections are marked with diamonds and nearby climate stations are marked with numbered circles and listed in Table 1. Star marks the archeological site Shamanka II. LS indicates the Little Sea (*Maloye More*) separating Ol'khon Island from the mainland.

piedmont plain. Shrubby pine (*Pinus pumila*) thickets are also typical for this area, occurring on rocky slopes and above the tree line in the mountains. Birch (*Betula*) species have no definite geographical distribution, and are common in all forest types and at sites with disturbed vegetation. Local forest vegetation near Ochkovoe bog is dominated by *P. sibirica* with abundant *Betula* trees and occasional *P. sylvestris* and *P. obovata* trees. The most important archeological site in the South LBR is Shamanka II which includes 96 Early Neolithic and 11 Early Bronze Age graves (Bazaliiskii and Weber, 2004; Weber and Bettinger, 2010). Ochkovoe peat bog is located about 90 km eastward from the Shamanka II site, i.e. relatively close to provide a regional-scale paleoenvironmental reconstruction, however, not close enough for direct assessment of the Shamanka II habitation history.

2.3. Cheremushka

Cheremushka peat bog (52°45′09″N, 108°05′50″E) is situated on the south flank of Lake Kotokel, about 2 km east of Lake Baikal (Fig. 1). Vegetation cover consists mainly of *P. sylvestris*, *L. sibirica*, and *Betula* forests accompanied by *P. sibirica*, *Populus tremula*, and *Alnus fruticosa* (Shichi et al., 2009; Bezrukova et al., 2010). Spots of *Abies* trees grow on the west-facing mountain slopes. *P. sylvestris* covers relatively dry sandy and stony soils while *L. sibirica* trees occupy wetter swampy habitats. *P. obovata* occurs on floodplains and wet sites near streams. The peat bog surface is covered mostly by *Sphagnum* mosses and shrubs of the heath family (*Ledum palustre* and *Oxycoccus palustris*). *Carex lasiocarpa* (sedge) forms patches around open water on the bog surface. Stunted *Betula* and *P. sylvestris* trees are found near the study site. The meteorological station at Cheremukhovo (Galaziy, 1993) records a mean January temperature of −19.5 °C, mean July temperature of 15.4 °C, annual precipitation of about 400 mm, and nearly 180 days with snow cover (Table 1). Cheremushka bog was previously studied by means of pollen analysis, providing a poorly-dated (one date for the entire Holocene) and coarse-resolution (average resolution of ca. 600 years) record of vegetation since the last glacial (Shichi et al., 2009). The average resolution of the new record presented here is about 150 years, based on six radiocarbon dates which help to establish a more reliable site age model.

3. Methods

3.1. Field sampling

The Ochkovoe and Cheremushka bogs were investigated and cored using a 5-cm diameter Russian peat sampler. The Kuchelga bog was sampled using an open outcrop on the low terrace of the Kuchelga River (Bezrukova et al., 2005b). Sediment samples from the Kuchelga River valley were recovered in summer 2004. Ochkovoe bog was cored later, in 2007, and the short core from Cheremushka peatland was taken in 2008. Core sections were recovered in plastic tubes and stored in the Institute of Geochemistry Russian Academy of Sciences, Siberian Branch (Irkutsk) under dark and cold (+4 °C) conditions before processing.

3.2. Radiocarbon dating

In total, 15 bulk samples from all three analyzed sections were dated using the conventional radiocarbon dating technique at the Institute of Geology and Mineralogy Russian Academy of Sciences, Siberian Branch (Novosibirsk). The results are presented in Table 2. All dates were calibrated using CalPal online software for radiocarbon calibration (Danzeglocke et al., 2008) with CalPal2007_HULU calibration curve. The calibrated ages were used to establish age-depth models for the analyzed sections (Fig. 2). Linear interpolation between the neighboring dates was used to calculate ages of the pollen and peat botanical composition zones and to discuss reconstructed environmental changes. Calibrated ages expressed in ka BP (1 ka = 1000 years before 1950 AD) are consistently used throughout the paper.

Table 2
Conventional radiocarbon dates from the analyzed peat sections. Radiocarbon years before present were converted to calendar years after Danzeglocke et al. (2008) using online calibration program (http://www.calpal.de).

Site name	Section depth (cm from the top)	^{14}C dates (yr BP; 68% range)	Laboratory number	Calibrated ages (cal yr BP; 68% range)
Kuchelga	1–2	130 ± 55	SOAN 5425	140 ± 103
	8–9	315 ± 90	SOAN 5426	358 ± 105
	14–15	915 ± 45	SOAN 5427	842 ± 56
	20–21	1460 ± 90	SOAN 5428	1394 ± 85
	33–34	2290 ± 90	SOAN 5429	2314 ± 131
	41–42	4525 ± 50	SOAN 5430	5181 ± 98
Ochkovoe	45	730 ± 60	SOAN 6548	668 ± 55
	68	1750 ± 85	SOAN 6549	1679 ± 103
	116	3195 ± 145	SOAN 6550	3415 ± 177
	123	3445 ± 80	SOAN 6552	3716 ± 104
Cheremushka	10	315 ± 25	SOAN 7256	382 ± 50
	24.5	1825 ± 35	SOAN 7257	1792 ± 48
	34.5	3025 ± 25	SOAN 7258	3259 ± 50
	44.5	4190 ± 95	SOAN 7260	4707 ± 121
	55.5	5210 ± 105	SOAN 7261	5994 ± 148

3.3. Pollen analysis

Pollen and botanical composition analyses were performed at the Institute of Geochemistry (Irkutsk). Samples for pollen analysis

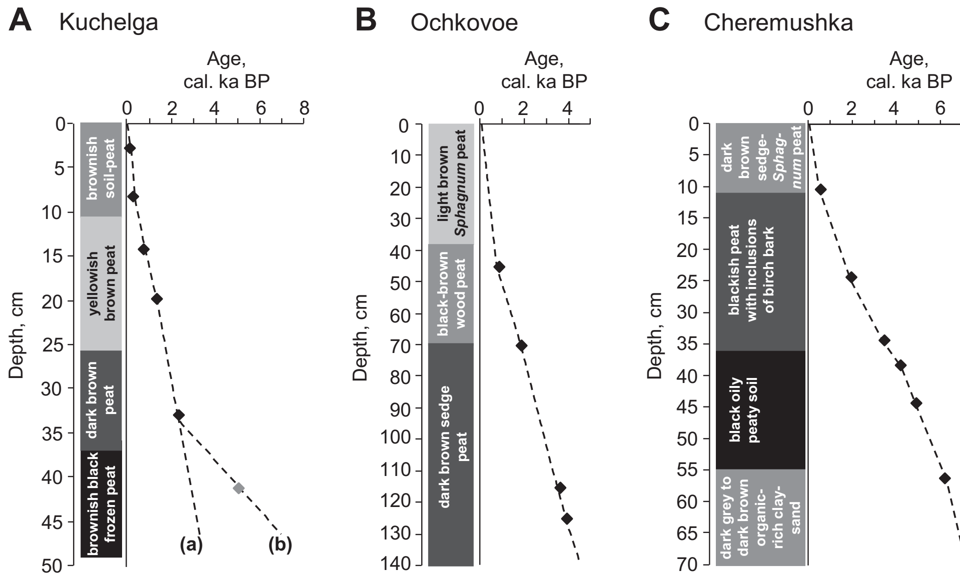

Fig. 2. Lithology columns and age-depth models of the Kuchelga (A), Ochkovoe (B) and Cheremushka (C) peat sequences discussed in this study.

from the Kuchelga section were taken continuously with a 0.5–1.0 cm interval, resulting in ca. 100-year resolution pollen record. The Ochkovoe peat sequence was sampled at 5-cm intervals giving a temporal resolution of about 150 years. Every second centimeter was taken for pollen analysis from the Cheremushka peat section, providing a temporal resolution of about 150 years. Standard laboratory methods (Fægri and Iversen, 1989) were used to extract pollen from the sediment matrix. Identification of the fossil pollen and spores was performed using regional pollen atlases (Kuprianova and Alyoshina, 1972, 1978; Bobrov et al., 1983) and the reference pollen collection at the Institute of Geochemistry in Irkutsk. In total between 200 and 800 terrestrial pollen grains were counted in each sample. Percentages for individual terrestrial pollen taxa at each level were conventionally calculated from the total sum of arboreal pollen (AP) and terrestrial non-arboreal pollen (NAP) taxa taken as 100%. Spore percentages for cryptogam plants (e.g. Polypodiophyta, *Selaginella*, *Lycopodium*, and *Sphagnum*) were calculated in relation to the total sum of counted pollen and spores.

The pollen diagrams (Figs. 3A, 4A and 5) were created using the Tilia/Tilia-Graph/TGView software package (Grimm, 2004). Visual determination of the local pollen zone boundaries was supported by cluster analysis performed using CONISS (Grimm, 1987). Within the pollen diagrams the pollen taxa are sorted alphabetically within

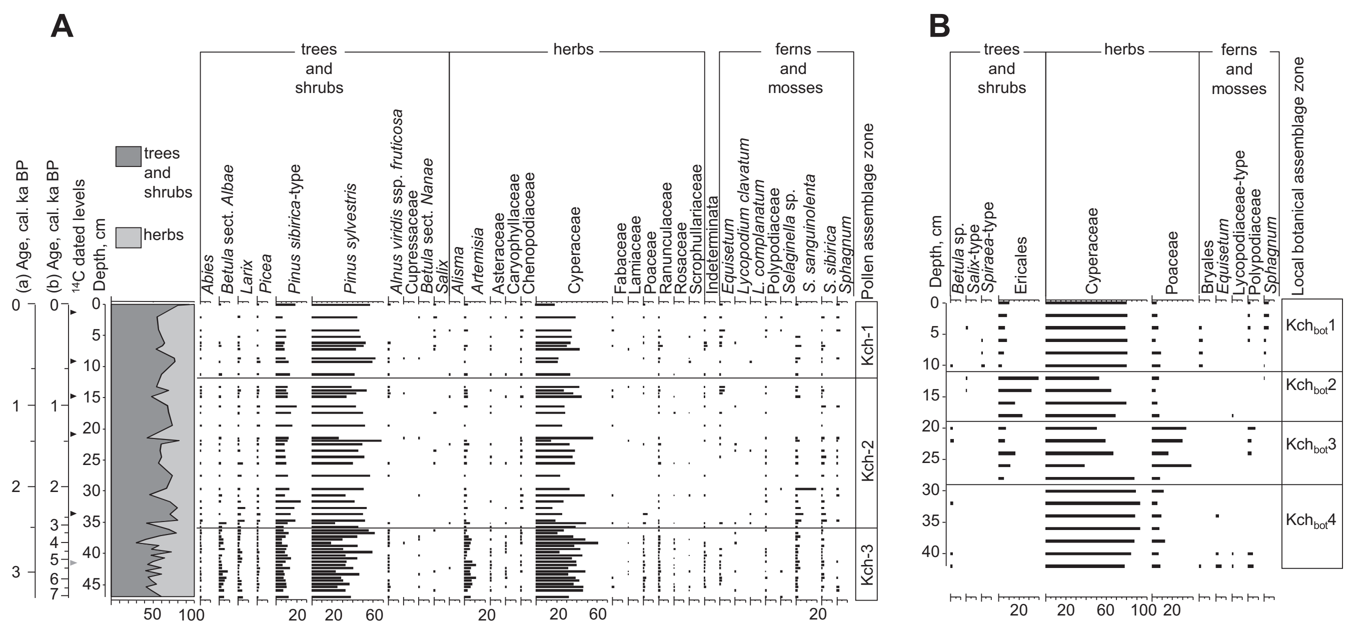

Fig. 3. Simplified (A) pollen assemblage diagram including two different age models (see explanation in Fig. 2 and corresponding text) and (B) botanical composition diagram for the Kuchelga peat.

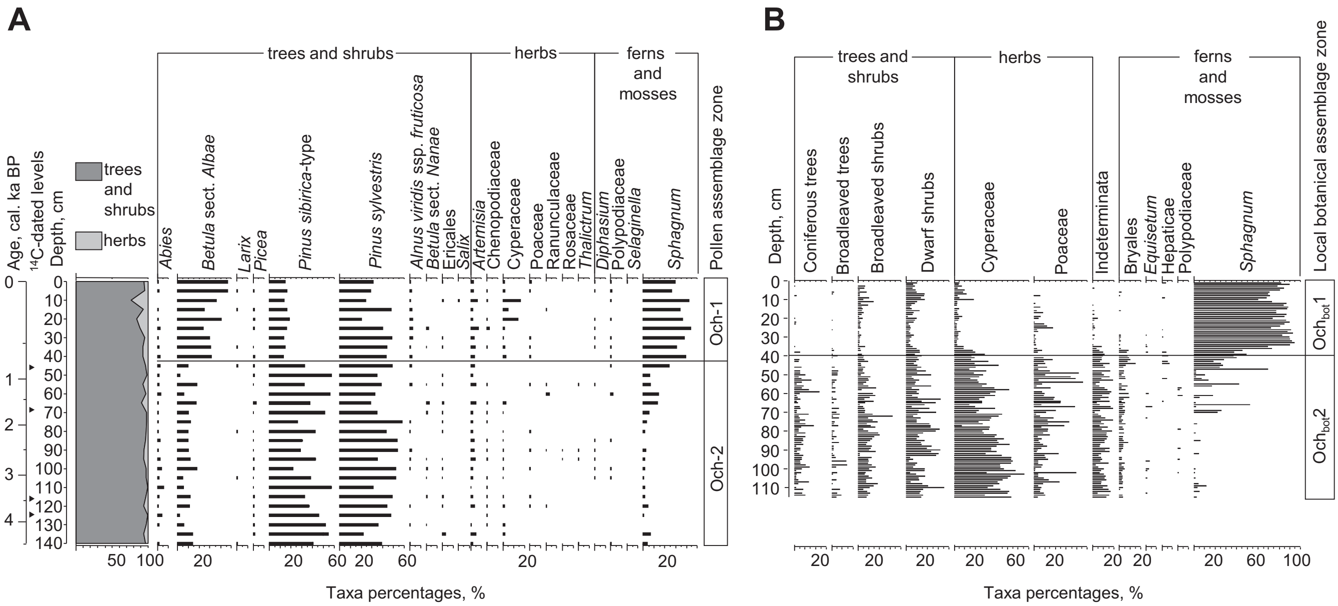

Fig. 4. Simplified (A) pollen assemblage diagram and (B) peat composition diagram for the Ochkovoe peat.

the groups of trees, shrubs, herbs and spores to facilitate comparison between the individual records.

3.4. Botanical composition analysis

Plant macrofossils were examined in each cm in the Ochkovoe peat core, and in each 2 cm depth interval in the Kuchelga section using the method of Lévesque et al. (1988). From each study level a 3 cm^3 sub-sample was taken and sieved with water on a 0.5-mm sieve. The plant remains were evenly distributed on a plastic tray and then examined under a binocular dissecting microscope. Taxonomical identification of the plant remains, mostly to a level of genus or family, was carried out using comparative collections along with the published regional atlases of fossil plant remains (Dombrovskaya et al., 1959; Katz et al., 1977), in addition to identification keys provided in Lévesque et al. (1988). The relative proportion of each fraction was quantified, in comparison to the total amount of identifiable remains. Peat botanical composition analysis for the Cheremushka core was not conducted. The diagrams of identified macrofossils created using the Tilia/TiliaGraph/TGView software (Grimm, 2004) are presented along with the pollen diagrams for comparison (Figs. 3B and 4B). All identified remains are sorted alphabetically within the three groups of plants (i.e. trees and shrubs, herbs, and mosses and ferns) and the local botanical assemblage zones are visually defined (Figs. 3B and 4B).

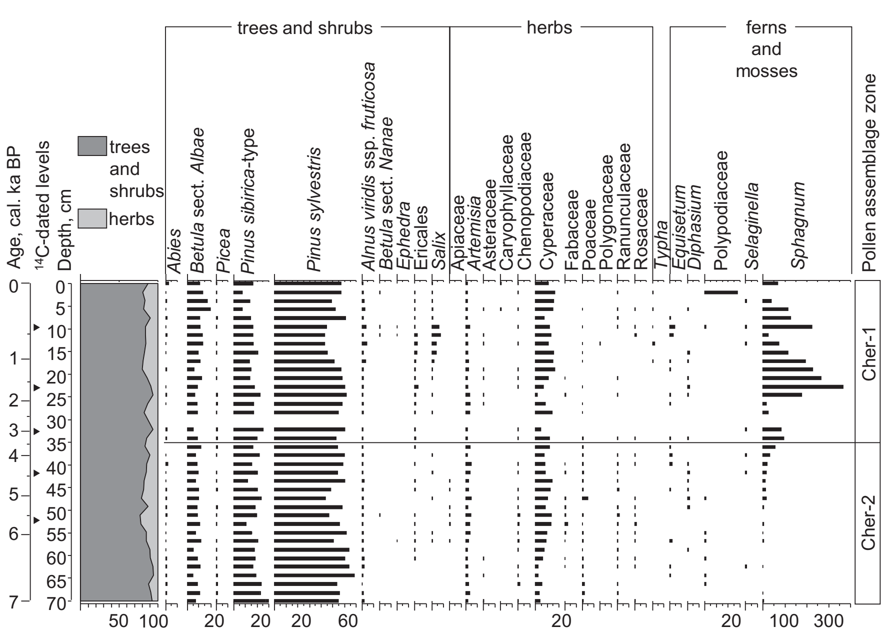

Fig. 5. Simplified pollen assemblage diagram for the Cheremushka peat.

4. Results and interpretations

4.1. Kuchelga site

4.1.1. Stratigraphy and dating

The analyzed Kuchelga section consists of four sedimentary units (Fig. 2A) represented by brownish soil-peat (0–11 cm), yellowish brown peat (11–26 cm), dark brown peat (26–37 cm), and brownish black frozen peat (37–47 cm) with an underlying sandy layer. The age model, which takes into account all available radiocarbon dates (indicated by 'b' in Fig. 2A), suggests that the record spans the time interval between ca. 7 cal ka BP and the present. Pollen-based correlation with regional vegetation development schemes, which show a major spread of Scots pine after ca. 7 cal ka BP and maximum distribution of pine forests ca. 6.5–5.7 cal ka BP (e.g. Demske et al., 2005; Bezrukova et al., 2010), is generally supported by the Kuchelga record. However, the recently generated pollen record from Lake Khall (52°41′14.54″N, 106°25′50.70″E), located in the Ol'khon Region ca. 40 km southwest of the Kuchelga site (Mackay et al., 2013), demonstrates that *P. sylvestris* pollen percentages increased from ca. 5% about 5 cal ka BP to ca. 35–40% at ca. 3.3–2.7 cal ka BP and did not reach its maximum level until ca. 2.6 cal ka BP. The age-depth model for the Lake Khall pollen record is based on seven AMS radiocarbon dates and two dates are available for the interval prior to 4 cal ka BP, whereas only one conventional date secures the chronology in the bottom part of the Kuchelga record (Fig. 2A). If to assume that the lowest date from the Kuchelga core is too old, the basal age of the whole section could be younger than ca. 3.5 cal ka BP (model 'a' in Fig. 2A). The absence of more robust data prevents resolution of the chronology problem. Therefore, two alternative chronologies are presented in Figs. 2A and 3, and this issue is addressed in the Discussion.

4.1.2. Pollen record

The pollen diagram of the Kuchelga peat is divided into three local pollen assemblage zones, labeled as Kch-3, Kch-2 and Kch-1 (Fig. 3). The lowermost zone Kch-3 (47–36 cm, ca. 7/3.3–3.2/2.5 cal ka BP) is characterized by almost equally high percentages of arboreal and non-arboreal pollen taxa. Pollen of *P. sylvestris* and Cyperaceae predominate in the pollen assemblages, while all other taxa are less prominent. Noticeably, *Artemisia*, *Betula* sect. *Albae* and *Larix* percentages reach highest values through the whole record in this pollen zone. Although *P. sibirica*-type, *Picea* and *Abies* are continuously present in the pollen assemblages their percentage values are relatively low. The Kch-2 pollen zone (36–12 cm, ca. 3.2/2.5–0.7 cal ka BP) shows an increase in the AP percentages, mainly due to generally higher values of *P. sylvestris* and *P. sibirica*-type pollen. Percentage values of Cyperaceae, *Betula* sect. *Albae* and *Artemisia* become lower than in Kch-3. The uppermost zone Kch-1 (12–0 cm, ca. 0.7 cal ka BP to the present) reveals rather minor changes in pollen percentages and pollen assemblage composition in comparison to Kch-2. An exception is the top core sample, which demonstrates the highest percentages of *P. sylvestris* and *P. sibirica* pollen and lowest NAP percentages through the entire record.

4.1.3. Peat botanical composition

Following the peat composition analysis, the Kuchelga record was divided into four local botanical assemblage zones labeled as $Kch_{bot}4$–$Kch_{bot}1$, respectively (Fig. 3B). In the lowest layer from 47 to 43 cm depth the botanical remains were not possible to determine because of its rather high mineralization and peat decomposition. The $Kch_{bot}4$ zone (42–29 cm, prior to ca. 2 cal ka BP) is characterized by the highest percentage of Cyperaceae remains and absence of Ericales fragments. Poaceae plant remains are most abundant in the following zone $Kch_{bot}3$ (29–19 cm, ca. 2–1.25 cal ka BP), which also reveals the presence of Ericales and Polypodiaceae and moderately high Cyperaceae percentages. In $Kch_{bot}2$ (19–11 cm, ca. 1.25–0.6 cal ka BP) tissues belonging to Cyperaceae and Ericales contribute most significantly to the peat composition. A decrease in Ericales percentages and an increase in Cyperaceae and *Sphagnum* remains are the most characteristic features of the uppermost zone $Kch_{bot}1$ (11–0 cm, ca. 0.6 cal ka BP to the present).

4.1.4. Site interpretation

The most significant changes in the Kuchelga records, including changes in lithology, sedimentation rate, pollen assemblages and peat botanical composition, occur at 36-29 cm depth, i.e. between ca. 3.2 and ca. 2 cal ka BP. Relatively low sedimentation rates (as low as 2.79 mm per hundred years in the age model 'b', but ca. 14.2 mm per hundred years in the age model 'a' in Fig. 2A) and high degree of peat decomposition suggest poor conditions for aquatic plants growth and peat accumulation, and relatively dry environments. The occurrence of frozen sediment in the lower part of the studied core likely reflects modern cold winter temperatures in association with very thin and unstable snow cover and relatively cool summer temperatures (Table 1). The amount of snow accumulation during the winter is an important factor controlling lake and ground water levels and tree growth, particularly in areas with relatively dry climate, i.e. such as observed around the Kuchelga site (Table 1). Lower than present winter precipitation in association with generally low summer precipitation and relatively high summer temperatures would also contribute to the development of open landscapes, as suggested by the relatively low arboreal pollen and relatively high *Artemisia* pollen percentages (Fig. 3A) and absence of tree and shrub tissue remains in the lower part of the Kuchelga section (Fig. 3B).

Changes in lithology, a significant increase in sedimentation rates (up to ca. 23.7 mm per hundred years in the upper part of the section) and higher percentage values of arboreal pollen indicate a shift towards wetter environments at and around the Kuchelga site prior to ca. 2.3 cal ka BP. In particular, the increase in *Pinus* pollen percentages might indicate greater snow accumulation (and higher soil moisture content) crucial for the survival and spread of young plants in the area.

The most pronounced change observed in the botanical record (i.e. partial replacement of sedge and grass communities at the coring site by heath shrubs and semi-shrubs) occurred later, around 2 cal ka BP (Fig. 3B). However, the absence of noticeable differences in the fossil pollen assemblages between ca. 3 and 0.6 cal ka BP (Fig. 3A) supports the interpretation that changes in the peat composition (Fig. 3B) during that time reflect local shifts caused by the natural plant succession and internal processes of mire development.

4.2. Ochkovoe site

4.2.1. Stratigraphy and dating

The Ochkovoe core (Fig. 2B) consists of light brown *Sphagnum* peat (0–38 cm) and blackish brown wood peat (38–70 cm) with underlying dark brown sedge peat (70–120 cm). The radiocarbon dates of the core sediment (Table 2) suggest relatively high peat accumulation rates during the last ca. 4.5 cal ka BP. The average rate is 25.6 mm per hundred years below 45 cm depth (ca. 0.7 cal ka BP) and reaches 67.4 mm per hundred years above this level.

4.2.2. Pollen record

Two pollen assemblage zones are distinguished for the Ochkovoe peat section (Fig. 4). AP predominates in the lower zone Och-2 (140–42 cm, ca. 4.5–0.63 cal ka BP). The dominant tree taxa are *P. sibirica* and *P. sylvestris*, and *Betula* sect. *Albae* plays a secondary role. *Abies*, *Picea* and *Larix* pollen also appear throughout this zone but percentages are low. The upper zone Och-1 (42–0 cm) reveals a co-dominance of *Betula* sect. *Albae* and *P. sylvestris*. *P. sibirica* pollen becomes less important. Among the NAP taxa Cyperaceae and *Sphagnum* play an important role and *Artemisia* pollen is slightly more abundant.

4.2.3. Peat botanical composition

The peat botanical composition diagram of the Ochkovoe section (Fig. 4B) has also been subdivided into two local assemblage zones. The bottom zone $Och_{bot}2$ (prior to ca. 0.6 cal ka BP) shows the dominance of Cyperaceae and Poaceae tissue remains, and a significant amount of woody coniferous and broadleaved plant remains. Dominance of *Sphagnum* moss tissues is the most prominent feature of the upper zone $Och_{bot}1$ covering the top 40 cm (Fig. 4B).

4.2.4. Site interpretation

Ochkovoe represents the wettest region around Lake Baikal, opposite to that of the Kuchelga record which is located in one of the driest areas within the LBR (Table 1). This major difference should be considered when interpreting the results. Stable and very high percentages of tree pollen (ca. 90–98%) in the Ochkovoe sediment core indicate the predominance of forest in the regional vegetation with wet climatic conditions during the last 4.5 cal ka BP. This interpretation is supported by abundant woody plant remains in the botanical assemblages and very high peat accumulation rates suggested by the radiocarbon dates, particularly during the last ca. 0.6 cal ka BP. The most intensive peat accumulation is associated with the upper *Sphagnum* peat layer. Phenol compounds in the *Sphagnum* cell walls slow down decay rates and thus stimulate quicker peat growth. In addition, the spread of *Sphagnum* may also cause acidification of the surroundings. This and high water content of the *Sphagnum* peat create less favorable environments for local tree growth and which may explain some opening of the landscape, which is suggested by a decrease in arboreal pollen taxa percentages (down to ca. 80%) and an almost complete disappearance of woody plant tissues in the upper sediment layer. An increase in percentages of *Betula* sect. *Albae* pollen in the boreal zone might also indicate landscape opening, as birches quickly occupy openings in the forests created by natural or/and anthropogenic factors, including fires and wood cutting. On the other hand this change in the pollen spectra might simply reflect a transition from the Cyperaceae-dominated mesotrophic environments to *Sphagnum*-dominated oligotrophic environments and consequent disappearance of conifers from the bog surface, as indicated by the botanical data.

4.3. Cheremushka site

4.3.1. Stratigraphy and dating

The Cheremushka section consists of four sedimentary units (Fig. 2C). The uppermost unit (0–11 cm) consists primarily of dark brown sedge and *Sphagnum* peat, and overlies blackish peat with rare small pieces of birch bark (11–36 cm). The third unit is represented by black oily peaty soil (36–55 cm), and an organic-rich dark gray-to-dark brown clay sand (55–68 cm) constitutes the lowermost part of the section. The average accumulation rate is 8.1 mm per hundred years in the lower part of the section between 10 and 55 cm depth (ca. 6–0.4 cal ka BP) and rises to 26.2 mm per hundred years in the upper 10-cm unit. Some changes in sedimentation rate and in sediment lithology (Fig. 2) recorded in the radiocarbon-dated part of the section prevent the use of extrapolation to calculate the exact age of bottom samples. However, the chronology is based on six radiocarbon dates (Table 2) and pollen-based correlation with the radiocarbon-dated cores from nearby Lake Kotokel (Bezrukova et al., 2010) suggest that the studied sediments from the Cheremushka section likely accumulated during the last ca. 7 cal ka BP.

4.3.2. Pollen record

Two pollen assemblage zones are recognized in the Cheremushka pollen diagram (Fig. 5). The spectra of zone Cher-2 (68–35 cm, ca. 7–3.4 cal ka BP) are dominated by tree pollen, with *P. sylvestris* being the main taxon. *P. sibirica* and *Betula* sect. *Albae* are relatively abundant and *Abies* and *Picea* provide only a minor contribution to the pollen assemblages. Herbaceous taxa are frequently identified, but only Cyperaceae and *Artemisia* are present in a noticeable amount. The upper pollen zone Cher-1 (35–0 cm, ca. 3.4 cal ka BP to the present) reveals some decline in *P. sibirica*-type pollen and associated increase in *Betula* sect. *Albae* pollen. Shrub taxa include *Alnus viridis* ssp. *fruticosa*, Ericales and *Salix*. Among the non-arboreal taxa Cyperaceae pollen and *Sphagnum* spores reach highest percentages in this zone.

4.3.3. Site interpretation

The pollen and sedimentary records obtained from the Cheremushka section reflect moderate forest coverage and relatively humid climate of the area (Table 1), which likely did not change much during the last 7 cal ka BP. This interpretation is supported by relatively high contents of tree and shrub pollen (ca. 80–90%), rather stable pollen percentages of major arboreal taxa (Fig. 5), and moderately high peat accumulation rates suggested by the radiocarbon dates (Table 2). An increase in peat accumulation rates, particularly during the last few centuries, can be satisfactorily explained by the spread of *Sphagnum* and development of quickly growing *Sphagnum* peat, which also provided habitat for a wide array of peatland plants, including sedges and ericaceous shrubs, which can be traced in the pollen record (Fig. 5).

5. Discussion

5.1. Vegetation history at Kuchelga, Ochkovoe and Cheremushka since ca. 7 cal ka BP

The pollen and botanical composition analyses obtained from the Kuchelga, Ochkovoe and Cheremushka sites reflect local to small-regional scale changes in vegetation during the middle and late Holocene. The longest vegetation record with the most reliable age model is from Cheremushka (Fig. 5), located in the area with moderately humid climate (Table 1), and demonstrates that *P. sylvestris* was a dominant taxon in the pollen record and played a prominent role in the forest cover around the site during the last ca. 7 cal ka BP. Comparison of the uppermost pollen sample composition with the modern vegetation cover does show some discrepancies, namely the absence of *Larix* pollen, though larch together with pine and birch is one of the most common tree taxa in the region (Shichi et al., 2009; Bezrukova et al., 2010). However, it is known that pine (as one of the great pollen producers) is almost always overrepresented in the pollen records, while larch usually remains strongly underrepresented (e.g. Gunin et al., 1999; Bezrukova et al., 2010; Müller et al., 2010).

The pollen diagram from Ochkovoe (Fig. 4) also demonstrates high percentage of *P. sylvestris* pollen during the last 4.5 cal ka BP. However, *P. sibirica*-type pollen percentages are often equally high, indicating that humid environments played a more important role in the vegetation cover around the Ochkovoe site than in the region of Cheremushka. This is not surprising, as climate conditions around Ochkovoe are very humid (Table 1). In the pollen record from the Kuchelga site, located in the driest area of the LBR (Table 1), *P. sylvestris* again becomes a dominant taxon (Fig. 3), though arboreal pollen percentages are never as high as in the Ochkovoe and Cheremushka records. The highest percentages of herbaceous pollen in the Kuchelga pollen diagram reflect generally dry climate conditions and low tree coverage in the area around the Kuchelga site.

5.2. Comparison of the Kuchelga, Ochkovoe and Cheremushka vegetation and environmental history with other records

Radiocarbon-dated pollen records from Lake Baikal (e.g. Demske et al., 2005; Tarasov et al., 2007) and from nearby Lake Kotokel (Shichi et al., 2009; Tarasov et al., 2009; Bezrukova et al., 2010) suggest that the major spread of *P. sylvestris* in the LBR occurred between ca. 7 and 5 cal ka BP. Since then Scots pine has remained a dominant taxon in regional forest cover and in the pollen spectra from lake and mire sediments. A similar vegetation development and spread of pine is reported for central and northern Yakutia northeast of Lake Baikal (e.g. Andreev and Tarasov, 2007; Müller et al., 2009, 2010; Werner et al., 2010 and references therein). Applying the same scheme to the vegetation development in the Kuchelga area would allow dating of the Kuchelga core back to ca. 7 cal ka BP. This interpretation though contradicts the newly generated pollen record from Lake Khall located ca. 40 km southwest of the Kuchelga site (Mackay et al., 2013). The Khall age model suggests a moderate increase in *P. sylvestris* pollen percentages (ca. 35–40%) from ca. 3.3–2.7 cal ka BP, while the highest percentages (ca. 60–80%) are dated to after ca. 2.6 cal ka BP. Though, it is possible that vegetation histories of two closely located coastal sites differ from each other. However, an earlier pine spread (i.e. comparable to the large-scale regional signal) is to be expected in the lacustrine record rather than in the Kuchelga peat, representing more local vegetation. On the other hand, the problem might lay in the accuracy of dating and reliability of the individual site age models. Unfortunately, there are very few data available from the western coast of Lake Baikal which could help to better evaluate these different hypotheses. The pollen diagram derived from the salt-water Lake Tsagan-Tyrm located in the Ol'khon region (Sklyarov et al., 2010) reveals regional vegetation changes since ca. 7.5 cal ka BP. The chronology of this record is based on four conventional radiocarbon dates (for comparison the published ^{14}C dates were converted into calendar ages using CalPal online calibration software) spanning the interval from ca. 3.66–7.19 cal ka BP. The pollen diagram from Tsagan-Tyrm shows very low percentages of *P. sylvestris* prior to ca. 6.6 cal ka BP and an increase of up to 20% about 6 cal ka BP, followed by a 10% minimum at ca. 5.8 cal ka BP and a 40% maximum at ca. 5.2 cal ka BP. All three records show highest pine pollen percentages (i.e. above 40%) during the late Holocene interval, i.e. after ca. 3.8 cal ka BP (Tsagan-Tyrm and Kuchelga, chronology 'b') and after ca. 2.6 cal ka BP (Khall and Kuchelga, chronology 'a'). However, direct correlation is extremely difficult for the older part of the discussed records. A need for high-resolution and accurately-dated pollen records from the western coast of Lake Baikal is therefore obvious and easy to justify.

It has been suggested that pollen data from the LBR reflect relative changes in major vegetation types controlled by moisture availability and temperature (e.g. Demske et al., 2005; Tarasov et al., 2009; Bezrukova et al., 2010), indicating near-synchronous vegetation shifts in response to large-scale climate variation across the LBR. A transition towards dry conditions (ca. 8–7 cal ka BP) was proposed to explain the nearly synchronous regional expansion of pine forests (Demske et al., 2005). This conclusion was further supported by quantitative biome and climate reconstructions derived from the Buguldeika pollen record (52°31′N, 106°09′E) of Lake Baikal (Tarasov et al., 2007) and the KTK2 pollen record from Lake Kotokel (Tarasov et al., 2009; Bezrukova et al., 2010), suggesting the warmest and wettest Holocene climate ca. 9–7 cal ka BP.

More recently published pollen records and other proxy data sets from the western coast of Lake Baikal now suggest a more complicated vegetation and climate history for this relatively dry and cold region, which could be explained by higher sensitivity of the forest-steppe vegetation and environments to the climate changes or/and other factors, including problems of radiocarbon dating, local climatic variability, sedimentary hiatuses, etc. Indeed, the Kuchelga record presented in this study shows higher variability in comparison to Cheremushka and particularly to Ochkovoe. Multi-proxy (geochemical, diatom, pollen) records from Lake Tsagan-Tyrm suggest that the Ol'khon Region became more arid during the last ca. 7 cal ka BP and reveals drastic and frequent changes in water level in response to the climate fluctuations (Sklyarov et al., 2010). Published results of climate modeling (Bush, 2005; White and Bush, 2010) also suggest a high degree of temporal climate variability driven by a combination of CO_2/H_2O and orbital forcing in the region of central Asia, including Lake Baikal during the Holocene. In line with the summarized paleoenvironmental data from the Lake Baikal Region, Mongolia and northern China, simulated humidity parameters indicate that the early Holocene was the wettest period of the last 12 cal ka BP, followed by a shift to more arid conditions by ca. 6.5–3 cal ka BP and subsequent increase in humidity at ca. 2.5 cal ka BP (White and Bush, 2010).

The published sedimentary, pollen and isotope records from across the central Asian mid-latitudes demonstrate spatially and temporally different Holocene vegetation and climate histories of eastern, western and northern regions reflecting spatial and temporal dynamics of the Pacific monsoon and the Atlantic westerlies (Rudaya et al., 2009). It was suggested that the 'northern region' (including Lake Baikal) displays two precipitation maxima during the last 12 cal ka BP. While the early Holocene (summer monsoon-associated) maximum was more pronounced in the eastern part of the region, the late Holocene (westerly-associated) precipitation maximum could be better seen in the western part (Rudaya et al., 2009). The conclusions of the latter study are supported by the model simulations of temperature, precipitation and woody cover in northern Eurasia over the last 8 cal ka BP (Kleinen et al., 2011) and by the $\delta^{18}O$ diatom record of Lake Kotokel reflecting changes in air temperatures, evaporation effects and in atmospheric moisture sources through the Holocene (Kostrova et al., 2013). Both proxy-based climate reconstructions and modeling results obtained for the larger region of Asia provide a clue for interpretation of the Holocene vegetation and climate dynamics in the LBR and suggest that spatial/temporal changes in atmospheric precipitation and in the seasonal distribution of precipitation could be major factors influencing regional and local vegetation, and possibly human populations.

5.3. Possible influence of climate dynamics on early societies

Debates on the impact of past climate and weather conditions on human behavior and the stability of human societies (De Menocal, 2001; Weber et al., 2002; Diamond, 2005; Costanza et al., 2007) have a long history (for the comprehensive review see, for example, Ingram et al., 1981 and references therein). In the flow of studies discussing the effects of the late Holocene century- to annual-scale climate fluctuations on economic and social activities two opinions representing different 'schools of thought' can be recognized. One considers climatic factors as one of the most important driving forces influencing human history (e.g. Huntigton, 1933; Gumiliev, 1967; Lamb, 1969), while the other tends to explain societal changes during the last few thousand years by the combined effect of different factors and suggests that the long-term climatic changes played a rather small or/and poorly understandable role (e.g. Le Roy Ladurie, 1971; Anderson, 1981). In recent decades, more and more scholars accept the possible importance of climatic variations on human affairs both in the long- and short-term, demanding, however, the highest standards of proof in each particular case (e.g. Marchant and Hooghiemstra, 2004). A hypothesis suggesting that people themselves substantially influenced global climate via agricultural practices and forest clearance since 8000 years ago (Ruddiman, 2003) makes studies of the 'climate-human' system even more complicated.

An attempt to find a relationship between the archeological data and the Holocene pollen record from Lake Baikal, in order to explain the spread of steppe and meadow communities in the eastern part of the LBR, demonstrates that despite a long habitation of the area human impact on vegetation was local rather than regional and likely did not affect the pollen spectra composition of Lake Baikal sediments (Tarasov et al., 2007). The latter study also reported that reconstructed peaks in the steppe biome scores during the last 9 cal ka BP are consistent with episodes of weak Pacific (summer) monsoon supporting the interpretation that the Holocene vegetation changes around Lake Baikal are mainly associated with large-scale circulation processes controlling regional water balance rather than with human activities. Recently an attempt to trace human impact along the Lake Baikal western coast was undertaken using a multi-proxy study of the small and shallow Lake Khall (Mackay et al., 2013). However, no evidence for anthropogenic activity was found in the lake sediment over the mid- to late-Holocene, despite the region having a long history of hunter–gatherers and, later, pastoralists. Pollen and charcoal analyses applied to the core sediments from Lake Kotokel and Cheremushka peat bog revealed that the percentages of Scots pine pollen reach maximum values soon after ca. 7 cal ka BP together with a significant increase in microscopic charcoal particles in Cheremushka bog (Shichi et al., 2009). Though this evidence indicating increased fire frequency could be caused by increased aridity (Tarasov et al., 2002; Shichi et al., 2009), the involvement of humans can not be fully excluded.

The current study shows that an increase in *Betula* pollen percentages occurred at Cheremushka after ca. 0.3 cal ka BP and this could be explained in part by intensified human activities. The settlements Cheremushka and Gremyachinsk, both located near the peatland, were established in the 18th century, and husbandry, farming and wood harvesting are practiced by a small local population even today. The subsistence of the indigenous Buryat (and earlier Mongol) population in the region is also based on animal husbandry since at least medieval times (Bogdanov, 2008). Modern field observation at the Kuchelga site reveals that *Salix* thickets are typical for the human-transformed hummocks. Therefore a more frequent appearance of *Salix* pollen in the uppermost peat sediments (this study) as well as a major increase in *Pediastrum* algae spores in the Lake Khall record (Mackay et al., 2013) could be seen as a possible indicator of intensified human presence during the last few centuries.

Reconstruction of the possible effects of past climate changes on human population dynamics, cultural traditions and subsistence strategies is one of the key tasks of the Baikal-Hokkaido Archaeology Project (Weber et al., 2013). Did climate changes influence humans in the LBR, and if so, in which way? These questions were raised in both archeological (e.g. Weber et al., 2002, 2010) and paleoenvironmental studies (e.g. Tarasov et al., 2007; White and Bush, 2010), particularly with respect to a hiatus in archeological records (i.e. lack of archeologically visible mortuary sites) occurring ca. 7/6.8–6/5.8 cal ka BP (Weber et al., 2010). Based on the much generalized model of Holocene climate in South Siberia (Khotinskii, 1977, 1984), Weber et al. (2002) suggested that changes in the hunter–gatherers cultural history of the region was likely caused by socio-cultural rather than by environmental-climatic processes. More recent environmental reconstructions suggest that the Early Neolithic Kitoi culture in the LBR is synchronous with a distinct amelioration of the regional climate ca. 9–7 cal ka BP, and the subsequent lack of archeological (cemetery) records along the southern and western coast of Lake Baikal roughly coincides with the major change in vegetation and climate (Tarasov et al., 2007; White and Bush, 2010).

The Kuchelga, Ochkovoe and Cheremushka records, representing three different climatic regions around Lake Baikal, demonstrate that the environments and vegetation of the driest western coast were more sensitive to the climate oscillations of the middle and late Holocene in comparison to the more humid areas to the east, and particularly south of Baikal. Therefore, it could be expected that environmental impact on early human societies was strongest in the arid region to the west of Lake Baikal. To test this hypothesis, however, accurately dated multi-proxy records of the Holocene climate and environments are absolutely necessary. Detailed pollen studies of lake and peat sediments in semi-arid Kulunda (Rudaya et al., 2012), in the Minusinsk Basin (Schlütz and Lehmkuhl, 2007), and in the adjacent Tuva Republic of the Altai (van Geel et al., 2004) provide attempts to generate such reconstructions of middle to late Holocene vegetation, climate and environmental dynamics in order to explain changes in the economic activities of the ancient populations of southern Siberia since the mid-Holocene.

6. Conclusions

The aim of this paper was to reconstruct local to small-regional scale vegetation changes and their probable causes in the Lake Baikal Region since ca. 7 cal ka BP. To achieve this goal, pollen content and peat botanical composition were analyzed at three sites located in climatically different environments near Lake Baikal.

The longest vegetation record with the most reliable age model is from Cheremushka. This site is located in the area with moderately humid climate, where *P. sylvestris* played the most prominent role in the forest cover around the site during the last ca. 7 cal ka BP. The pollen record from Ochkovoe, spanning the last 4.5 cal ka BP, demonstrates equally high percentages of *P. sylvestris* and *P. sibirica*-type pollen. Siberian pine played and continues playing an important role in the vegetation cover around Ochkovoe, which is located in the most humid area of the LBR. In the pollen record from Kuchelga, *P. sylvestris* again becomes a dominant taxon, though arboreal pollen percentages are never as high as in the other two records, in line with the generally low summer and winter precipitation and low tree coverage around the study site.

Comparison of the Kuchelga record with the two pollen records available from the Ol'khon Region reveals some differences in *P. sylvestris* pollen curves, which can be related to the accuracy of dating and reliability of the individual age models or/and to the local differences between the sites. Unfortunately, there are very few data from the western coast of Lake Baikal which help to evaluate different hypotheses.

The Kuchelga record reveals more pronounced changes in vegetation, suggesting greater sensitivity of the region to middle and late Holocene climate changes, in comparison to Cheremushka and particularly to Ochkovoe. It could be expected that environmental impact on early human societies was strongest in the more arid region to the west of Lake Baikal. To test these hypotheses, however, accurately dated multi-proxy records of Holocene climate and environments from this so far poorly studied region are absolutely necessary. Across the central Asian mid-latitudes the published sedimentary, pollen and isotope records demonstrate spatially and temporally different Holocene vegetation and climate histories. It has been suggested that the northern region including Lake Baikal displays two main precipitation maxima during the Holocene. The early Holocene maximum is more pronounced in the eastern part of the region, while the late Holocene precipitation maximum is better seen in the western part. The data presented in the current study seem to support this interpretation.

The comparison of these results with published environmental records and climate model simulations confirms the earlier interpretations that the middle and late Holocene vegetation dynamics in the LBR was primarily driven by natural forcing and likely was associated with large-scale circulation processes controlling the regional water balance rather than with human activities. Some synchronous changes in environmental and archeological data likely point to a possible causal link between past climate changes and cultural history of the region.

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