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Mid-late Holocene environmental history of Kulunda, southern West Siberia: vegetation, climate and humans

Natalia Rudaya [a,*], Larisa Nazarova [b,d], Danis Nourgaliev [b], Olga Palagushkina [b], Dmitry Papin [c], Larisa Frolova [b]

[a] Institute of Archaeology and Ethnography SB RAS, Ak. Lavrentieva 17, 630090 Novosibirsk, Russia
[b] Kazan Federal University, Kremlevskaya St., 18, 420008 Kazan, Russia
[c] Altai State University, Lenina Av., 61, 656049 Barnaul, Russia
[d] Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Telegrafenberg A43, 14473 Potsdam, Germany

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ABSTRACT

An environmental reconstruction of mid-late Holocene vegetation, climate and lake dynamics was inferred from pollen and diatom records of Lake Big Yarovoe in Kulunda, southern West Siberia. The reconstruction suggests a general prevalence of steppe during the last 4.4 ka. Under a relatively warm and dry climate, open semi-desert and dry steppes with patchy birch forest spread between 4.4 and 3.75 ka BP. The largest development of conifer forest started in Kulunda after 3.75 ka BP. The onset of the Late Holocene is characterised by the dominance of steppe with birch and pine forests in the lowlands and river valleys. After AD 1860, open steppe and semi-desert vegetation with fragmentary birch forest have been dominant in Kulunda, along with a sharp reduction of conifers. These results are in agreement with the general pattern of the Holocene environmental history of the surrounding areas, including the Baraba forest-steppe, Kazakh Upland and Altai Mountains. The penetration of coniferous forest into the Kulunda steppe after 3.75 ka BP was related to its geographical location northwest of the Altai Mountains. The economic activities of the ancient population of Kulunda depended on the environmental changes during the Holocene.

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1. Introduction

The Kulunda depression is located in the southern part of West Siberia and used to provide a paramount connection between the Central Asian steppe and the North Asian forest-steppe. This is reflected in a variety of archaeological sites that belong to diverse human cultures of the Bronze, Iron and Middle Ages. Despite the importance of palaeoenvironmental studies in the Kulunda depression and neighbouring Baraba forest-steppe, there are only few radiocarbon-dated sedimentary records from the several lakes and peat sites, and all of them are published in Russian (Klimanov et al., 1987; Levina et al., 1987; Nenasheva et al., 2006; Khazin and Khazina, 2009). Middle and Late Holocene environmental changes might have had a significant influence on the development of the human societies in the region. However, until now, this question has not been studied. The present study focuses on the reconstruction of environmental changes in the Kulunda region during the last 4.4 ka, and we discuss the probable interaction between climatic changes and human activities in the Middle and Late Holocene.

In this study, we present (1) the results of pollen and diatom analyses of sediment core from Lake Big Yarovoe; (2) a reconstruction of the vegetation, climate and lake environmental changes during the second half of the Middle and Late Holocene; (3) a discussion of our results and the environmental records from the neighbouring regions of Kazakhstan and Altai Mountains; and (4) a discussion of the environment–human interactions in Kulunda during the last 4.4 ka.

2. Site setting and environment

The Kulunda depression is an extensive accumulative lowland in the southeastern part of the West Siberian plane and is located at an altitude of 100–140 m asl. In the Middle and Late Pleistocene,

* Corresponding author. Tel.: +7 383 316 54 11; fax: +7 383 330 11 91.
E-mail addresses: nrudaya@gmail.com, nrudaya@yandex.ru (N. Rudaya), larisa.nazarova@awi.de (L. Nazarova), danis.nourgaliev@ksu.ru (D. Nourgaliev), opalagushkina@mail.ru (O. Palagushkina), papin@mc.asu.ru (D. Papin), larissa.frolova@mail.ru (L. Frolova).

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Kulunda was flooded by fluvioglacial waters. Presently, a thick layer of alluvial sediments (up to 50–60 m) covers the Kulunda depression (Nikolaev, 1970). A distinctive feature of the Kulunda and the neighbouring Baraba forest-steppe is the high number of salty and freshwater lakes.

The Kulunda depression is affected by cold air from the Karskoye Sea and warm and dry air masses from the Kazakhstan steppe and the Central Asian deserts (Vandakurova, 1950). The continental climate of Kulunda is characterised by long cold winters ($T_{Jan} = -17$–$19\,^{\circ}C$) and short warm summers ($T_{July} = 19$–$21\,^{\circ}C$), and the mean annual temperature is approximately 0 °C. The average annual precipitation is 240–360 mm, most of which falls in the summer. The thickness of the snow cover varies from 13 to 40 cm (Atlas of Altai Region, 1978).

Kulunda is situated in the Eurasian steppe zone with a prevalence of grass communities (Lavrenko, 2000). Numerous salty lakes are surrounded by plant associations that include *Festuca valesiaca, Goniolimon speciosum, Koeleria gracilis, Artemisia maritima, Kochia prostrata*, and *Achnatherum splendens*. Pine forests with *Pinus sylvestris*, which spread southward from the Kulunda steppe, are the most xerophytic Siberian forests (Ermakov et al., 2000). A unique forest-steppe with isolated birch-aspen stands of *Betula pendula* grow to the east of Kulunda. Such a vegetation type, called "kolki", is floristically more related to European deciduous forests than to subarctic or boreal vegetation (Nimis et al., 1994). In the north, Kulunda borders on Baraba forest-steppe with mosaic vegetation composed of steppe communities and birch kolki. The west part of Kulunda borders on the eastern Kazakhstan hills.

The coastal vegetation of Lake Big Yarovoe consists mostly of *Carex vesicaria, C. pseudocyperus, Typha latifolia, Phalaroides arundinacea, Phragmites australis, Eleocharis sareptana, Juncus gerardii* and *Ranunculus repens* (Zarubina and Durnikin, 2005). Recently, vegetation around Lake Big Yarovoe has been significantly changed by human economic activity.

Lake Big Yarovoe (52°56′00″N, 78°35′00″E; 79 m asl; Fig. 1A) is the deepest closed lake in the western part of the Kulunda depression in the Ob'-Irtysh interfluve (Altai region, southern West Siberia). The lake has an area of 66.7 km^2 with a maximum water depth of 7.4 m and an average depth of 4.4 m (Altai Region Atlas, 1978). Intense evaporation and low precipitation in the region have led to a high degree of water salinisation (Malikova et al., 2008). The water of Lake Big Yarovoe is a brine with mineralisation of 135–172 g per litre.

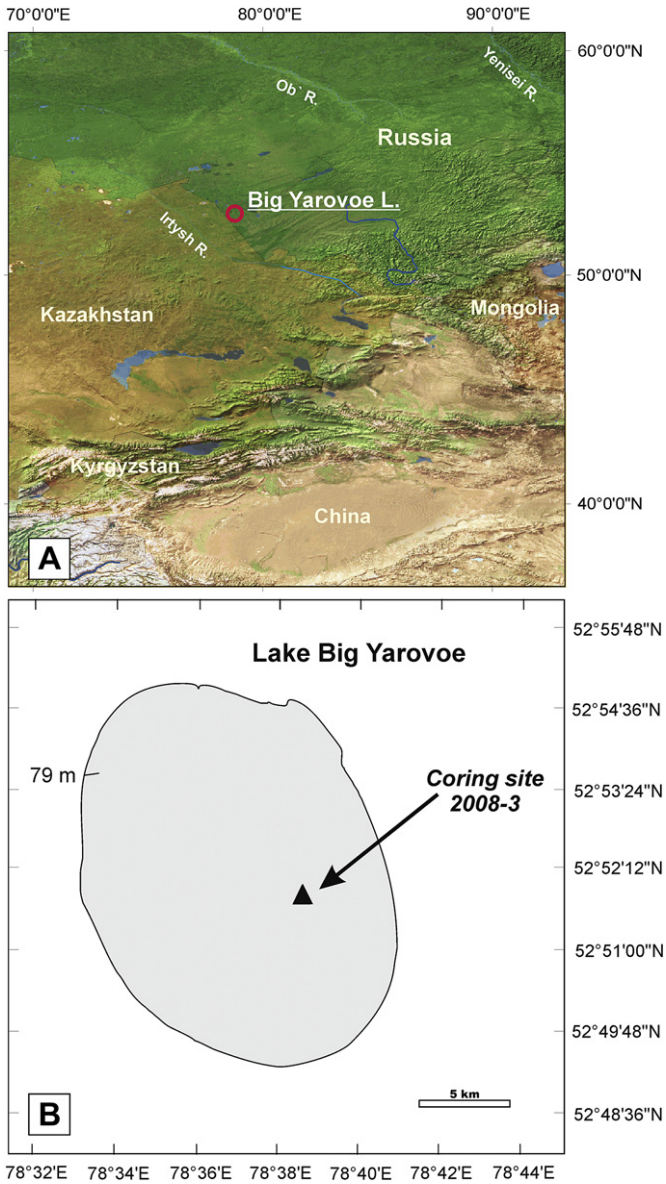

Fig. 1. Map of the studied region (A) and Lake Big Yarovoe with the location of the analysed pollen and diatom records (B).

3. Data and methods

3.1. Coring and chronology

In 2008, a 404 cm long sediment core (2008-3) was recovered from 8 m depth in the southern part of Lake Big Yarovoe (52°51.156′N, 78°37.601′E; Fig. 1B). The core was retrieved with a modified Mackereth corer (Nourgaliev et al., 2007). It consists mostly of striated black, grey and greenish-grey silts. The lower portion of the sediments contains gypsum crystals.

The poor organic content of Lake Big Yarovoe sediments posed a problem for radiocarbon dating, but the problem was solved with a geomagnetic approach. A record of geomagnetic inclinations from the studied core was compared with Holocene records of inclinations from Lake Biva, Japan (Fig. 2). The age model of Lake Biva is based on two widespread tephra layers: Kawagodaira (3.15 ka BP) and Kikai-Akahoya (7.25 ka BP) (Fig. 3; Ali et al., 1999). To produce an adequate age-depth model for Lake Big Yarovoe, we transferred the ages of the extremes that the two geomagnetic curves have in common from the Lake Biva age model to the Lake Big Yarovoe record (Table 1; Fig. 3).

3.2. Pollen analysis

A total of 23 samples, each consisting of 2 g of dry sediment that were taken at a 20-cm average intervals from core 2008-3, were treated for pollen analysis using standard procedure (Faegri and Iversen, 1989). *Lycopodium* spore tablets were added to each sample to calculate the total pollen and spore concentrations. Pollen residues mounted in glycerin were analysed under a light microscope with 400× magnification. Identification of pollen and spores was performed using a reference collection and atlases (Kuprianova and Alyoshina, 1972; Reille, 1992, 1995, 1998).

The microscopic analysis revealed a high pollen concentration and generally good preservation, which allowed the identification of at least 300 terrestrial pollen grains per sample (average 317; Appendix 1). Percentages of all taxa were calculated based on a pollen sum of all pollen taxa taken as 100%, excluding spores and non-pollen palynomorphs (NPP). The results are displayed in a diagram (Fig. 4) produced with Tilia/TiliaGraph software (Grimm,

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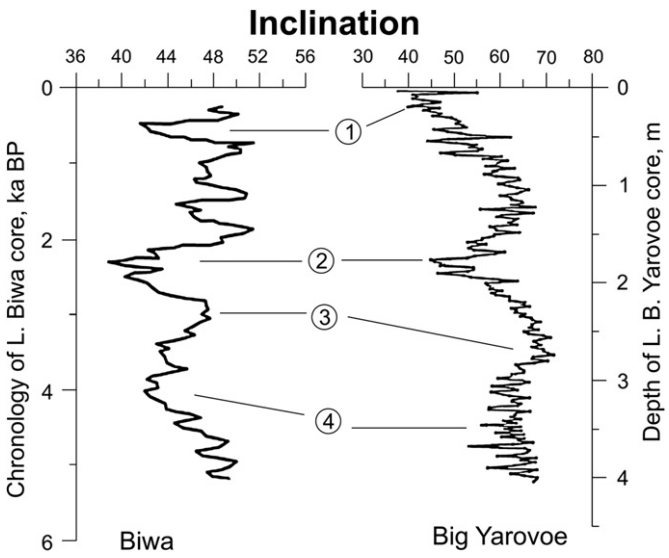

Fig. 2. The geomagnetic extremums of inclination records of Lake Biva (Ali et al., 1999) and Lake Big Yarovoe (this study): 1, 2, 3 and 4 – points of extremes (see Table 1).

1991). In the diagram, a visual definition of local pollen zones is supported by CONISS (Grimm, 1987).

3.3. Method of biomisation

For biome reconstruction (biomisation), we used a quantitative approach that is based on fuzzy logic introduced by Prentice et al. (1996). Biomisation is a powerful tool for objective vegetation reconstruction from late Quaternary pollen data of Eurasia (Tarasov et al., 1998; Gunin et al., 1999; Prentice et al., 2000; Rudaya et al., 2009). The method is based on an objective assignment of pollen taxa to plant functional types (PFTs) and to biomes on the basis of modern ecology, bioclimatic tolerance and the geographical distribution of pollen-producing plants. The method has been adapted for the reconstruction of northern Eurasian biomes (Tarasov et al., 1998). In this study, we used a biome-taxon matrix and a calculation equation in which 34 pollen taxa are attributed to ten biomes occurring in the northern Eurasia. When applied to 51 surface pollen spectra from the Altai region (including mountainous areas), this method assigned 71% of the samples to the correct biome (Rudaya, 2010). Dominant biomes and their

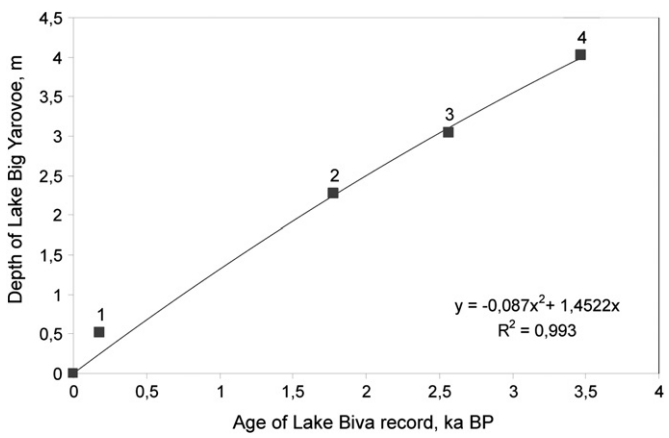

Fig. 3. Age-depth model applied to the sedimentation record of Lake Big Yarovoe. The black squares indicate points of geomagnetic extremes that coincide in the Lake Biva and Lake Big Yarovoe inclination records.

Table 1
Transferred ages of the geomagnetic record extremums from Lake Biva to Lake Big Yarovoe (this study).

Points of extremums	Age of Lake Biva record, ka BP	Depth of Lake Big Yarovoe, m
1	0.52	0.18
2	2.31	1.76
3	3.05	2.56
4	4.03	3.46

characteristic PFTs with pollen taxa as well as the results of biomisation are displayed in Table 2 and Fig. 5, respectively.

3.4. Diatom analysis

A total of 23 samples, taken at 20-cm intervals, were prepared for diatom analysis using the standard hydrogen peroxide technique (Battarbee, 1986). Aliquots of evaporated suspensions were embedded in Naphrax. Using ten horizontal transects under a light microscope with phase-contrast oil immersion at 400–1000× magnification, the counting of up to 300 diatom valves per sample was possible only for three samples (with average of 71 valves per sample). Diatom valves were rare or not found in several horizontal transects (Fig. 6). We accepted the following abundance classes for the individual taxa: up to 5% valves in one sample were classified as rare, 5–10% as subdominant and more than 10% as dominant. Following Aleshinskaya and Zaikina (1964), Davydova (1985) and Barinova et al. (2006), the diatoms were assigned to ecological groups based on the relation of species to habitats, salinity, pH, and geographical distribution (Appendix 2). The diatoms were classified by their relation to salinity following system of Kolbe (1927), adjusted for reservoirs of the USSR by Proshkina-Lavrenko (1953). The relation of diatoms to pH was defined according to the classification of Hustedt (1937, 1938, 1939), supplemented by Meriläinen (1967). Diatom nomenclature followed Krammer and Lange-Bertalot (1986–1991) and the Finish training set (FTS) guidelines (Weckström et al., 1997). The results are displayed in a diagram (Fig. 6) produced with the computer program C2 ver. 1.5 (Juggins, 2007). ZONE software (Juggins, 1991) was used to split the diatom diagram into stratigraphic zones. The statistical significance of the zones was established using the program BSTICK (Bennett, 1996). pH was reconstructed on the basis of the Finish Lapland training set, which comprises 151 samples from lakes in the pH range 5.0–7.8. A subset of 30 of these has been published as a training set (Weckström et al., 1997). These lakes are distributed across the treeline and span boreal forest to tundra along a steep

Table 2
Dominant biomes and their characteristic plant functional types (PFTs) with pollen taxa reconstructed from Lake Big Yarovoe. PFTs in parentheses are restricted to part of the biome.

Biome	PFTs	Plant taxa
Steppe	Steppe forbs Grass	Apiaceae, Asteraceae (including *Artemisia*), Brassicaceae, Caryophyllaceae, Chenopodiaceae, Fabaceae, Geraniaceae, *Ipomea*, Lamiaceae, *Limonium*, *Plantago*, Poaceae, Polygonaceae, Ranunculaceae, Rosaceae, *Thalictrum*, *Urtica*
Taiga	Boreal summergreen	*Betula*, *Larix*, *Salix*, *Alnus*
	Boreal evergreen conifer	*Pinus* s/g *Haploxylon*, *Picea*, *Abies*
	Eurythermic conifer	*Juniperus*, *Pinus* s/g *Diploxylon*
Desert	Desert forbs	*Ephedra*, *Limonium*-type, Chenopodiaceae, Polygonaceae

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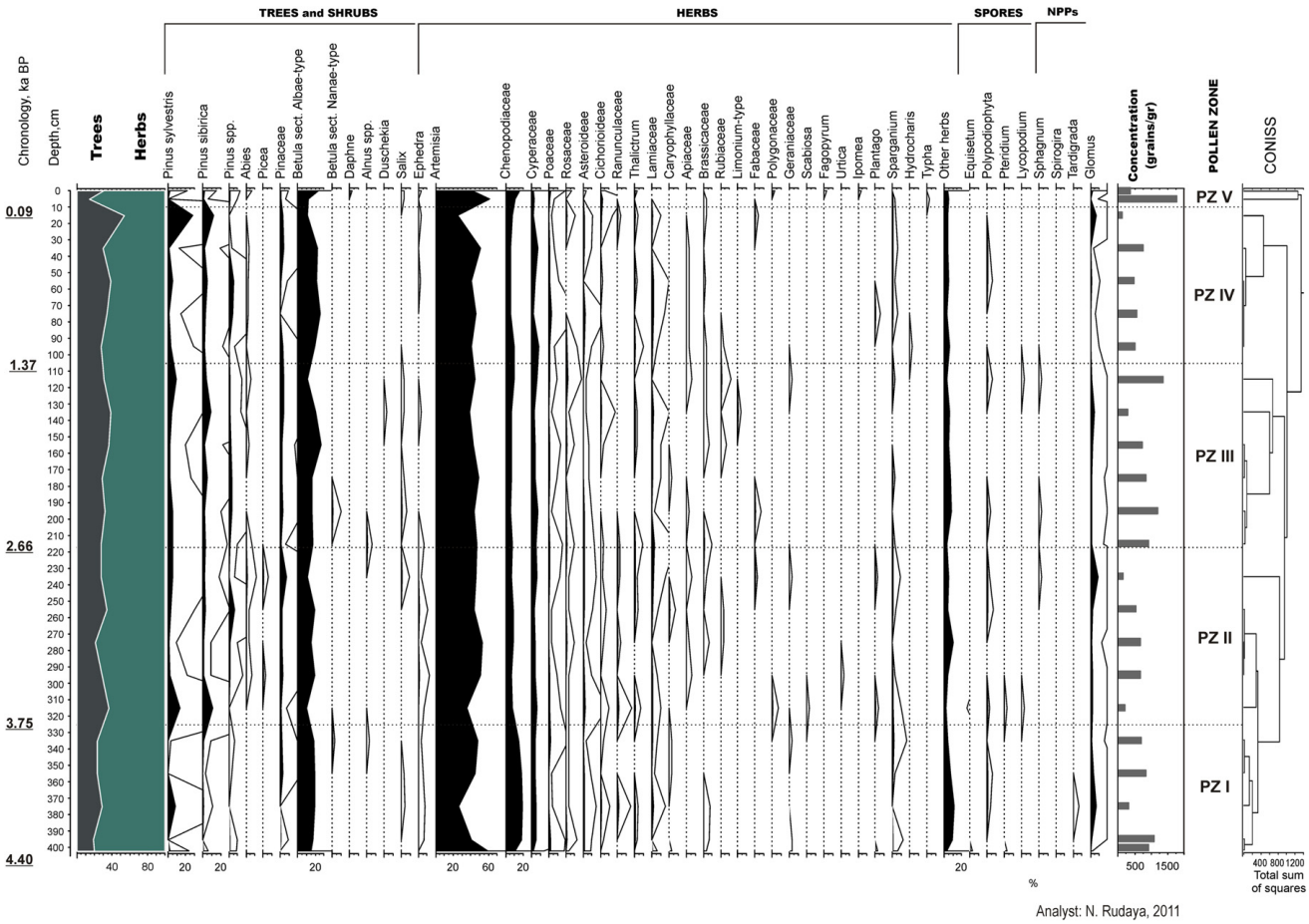

Fig. 4. Palynological analysis of the Lake Big Yarovoe core, produced with the Tilia/TiliaGraph software (Grimm, 1991). The visual definition of the pollen zones is supported by CONISS (Grimm, 1987).

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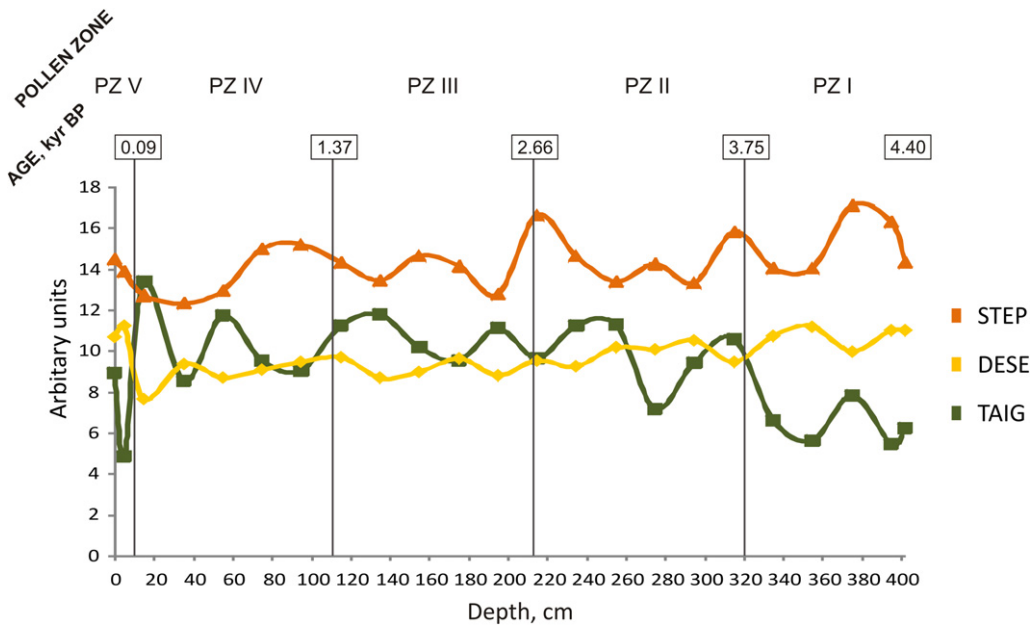

Fig. 5. Scores of the dominant biomes reconstructed from the Lake Big Yarovoe pollen record. STEP – steppe; DESE – desert; TAIG – taiga (Table 2).

climatic gradient. The fossil diatom assemblages of Lake Big Yarovoe are generally well represented in the FTS. The pH reconstruction was performed using the program C2 ver. 1.5. Weighted Averaging (WA) regression with inverse deshrinking regression coefficients showed the best predictive performance ($r^2 = 0.812$; RMSE = 0.237; Max Bias = 0.39472), so was used.

4. Results and interpretation

4.1. Pollen record and biome reconstruction

The results of pollen analysis provide qualitative and quantitative information for the regional vegetation reconstruction. The qualitative interpretation of the pollen diagram is supported by the quantitative reconstruction of the dominant biomes (vegetation types).

The pollen assemblage of the last ca 4.4 ka BP is characterised by the dominance of steppe and semi-desert herbaceous pollen taxa (*Artemisia*, Chenopodiaceae) and arboreal pollen of *Betula* sect. *Albae* (Fig. 4). Other arboreal pollen has a relatively low abundance and is represented mostly by *Pinus*. Cyperaceae pollen has constant percentages throughout the core and likely relates to coastal aquatic vegetation. Steppe communities of Kulunda are characterised by absence of Cyperaceae and dominance of grasses and forbs (Vandakurova, 1950), whereas coastal vegetation contains up to 27% of sedges (Zarubina and Durnikin, 2005). NPPs are poorly represented in the record. Only *Glomus* is relatively abundant (Fig. 4).

In the biome reconstruction, the steppe biome has the highest scores, which suggests dominance of this vegetation type. The scores of taiga and desert biomes are relatively high (Fig. 5).

Zone PZ I (404–325 cm; ~2440–1795 BC; 4.4–3.75 ka BP) is characterised by predominance of herbaceous taxa including *Artemisia* (up to 50%) and of arboreal *Betula* sect. *Albae* (up to 20%). Chenopodiaceae pollen (up to 20%) reaches its maximum. Pollen of desert/semi-desert *Ephedra* is relatively abundant. Other arboreal pollen is represented mostly by *P. sylvestris* with a single peak (10%) at 375 cm (approximately 4.16 ka BP). The biome reconstruction reveals the highest scores for steppe and desert, whereas of taiga has minimal values (Fig. 5).

Zone PZ II (325–215 cm; ~1795–710 BC; 3.75–2.66 ka BP) reveals a decrease in Chenopodiaceae and an increase in *Pinus sylvestris* (up to 15%) and *Pinus sibirica* (up to 10%). *Abies* and *Picea* have low abundances in five samples. *Ephedra* has the same percentages as in PZ I. *Artemisia* (up to 60%), *Betula* sect. *Albae* (20%), and Chenopodiaceae (10–12%) dominate. *Sphagnum* occurred for the first time in the upper part of this zone at 255 cm (ca 3.1 ka BP). This zone is characterised by a sharp increase in taiga biome scores and a general prevalence of steppe biome scores (Fig. 5).

Zone PZ III (215–105 cm; ~710 BC–AD 580; 2.66–1.37 ka BP) is noticeable for a slight decrease in *Artemisia* (up to 40%) and increase in *Betula* sect. *Albae* (up to 25%) and *P. sibirica* (5–10%). *Salix* is not abundant, but it occurs throughout the zone. In the upper part (140–105 cm; ~AD 145–580; 1.80–1.37 ka BP), *P. sibirica* and *P. sylvestris* increase slightly. This increase is reflected in the increasing taiga biome scores. A distinctive feature of the zone is the presence of *Sphagnum* spores in two samples.

Maximum arboreal pollen percentages occur in PZ IV (105–10 cm; ~AD 580–1860; 1.37–0.09 ka BP) because of an increase of *Pinus* spp. A sharp increase in *P. sylvestris* (up to 40%) is recorded at a 10–20 cm (ca AD 1720–1860 or ca 0.09–0.23 ka BP). This event is reflected in a change in the dominant biome from steppe to taiga. A maximum decrease in the steppe biome scores is observed at 10–70 cm (ca AD 1030–1860; 0.92–0.09 ka BP).

Zone PZ V (10–0 cm; ~AD 1860–2008; 0.09 ka BP – today) mainly reflects modern vegetation with the dominance of *Artemisia*, Chenopodiaceae, and *Betula* sect. *Albae* (up to 60, 20 and 20%, respectively). Biomisation reveals a sharp decrease in taiga forest scores and an increase in steppe and desert scores (Fig. 5).

4.2. Diatom record

The fossil diatom assemblages of the core from Lake Big Yarovoe comprise 79 taxa belonging to 27 genera (Appendix 2). The reconstructed pH shows some changes throughout the core, with variation from 6.11 to 7.42. Four significant zones were identified (Fig. 6).

Zone DZ I (400–350 cm; ~4.4–3.96 ka BP). Diatoms are completely absent in the lowest part. At 360 cm (4.1 ka BP), the maximal number of diatom species of the entire core was found (26

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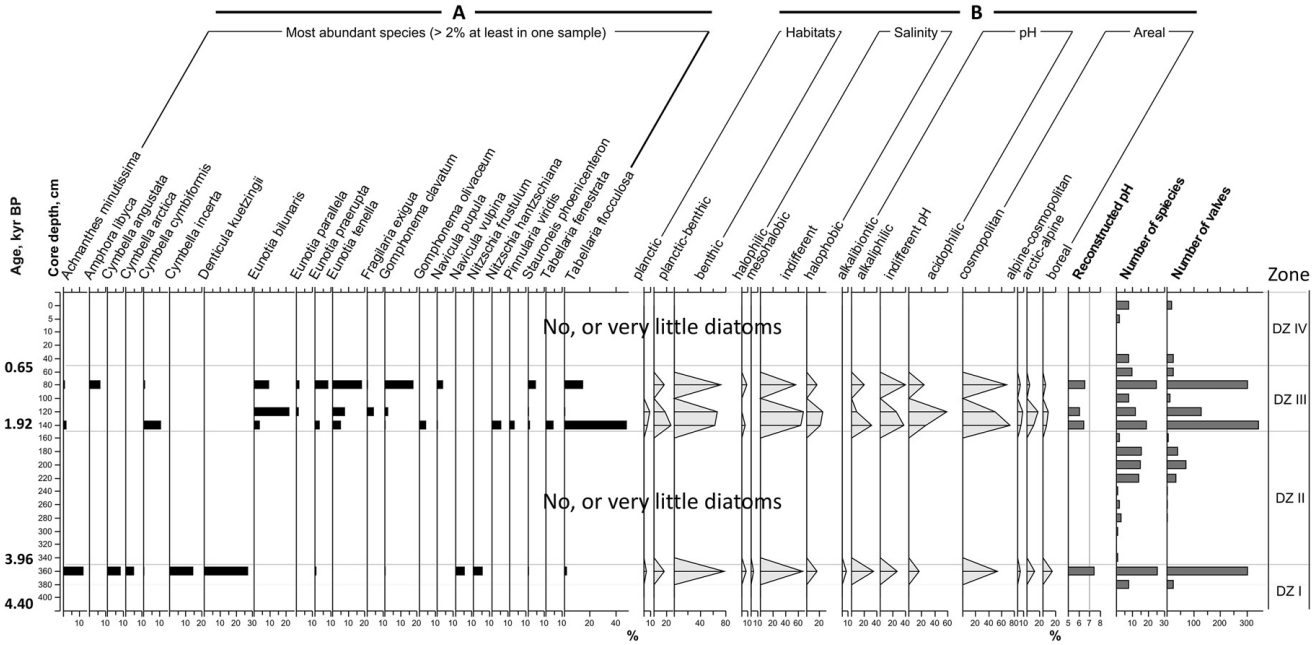

Fig. 6. Diatom stratigraphy of Lake Big Yarovoe with number of species, diatom valves concentrations, and FTS-reconstructed pH. A. All diatom taxa with an abundance ≥2% at least in one sample are shown. B. Abundance of ecological groups of diatoms of Lake Big Yarovoe in relation to habitats, salinity, pH and geographical distribution.

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species). High abundance of benthic diatoms (77%) and dominance of *Cymbella incerta* (Grun.) Cl., *C. angustata* (W.Sm.) Cl., and *C. arctica* (Lagerst.) Schmidt indicate a shallow depth and a high transparency of the lake water. Cosmopolitan species prevail. The for the entire core highest abundance of boreal species (15.3%) reflects some warming of the environment. A high abundance of halophilic species and the presence of *Denticula kuetzingii* Grun., which prefers waters with high conductivity, and mesohalobic the *Achnanthes flexella* (Kutz.) Brun are indicative of increasing water mineralisation. The high abundance of alkalibionthic and alkaliphilic diatom forms (in total 41.3%) and the dominance of *Achnanthes minutissima* Kütz., which prefers alkaline waters, reflects an increasing pH (reconstructed pH = 7.42 at of 360 cm).

Zone DZ II (350–150 cm, ~3.96–1.92 ka BP), diatoms are found in very low concentrations, which is most likely caused by a strong shallowing and periodic desiccation of the lake. The diatom flora is mainly represented by cosmopolitan and benthic species, which are indifferent to salinity, or halophilic and alkalibiontic forms. The increase of species of *Cymbella* and *Pinnularia* confirms the decreasing water level and occasional exsiccation of the lake.

Zone DZ III (150–50 cm, ~1.92–0.65 ka BP) includes two peaks of diatoms, at 140-120 cm and 80 cm. Fresh-water cosmopolitan species prevail. However, the lower and upper parts of this zone differ in dominants and environmental conditions that they indicate. The occurrence and increase of planktonic (up to 8.3%) and planktonic-benthic (up to 16.7%) forms at 140 cm reflect an increase in the water level. Halophobic (25%) and acidophilic (58%) species reach their maximum in the core, which indicates a decrease in water conductivity and a slight acidification (reconstructed pH at 120–140 cm is 6.11–6.48). An increase in arctic-alpine and alpine-cosmopolitan species at 140 and 120 cm (~1.80–1.56 BP) can indicate cooling of the climate. The dominance of acidophilic species (*Tabellaria flocculosa* (Roth.) Kutz., *Eunotia bilunaris* (Ehrb.) Grun., and *E. tenella* (Grun. in Van Heurck) Hust.), which prefer waters with low conductivity, confirms the lake's acidification, increase in water level and decrease in water mineralisation.

The upper peak in diatoms (80 cm; ca 1.05 BP or AD 902) is characterised by absence of planktonic species and increase of benthic species, which indicates a decrease in the water level. Halophobic and acidophilic species decreased, which is connected with increases in conductivity and pH (reconstructed to 6.55). Species that dominate the lower part of the zone are gradually replaced by species that prefer water with high conductivity and pH (*Amphora libyca* (Kutz.) Schoeman et Archibald, *Gomphonema clavatum* Ehrb.). A decrease of arctic-alpine and alpine-cosmopolitan species reflects slight warming.

Zone DZ IV (50–0 cm, ~0.65 ka BP – today) has low diatom concentrations and low taxonomic diversity. The absence of diatoms at the bottom of the zone likely indicates partial exsiccation of the lake at approximately 0.09–0.23 ka BP (~AD 1720–1860). Diatoms from 10 cm (0.09 ka BP) and deeper are mostly represented by benthic alkaliphilic mesohalobic cosmopolitan species, and there is a prevalence of *Amphora coffeaeformis* (Ag.) Kütz., *Nitzschia constricta* (Kütz.) Ralfs and presence of halophilic species such as *Fragilaria fasciculata* (Ag.) Lange-Bert (not shown). These species are permanent inhabitants of brackish waters and sea shelf and reflect relatively low water levels and slightly alkaline and highly mineralised water.

4.3. Vegetation and lacustrine dynamic

An arid and warm climate is reflected in the pollen composition between 4.4 and 3.75 ka BP. Semi-desert steppes with *Artemisia*, Chenopodiaceae and *Ephedra* spread in the western part of the Kulunda depression. Large amounts of chenopod may represent the formation of solonez and solonchak dry steppes around the lake. Scots pine forest was restricted to river valleys; however, patchy birch forest (kolki) was widespread in the region. The diatom taxonomic composition indicates that between 4.4 and 3.96 ka BP, Lake Big Yarovoe remained quite shallow and had lower water mineralisation than today. This is reflected in the diverse diatom flora with maximal biodiversity at the end of the period. Together with the presence of boreal diatom species, this indicates warm climatic conditions, the warmest approximately 4.0 ka BP.

A sharp decrease in chenopod and an increase in conifer pollen is recorded spectra after 3.75 ka BP. The pollen composition and the biome reconstruction reflect the spread of conifers in the region from this time until 0.09 ka BP (~AD 1860). The dominance of *Artemisia* and decrease in Chenopodiaceae pollen indicate a greater role of steppe communities and a reduction of halophytic vegetation around Lake Big Yarovoe. Between 3.96 ka BP and 1.92 ka BP, the lake underwent shallowing or even exsiccation; the diatom flora nearly disappears.

The onset of the Late Holocene (after ca 2.6 ka BP) in Kulunda is characterised by a general prevalence of steppe with patchy birch and pine forests in the lowlands and river valleys. Willow associations and halophytic communities most likely represented shore vegetation. The occurrence of *Sphagnum* spores in the pollen spectra corresponding to ca 2.8–1.4 ka BP is evidence of paludification and the presence of forests in the area. After 1.92 ka BP, the taxonomic composition of the diatoms indicates increasing lake depth and decreasing mineralisation. Slight water acidification can be connected with the gradual spreading of conifers in the region, which is revealed by pollen. The coldest and most humid period, according to the diatom composition, was between ca 1.8 and 1.0 BP (AD 145–900). However, based on pollen, the coldest and most humid time in the last 4.4 ka was from about AD 1000 to 1860. The quantitative reconstruction demonstrates a decrease of steppe between ca AD 1000 and 1860 and an increase of taiga that is the dominant vegetation type around AD 1720–1860. Around AD 1720–1860, the lake undergoes another exsiccation. This event corresponds to the end of the Little Ice Age in this region. After about AD 1860, the diatom flora indicates a period of warmer climatic conditions, low water levels and high mineralisation. At that point, open steppe and semi-desert vegetation with fragmentary birch kolki spread parallel to a sharp reduction of conifers.

5. Discussion

5.1. Kulunda and neighbouring regions: mid-late Holocene environmental history

Regional evidence provided by various environmental proxy data from the neighbouring areas of Siberia, Kazakhstan and Mongolia indicates spatially and temporally different mid-late-Holocene vegetation and climate histories (Rudaya et al., 2009, and references therein). The pollen and diatom data from Lake Big Yarovoe can be placed in a regional context by comparing them to other regional mid-late-Holocene records.

The Mid-late Holocene environment of the region north of Kulunda was reconstructed using two radiocarbon-dated pollen records from the Baraba forest-steppe (Fig. 7): Kayakskoye Zaimitsche (Levina et al., 1987) and Suminskoye Zaimitsche (Klimanov et al., 1987). These pollen records reveal the onset of afforestation with a sharp increase in arboreal pollen (especially *P. sylvestris*) occurring at about ca 3.5 ka BP. After 2.4 ka BP, Scots pine forests, including *P. sibirica*, became widespread in Baraba. The climate was relatively warm and wetter than in modern times. The share of herbaceous taxa and birch began to increase approximately 1.95 ka BP and open grass-sedge communities penetrated the

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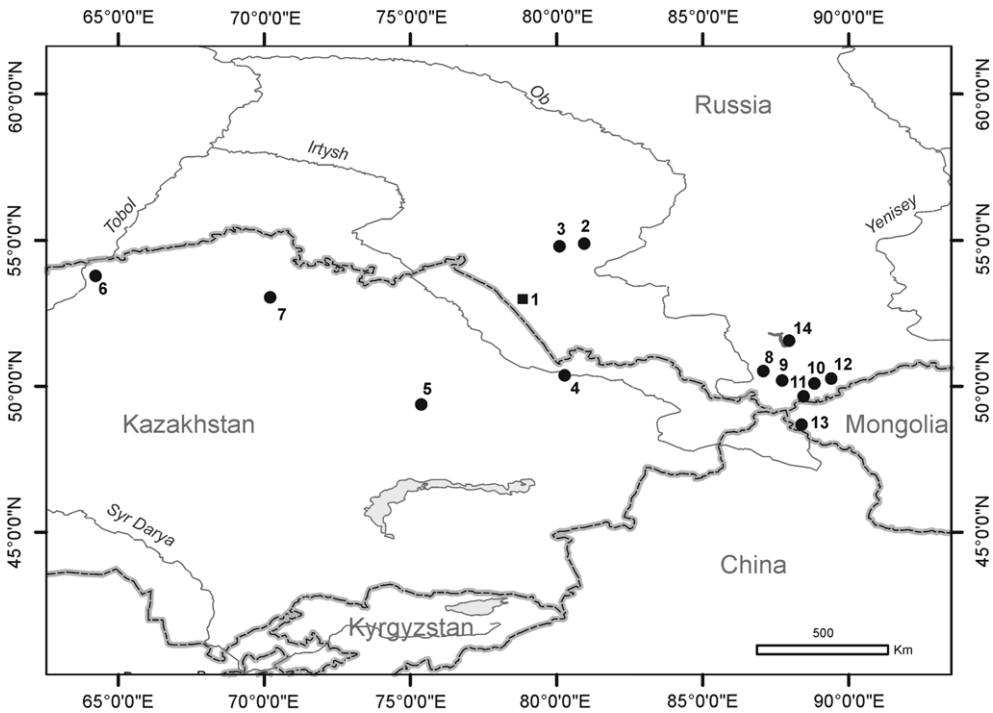

Fig. 7. Summary chart showing the distribution of the mid-late-Holocene palaeoclimate records from Kulunda and the neighbouring regions discussed in the text: 1. Lake Big Yarovoe (this study), 2. Kayakskoye Zaimitsche (54°57′ N; 81°01′ E; Levina et al., 1987), 3. Suminskoye Zaimitsche (54°45′N; 80°31′E; Klimanov et al., 1987), 4. Ozerki Swamp (50°24′N, 80°28′E; Kremenetski et al., 1997), 5. Pashennoe Lake (49°22′N, 75°24′E; Kremenetski et al., 1997), 6. Lake Mokhovoe (53°46′N, 64°15′E; Tarasov et al., 1997), 7. Lake Karasye (53°02′N, 70°13′E; Kremenetski et al., 1997), 8. Lake Uzun-Kol (50°29′00″N, 87°6′30″E; Blyakharchuk et al., 2004), 9. Lake Dzhangyskol (50°11′N, 87°44′E; Blyakharchuk et al., 2008), 10. Kuray Range (50°08′04″N, 88°51′10″E; Schlütz and Lehmkuhl, 2007), 11. Tarkhata Valley (49°39′01″N, 88°28′10″E; Schlütz and Lehmkuhl, 2007), 12. Lake Ak-Kol (50°15′N, 89°37′30″E; Blyakharchuk et al., 2007), 13. Hoton-Nur Lake (48°40′N, 88°18′E; Tarasov et al., 2000; Rudaya et al., 2009), and 14. Lake Teletskoye (51°35′N, 87°40′E; Andreev et al., 2007).

forested landscapes. The climate became drier, and vegetation consisted mostly of dry steppe associations. Between 0.75 and 0.5 ka BP (AD 1200–1450), pine forest and birch kolki penetrated into steppe vegetation again; the modern forest-steppe had been established.

Pollen records from the Kazakh Uplands (Ozerki Swamp, Pashennoe Lake, Lake Mokhovoe, Lake Karasye; Fig. 7) were used to reconstruct the post-glacial vegetation dynamics in this part of Central Asia. The penetration of pine forest into the Kazakhstan steppe became a distinctive feature of the second half of the Holocene (Kremenetski et al., 1997; Tarasov et al., 1997). After 6.5 ka BP, pollen data indicate the spread of Scots pine from the Southern Urals and West Siberia to Northern and Central Kazakhstan; however, pine forests reached their modern limit in Central Kazakhstan only after 2 ka BP (Andreev and Tarasov, 2007).

The mid-late Holocene environments of the regions south of Kulunda are reconstructed from several high-resolution and accurately dated pollen records from the Russian and Mongolian Altai (Gunin et al., 1999; Tarasov et al., 2000; Blyakharchuk et al., 2004, 2007, 2008; Andreev et al., 2007; Schlütz and Lehmkuhl, 2007; Rudaya et al., 2009; Fig. 7). Pollen records from three freshwater lakes on the Ulagan Plateau (1985–2150 m asl; Blyakharchuk et al., 2004) suggest the dominance of mountain taiga with *P. sibirica, P. sylvestris* and *Larix sibirica* at the end of the Middle Holocene and in the Late Holocene. The share of *Picea obovata* and *Abies sibirica* pollen was significant in the spectra until ca 1.0 ka BP. The climate between 4.0 and 1.0 ka BP was relatively warm and humid. During the last millennium, *P. sylvestris, P. obovata* and *A. sibirica* pollen decreased, whereas *P. sibirica* and *Betula* sect. *Nanae* pollen noticeably increased. The climate became colder and drier (Blyakharchuk et al., 2004). Pollen data from Lake Dzhangyskol (1800 m asl) in the Kurai basin 30 km south of the Ulagan Plateau, reveals that the maximal expansion of taiga in the region occurred during the Late Holocene (Blyakharchuk et al., 2008).

Holocene environments in the southern part of the Russian Altai were reconstructed from the pollen records from two sites in the Chuya Basin (Kuray Range, 2330 m; and Tarkhata Valley, 2210 m). The environments are now covered by semi-desert steppe and have relatively cold and dry climates (Schlütz and Lehmkuhl, 2007). Pollen records suggest the presence of taiga with *P. obovata* and a warm humid climate between ca 4.95–3.4 ka BP. The forest with *L. sibirica* and *P. obovata* abruptly disappeared approximately 3.4 ka BP, and mountain steppe began to spread in the cool semi-humid climate. In the last two millennia, three climatic declines are documented from pollen records in the Tarkhata Valley: a cold and wet period around AD 370–580, a cold and dry period around ca AD 1100–1380 and the Little Ice Age starting ca AD 1600.

Pollen data from two small lakes in Tuva (2204–2413 m asl), located in the arid eastern part of the Russian Altai (Fig. 7), demonstrate complete disappearance of dark-coniferous forest with *Picea* and *Abies* and the spreading of steppe communities after 5 ka BP. This trend was associated with cooling, and aridisations of the climate were strengthened after 2 ka BP (Blyakharchuk et al., 2007).

The main feature of the late Holocene in the Mongolian Altai, which is reconstructed from pollen of the high-mountain Lake Hoton-Nur (2083 m asl; Fig. 7), is a reduction of forest and the establishment of steppe as a dominant vegetation type. These changes are associated with a significant decrease in atmospheric precipitation after ca 5 ka BP (Tarasov et al., 2000; Rudaya et al., 2009).

The pollen data summarised above reveal spatial variation in mid-late-Holocene vegetation and climates in the neighbouring regions. The mechanisms that drive vegetation and climate

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dynamics in this part of Asia suggest that the Altai Mountains form an important climate boundary for the Holocene environmental history of Central Asia (Rudaya et al., 2009). A shift towards wetter conditions occurred in the regions west of the Altai Mountains during the second half of the Holocene. At that time, the mid-latitudinal belt, which stretches from the Baltic Sea to Kazakhstan and southern Siberia, gained control of the Atlantic air masses. In contrast, the climatic conditions of the eastern slope of the Mongolian Altai became arid because of weakening of the Pacific monsoon after ca 5 ka BP.

Areas of the Russian Altai north and west of the main watershed are now covered by conifers. A climatic optimum for the distribution of dark-coniferous forests with *Abies* occurred approximately 9.5–6.0 ka BP (Blyakharchuk et al., 2004). However, in the southeast of the Russian Altai (the Kurai Basin), the role of steppe communities on the lower mountain levels remained considerable until ca 6.5 ka BP. After ca 6.5 ka BP, Siberian pine and larch forests expanded in the mountains, and steppe vegetation was reduced to intermountain depressions (Blyakharchuk et al., 2008). Pollen records demonstrate that the region experienced two precipitation maxima during the past 12 ka BP (Rudaya et al., 2009). The early Holocene maximum was more pronounced in the eastern part of the region and was associated with a summer monsoon. The late Holocene maximum was influenced by Atlantic air masses, which is in line with the records from Kazakhstan, Baraba and Kulunda. However, the disappearance of forest with *Larix* and *Picea* in the Thuya Basin (the southeastern point of the Russian Altai) after 3.4 ka BP (Schlütz and Lehmkuhl, 2007) is evidence of the irregular distribution of westerly associated moisture during the late Holocene, which was a result of the mountainous landscape.

The pollen records from Lake Big Yarovoe demonstrate that the mid-late Holocene vegetation and the climate dynamics of Kulunda are consistent with the general pattern of Holocene environmental history of the surrounding areas, including those of the Baraba forest-steppe, the Kazakh Upland and the Altai Mountains. The penetration of coniferous forest into the Kulunda steppe after 3.75 ka BP was related to its geographical location on the northwest of the Altai Mountains. The delay of the Kulunda afforestation in comparison with the Kazakh Upland was connected with the local environmental setting, such as the absence of sufficient drainage, small amounts of annual precipitation and high levels of evaporation.

A sharp increase in reconstructed steppe and desert biome is in accordance with higher percentages of *Artemisia* and chenopod pollen after AD 1860 in the Lake Big Yarovoe record; the increase is also consistent with changes in the lacustrine environments reconstructed from diatoms reflecting aridisation. These patterns are in agreement with the general warming trend in the Northern Hemisphere from the middle of the 19th century onwards (Jansen et al., 2007, and references therein). This assumption is for South Siberia confirmed by the high-resolution pollen record from Lake Teletskoye (430 m asl), which is located in the northern part of the Russian Altai (Fig. 7). The climate warming after AD 1840 documented in pollen is consistent with instrumental data from the Barnaul meteorological station (Andreev et al., 2007). However, the desertification and land degradation around Lake Big Yarovoe in the last 200 years may have been caused by various factors, including climatic variation and human activities.

5.2. "Human-environment" interactions in Kulunda during the Middle and Late Holocene

Many well-studied archaeological sites from the Bronze, Iron and Middle Ages are situated in Kulunda (e.g., Tishkin, 2007; Kirushin et al., 2010; Rednikov, 2010). The second half of the Bronze Age corresponds to zone PZ I (~2440–1795 BC; 4.4–3.75 ka BP) and is represented by local human cultures or migrants from north Kazakhstan (Rednikov, 2010). The main archaeological culture of Kulunda and in the whole Ob'-Irtysh interfluve in this period was Elunino (Table 3). The economic activities of the Elunino community were connected with animal breeding (Kosinzev, 2005).

The lower border of zone PZ II (~1795–710 BC; 3.75–2.66 ka BP) corresponds to the end of the early Bronze Age, and the upper limit of zone PZ II corresponds to the onset of the Iron Age. In the 18th century BC, the Andronovo culture, which is associated with the Indo-Iranians and migrants from Central Kazakhstan, spread into the region (Kirushin et al., 2010). A cattle-breeding economy was a distinctive feature of the Andronovo culture. However, a transition to a nomadic lifestyle led to an increase in sheep, goat and horse breeding, which became a characteristic of the late Bronze Age. This trend aligns with the increase in humidity and the development of winter snow cover (in the lower part of zone PZ III). Horses and small animals, such as sheep and goats, can forage under the snow. A new economic type finally established in the early Iron Age and remained until the occupation of the region by Russian migrants at the onset of the 19th century AD (Kirushin et al., 2010).

Afforestation of Kulunda started in the beginning of the Middle Ages (zone PZ IV) and coincided with a substantial population migration (Table 3). During the second half of the first millennium AD, the First and Second Turkic Khaganates were established in Kulunda. From the beginning of the 13th century AD, the Altai was under Mongolian influence. There is no archaeological or literary

Table 3
Humans and environmental events in Kulunda during the Middle and Late Holocene.

Chronology	Pollen zone	Archaeological period or historical event	Environment	Human economic activities
~2440–1795 BC	I	Bronze Age Elunino culture	Semi-desert steppe Birch kolki Dry climate	Animal breeding
~1795–710 BC	II	Bronze Age Onset of Iron Age Andronovo culture	Grass and forb steppes Conifers started to spread More humid climate	Cattle breeding Transition to a nomadic lifestyle Increase of sheep, goat and horse
~710 BC–AD 580	III	Iron Age Early Scythian	Spread of conifers Relatively humid climate	Animal breeding with sheep, goat and horse, which can forage under the snow
After AD 500	IV	First and Second Turkic Khaganates	Maximum of forest distribution and reduction in steppe communities	Nomadic lifestyle
AD 1200–1700		Mongolian Golden Horde	Relatively humid climate	Increase of population
After 1750 AD		Start of Russian colonisation		
After ~1860 AD	V	Settlements of Russian peasants	Sharp decrease in woodland Aridisation	Sedentism of population Development of industry and agriculture

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evidence from Kulunda between the 15th and 16th centuries AD (Tishkin, 2007). Environmental conditions during the Little Ice Age likely caused a southward migration of the population. Mongolian nomads inhabited the territory of Kulunda in 17th and 18th centuries AD. In the middle of the 18th century AD, Kulunda was settled by Russians (Bulygin, 1967).

The most significant population of Russian peasants only started to settle Kulunda in the second half of the 19th century AD (Bulygin, 1967). The pollen data of Lake Big Yarovoe indicate that the forests started to decrease and the open steppe began to spread in Kulunda at this time. Development of industry and agriculture on the border of 19th and 20th centuries AD may also cause deforestation and land degradation of Kulunda in modern time.

6. Conclusions

(1) A reconstruction of the mid-late Holocene vegetation and climate was inferred from the Lake Big Yarovoe pollen record of the Kulunda depression in the steppe zone of southern West Siberia. A relatively warm and dry climate, an open semi-desert and dry steppes with patchy birch forest (kolki) spread between 4.4 and 3.75 ka BP. The largest development of conifer forest started after 3.75 ka BP. The onset of the Late Holocene is characterised by dominance of steppe with birch kolki and pine forests in lowlands and river valleys. After AD 1860, open steppe and semi-desert vegetation with fragmentary birch forest dominated parallel to a sharp reduction of conifers.

(2) The diatom assemblages from Lake Big Yarovoe revealed several stages in the development of the lacustrine ecosystem and the adjacent area. Between 4.4 and 3.96 ka BP, the lake remained shallow and had high water mineralisation. The diatom flora indicates warm climatic conditions. Between 3.96 and 1.92 ka BP, the lake ecosystem underwent shallowing, in which salinity increased and diatoms nearly disappeared. After 1.92 ka BP, the taxonomic composition of diatoms in the lake indicates an increase in lake depth and a decrease in mineralisation. Approximately at 0.09–0.23 ka BP (~AD 1720–1860), the lake underwent another shallowing, which was most likely connected to another period of aridisation and cooling of the climate. After 0.09 ka BP (~AD 1860), the diatom flora indicates warmer climatic conditions, low water levels and highly mineralised water.

(3) These reconstructions are consistent with the general pattern of Holocene environmental history of the surrounding areas, including the Baraba forest-steppe, the Kazakh Upland and the Altai Mountains. After 3.75 ka BP, penetration of coniferous forest into the Kulunda steppe was related to its geographical location northwest of the Altai Mountains.

(4) Economic activities of the ancient population of Kulunda depended on the environmental changes in the Middle and Late Holocene. Industrial development of the territory began after AD 1860 when Russian peasants settled in Kulunda, which coincided with deforestation and the spread of open vegetation.

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Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.quascirev.2012.06.002.

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