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**Main drivers affecting the Holocene sedimentary record –
implications from small lake in Latvia**

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Abstract A multi-indicator paleolimnological study of sediments from Lake Kõõzi (central Latvia) was used to obtain a comprehensive record of environmental changes in the Holocene. Periodicity in the changes and the main drivers (lake basin development, catchment properties, climate, human activities) of the sedimentary record was studied. In order to comprehend the whole-lake sedimentation during the Holocene, a detailed multi-indicator record from the central part of the lake was integrated with records of sediment mass accumulation rates from four cores from different parts of the lake and a GPR (ground-penetrating radar) survey of the lake basin. The observed changes in the sedimentation regime that took place during the early Holocene are strongly linked with variations in climatic conditions, but the catchment and lake basin also played an important role. In the middle Holocene the water level was stable and the lake was influenced by climate mediated through changes in the catchment vegetation. Around 5 000 cal. BP sedimentation pattern changed, and three of the four main drivers made a comparably strong impact on the sedimentary signal. Since 2 000 cal. BP multiple indicators point to a major disturbance clearly related to human activity, which conceals the impact of the natural drivers.

Keywords • sedimentary signal • lake basin • catchment properties • climate • human impact • multi-proxy

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INTRODUCTION

Lacustrine deposits represent one of the most complete stratigraphic records (physical, chemical and biological) that can be used to provide evidence of climate, of vegetation development and of geomorphological as well as hydrological processes. Holocene environmental change in northern Europe has been studied by numerous authors (e.g. von Grafenstein *et al.* 1998; Nesje, Dahl 2001; Heikkilä, Seppä 2010; Shala *et al.* 2014; Whitmore, Riedinger-Whitmore 2014). These studies confirm that the hydrology of the Baltic Region is important for understanding changes in regional climatic regimes. Because of atmospheric circulation and its location in a maritime/continental gradient, the region

is sensitive to fluctuations in climate. Climatic reconstructions based on pollen (Seppä, Poska 2004; Heikkilä, Seppä 2010) have revealed a pronounced climate variability over the Holocene. They suggest a decrease in summer temperature in Estonia and Latvia up to 2°C at 8 600–8 000 cal. BP. Following the Holocene thermal maximum (HTM), which is described as occurring in Estonia between 8 000 and 4 000 cal. BP (Seppä, Poska 2004) and in Latvia between 8 000 and 4 500 cal. BP (Heikkilä, Seppä 2010), after that the climate became again cooler (Seppä *et al.* 2009).

Climatic conditions are often considered as the most important factor influencing the ontogeny of lakes and their water levels as well as the surrounding landscape. Yet, studies of the fluctuations in lake water

levels in the Baltic region (Latvia, Estonia and Belarus; Saarse, Harrison 1992; Koff *et al.* 2005; Punning *et al.* 2005; Novik *et al.* 2010) have shown different patterns in water level fluctuation. During the Late Glacial and Early Holocene, some common patterns in lake level fluctuation were detected, whereas during the latter half of the Holocene, the changes in water level were generally asynchronous. There is some evidence that the influence of climate decreased with time, and that the geochemical and lithological variations in sediment composition were caused primarily by other local factors (e.g. morphological structure of the catchment area, genesis and shape of the lake depressions, intensity of the water cycle, and position of the subsoil water level; Fritz 2003; Shala *et al.* 2014; Drzymulska *et al.* 2014; Bešta *et al.* 2015). However, the reasons for the increased variability in the changes in water level have not been fully identified. Therefore, in order to discern the links between lake water levels and climate and other environmental controls, we need more studies that take into account the role of the topography of a lake basin and the changes in sedimentation dynamics (Håkanson, Jansson 1983; Rowan *et al.* 1992; Terasmaa 2005; Engstrom, Rose 2013), as well as the lake-catchment dynamics (Kangur 2009; Puusepp, Kangur 2010), catchment vegetation (Vainu, Terasmaa 2014) and lake hydrodynamics (Terasmaa, Punning 2006). An increasing number of studies show that integration of palaeoecological records of terrestrial and aquatic biota together with lithology and geochemistry from multiple cores gives a wider perspective that enables a more detailed assessment of changes in past environmental conditions. In the most recent developments in paleolimnological studies (Birks, Birks 2006; Bjerring *et al.* 2013; Terasmaa *et al.* 2013; Whitmore, Riedinger-Whitmore 2014), the method of using set of multiple indicators is considered especially important for a reliable reconstruction. The existences of coincident boundaries that are associated with different variables indicate substantial changes in one or more environmental factors, while the existence of zone boundaries that do not coincide with some proxies may be the result of events that are important only for one particular variable (Lotter, Birks 2003). Using only one single indicator to reconstruct changes in different aspects of a paleoenvironment can lead to incorrect conclusions. It has been pointed out by Telford and Birks (2011) that different reconstructions based on one paleoindicator should be interpreted and viewed as multiple alternatives that do not contain unique information for every detectable change.

In this study, we focus on the Holocene sedimentary record using such variables as lithological composition, geochemistry, diatoms, pollen and macrofossils in a small lake in the humid temperate zone of Latvia. The principal aim of the study is to define the

main drivers affecting the sedimentary signal and analyse their contribution to the periodicity. To achieve this aim we used a multiple-core and multi-indicator approach. In order to understand lake sedimentation over the entire lake during the Holocene, we integrated records of sediment mass accumulation rates from four cores taken along the longitudinal axis of the lake. The main core from the depocenter of the lake was used for detailed multi-indicator record. The collection of these multiple dataset allowed us to distinguish the different influences, define the main phases of stability or change and connect regional and local control factors with responses in the lake environment.

STUDY SITE

Lake Ķūži (hereafter L. Ķūži) is located in Latvia in the Piebalga hilly area of the Vidzeme Heights (57°2'N and 25°20'E; absolute height 191.5 m a.s.l.) (Fig. 1). The topography of the Vidzeme Heights is complex, and is dominated by subglacial landforms. The elevation of the area varies from 180 to 240 m a.s.l. Lake Ķūži is glaciokarstic in origin. As a result of the undulating topography, the soils of the region are extremely varied, being dominated by podzols, which are being intensively eroded on cultivated slopes (Āboltiņš 1997). Only 25% of the Vidzeme Heights are covered with forest, with the largest part (50%) being spruce. The remainder of the area is mostly cultivated.

Climate in the region is moist (mean annual precipitation ~800 mm), of which 550 mm falls during the summer and 250 mm during the winter. The mean monthly temperatures are -7.5 °C in January and 16.5 °C in June. The growing period is 175–185 days. The area is normally covered with snow from November to April, the frost-free period lasts for 120 days (Āboltiņš 1997).

Lake Ķūži covers an area of 6.3 ha (maximum length 380 m, width 210 m, maximum depth 8 m, average depth 3.7 m and average slope inclination 5.8%) and allows the passage of an artificially created, limited flow of water. The volume of the lake is 240 000 m³ and its mean residence time is 0.6 years. The 1.55 km² catchment is covered with forest to the east and west of the lake, while meadows and agricultural land are found to its north and south. Clearly visible a 2 m high terrace surrounds the lake. The lake is located in an undulating landscape and is bordered to the NW by a peaty area that has a width of up to 100 m (Fig. 1B).

Although there is no direct archaeological evidence for human habitation near L. Ķūži, the crop cultivation in Latvia can be traced to about 6 000 years ago (Ozola *et al.* 2010). This is indicated not solely by the presence of cereal pollen, but is also supported by evidence from archaeological finds. According to Vasks *et al.* (1999), farming became the dominant form of

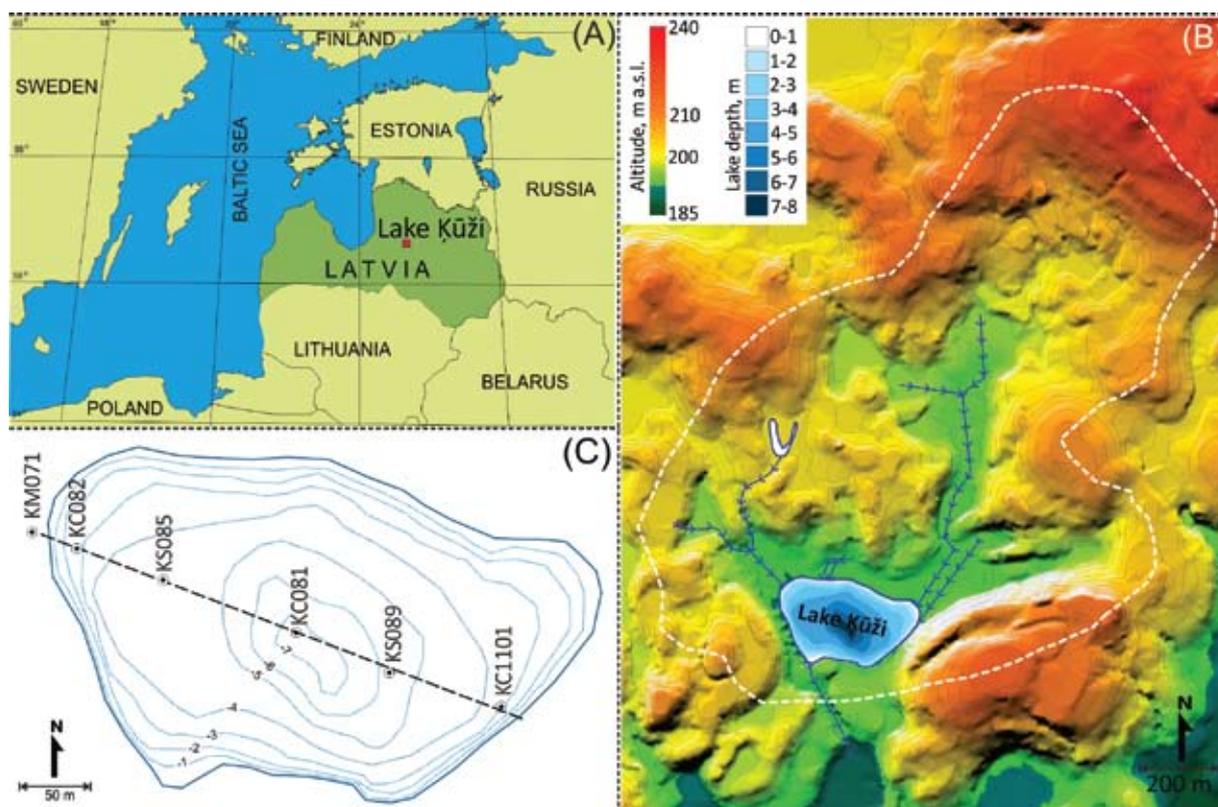


Fig. 1 (A) Location of the study site, (B) topography and the location of the Lake Ķūži, (C) bathymetry and coring sites. Compiled by J. Terasmaa.

economy in Latvia in the middle of the Bronze Age (ca 3 000 cal BP). Significant changes in the terrestrial environment induced by human activity as indicated from palynological data appear only in the last two millennia (Stivrins *et al.* 2014).

METHODS

Fieldwork

Coring was carried out on a profile along the longitudinal axis of the lake (Fig. 1C and 2). The main (KC081) and an additional core (KC082) used in this study were obtained from a raft during the summer of 2008, same time the piston corer was used to determine the topography of the bottom of the lake and the lithostratigraphy of the sediment (KS085, KS089). Core KC1101 was obtained through ice during the winter of 2011. Core from the surrounding mire (KM071) was obtained in the summer of 2007. The upper unconsolidated sediments (80 cm) were sampled using a modified Livingstone–Valentyne piston corer, divided into 2 cm sections and packed into PVC boxes. The lower sediments of each core were sampled using a Belarus (Russian) peat sampler, described and photographed in the field, and then packed into bisected tubes for transportation. The lake basin was mapped from the ice with ground-penetrating radar (GPR) Sir-3000 (100 MHz frequency). The GPR profiles were verified and calibrated with additional coring.

Sediment chronology

The chronology of the sediment cores was determined using 19 AMS ^{14}C dates obtained from terrestrial macrofossils (Table 1). The samples were analysed in the Poznan Radiocarbon dating laboratory, Poland. The radiocarbon calibration program OxCal v4.1.3 and IntCal09 dataset (Bronk Ramsey 2009; Reimer *et al.* 2009) were used for the calibration. The age-depth model is based on linear interpolation between calibrated radiocarbon dates.

Sedimentological indicators

Core KC081 was sectioned into 2 cm intervals. Dry matter content in the sediment was determined by drying the samples at 105 °C. The organic content was estimated from the loss-on-ignition (LOI) after heating the samples at 550 °C for 3.5 h. The CaCO_3 content was calculated from the loss of weight after heating at 950 °C for 2.5 h. The methodology and calculations followed the standard methods (Boyle 2001; Heiri *et al.* 2001). Based on LOI data and AMS dates, mass accumulation rates (MAR) of dry matter was calculated for four dated cores. MAR was expressed as a mean value ($\text{g m}^{-2} \text{yr}^{-1}$) for each of the dated period.

The distribution of grain-sizes in core KC081 were obtained from 90 pre-treated sediment samples. All the chemical reactions were carried out in a standard 1 litre beaker using a hot plate (Konert, Vandenberghe

Table 1. Radiocarbon dates obtained from Lake Kūži, showing sample depths, type of dated material, laboratory number, ¹⁴C age BP and ¹⁴C-calibrated age BP. The dates were calibrated using IntCal09 (Reimer *et al.* 2009) in OxCal v4.1.3 (Bronk Ramsey 2009)

	Depth, cm	Dated material	Laboratory number	¹⁴ C date, yr BP	Calibrated age (mid intercept cal yr BP)
KC081	260–265	<i>Picea</i> seeds	Poz-26181	2 508±30	2 714
	365–370	<i>Picea</i> needle, <i>Betula</i> fruits, <i>Salix</i> remains	Poz-26182	4 553±35	5 034
	460–465	<i>Betula</i> fruits, <i>Picea</i> seeds	Poz-26184	5 257±40	6 030
	660–665	<i>Betula</i> fruits, <i>Alnus</i> fruits	Poz-26185	7 123±60	8 123
	860–865	Wood remains	Poz-26186	9 891±60	11 268
KC1101	441–443	Plant remains	Poz-42184	2 010±40	1 990
	532–533	Plant remains	Poz-42185	4 420±35	5 070
	585–587	Plant remains	Poz-42187	5 310±40	6 080
	691–692	Plant remains	Poz-42188	7 250±70	8 070
	725–727	<i>Sphagnum</i> moss stems	Poz-42189	8 400±50	9 410
	794–795	<i>Betula</i> and <i>Pinus</i> seeds	Poz-42190	9 200±60	10 380
KC082	98	<i>Pinus</i> seed coat and needle remains	Poz-30576	3 810±50	4 400
	168	<i>Pinus</i> twig	Poz-30577	5 670±50	6 230
	268	<i>Salix</i> twig	Poz-30579	7 960±50	8 970
KM071	190	Plant remains	Poz-23170	925±30	850
	269	Plant remains	Poz-23171	2 825±35	2 920
	345	Plant remains	Poz-23172	6 240±50	7 140
	490	Plant remains	Poz-23174	8 030±50	8 900
	625	Wood remains	Poz-23175	9 810±60	11 230

1997). Concentrated H₂O₂ (30%; Mikutta *et al.* 2005) was used to remove organic matter. Carbonates were removed using 10% HCl (Lu, An 1997). In order to avoid flocculation prior to analysis by a laser particle sizer, a 1% solution of (NaPO₃)₆ and ultrasonic agitation was used (Vaasma 2008). The grain-size spectra were obtained using a Fritsch Laser Particle Sizer “Analysette 22” (measuring range 0.3–300 μm). The results of the grain-size analyses are presented according to the Udden-Wentworth scale (Last 2001).

Computerised axial tomography (CAT) was used for measuring sediment density. Core KC081 was scanned using a Somatom Definition (Siemens) at the Tallinn Diagnostic Centre Ltd. The software *eFilm Light 3.0* and *OSIRIS* were used to measure the tomographic intensity; CAT scan results are expressed in CT numbers in Hounsfield units (HU) (Hounsfield 1973). Spatial resolution of scans (2 mm) was reduced by smoothing to 2 cm.

Bulk geochemical composition of sediment was analysed by X-ray fluorescence spectrometry, following methods described by Boyle (2000). Analyses were carried out using the energy dispersive XRF analyser - *Bruker Axs S2 Ranger* at the Department of Geography of the University of Liverpool, UK.

The total content of organic carbon and nitrogen were measured, using a Perkin-Elmer 2400 Series II CHNS/O Elemental Analyser at the University of

Tartu, Estonia. The values were calculated as a percentage of dry matter.

Biological indicators

Diatom samples from every 10 cm were prepared using 30% H₂O₂ and 10% HCl (Battarbee *et al.* 2001). At least 500 valves were counted per sample and the abundance of diatom species was expressed in terms of a percentage of the sum of all diatoms counted in each sample and concentrations as frustules per mass of oven-dried sediment. These were calibrated by adding a known quantity of microspheres to the samples (Battarbee, Kneen 1982). The identification and nomenclature of the diatoms were mainly based on the work of Krammer, Lange-Bertalot (1988–1991, 1999–2004).

Preparation of pollen samples (1 cm³ block samples from every 10 cm) followed a standard acetolysis method according to Moore *et al.* (1991). Three tablets containing a known number of *Lycopodium* spores were added to each sample at the beginning of the treatment, thus enabling the calculation of pollen concentrations and accumulation rates (Stockmarr 1971). Generally all pollen grains and spores were counted to at least 500 arboreal pollen (AP) grains and at least 100 *Lycopodium* spores per sample. Pollen and spore nomenclature follows Moore *et al.* (1991).

For macrofossil analysis, samples of 100 cm³ were collected after every 10 cm and washed with water

through a sieve with a mesh of 250 μm . The residues were examined on a white plate under a stereomicroscope. Seeds, fruits and other remains were counted and identified with the aid of reference collections and descriptive manuals (Birks 1980; Cappiers *et al.* 2006). The results were expressed in terms of the number of macrofossils per 100 cm^3 of wet sediment.

Numerical methods

In order to calculate the compositional turnover of the data obtained, the stratigraphical data (diatoms, pollen, macrofossils, geochemistry and grain-size) from the core KC081 were analysed using the multivariate ordination techniques of the program Canoco 4.5 for Windows. The use of detrended correspondence analysis (DCA) revealed that all the datasets fell within 2 S.D. units, so we carried out principal component analysis (PCA; Birks 1995). Because of different numerical properties of the data sets, the data were individually transformed. A square root transformation was applied to the diatom, pollen and

grain-size data, and a log transform was applied to the macrofossil data. The geochemical data were centred and standardised to avoid skewed distributions and to stabilise their variances.

RESULTS

Geomorphology and sediment accumulation

The GPR survey of the Lake $\text{K}\ddot{\text{u}}\text{z}\ddot{\text{i}}$ revealed that the lake has two sub-basins (Fig. 2A). The smaller sub-basin is nowadays in-filled with lacustrine sediments and does not show in a conventional hydrographical survey. The ridge that separates these two sub-basins crosses the lake in the north-south direction and follows partly the topography of the surrounding landscape (Fig. 1B). Because of sediment focusing, the sediment layer is thickest in the central part of the lake.

The lithology of the sediment cores is based on visual description in the field and on photographs (Fig. 2A). The lowermost parts of all cores contain

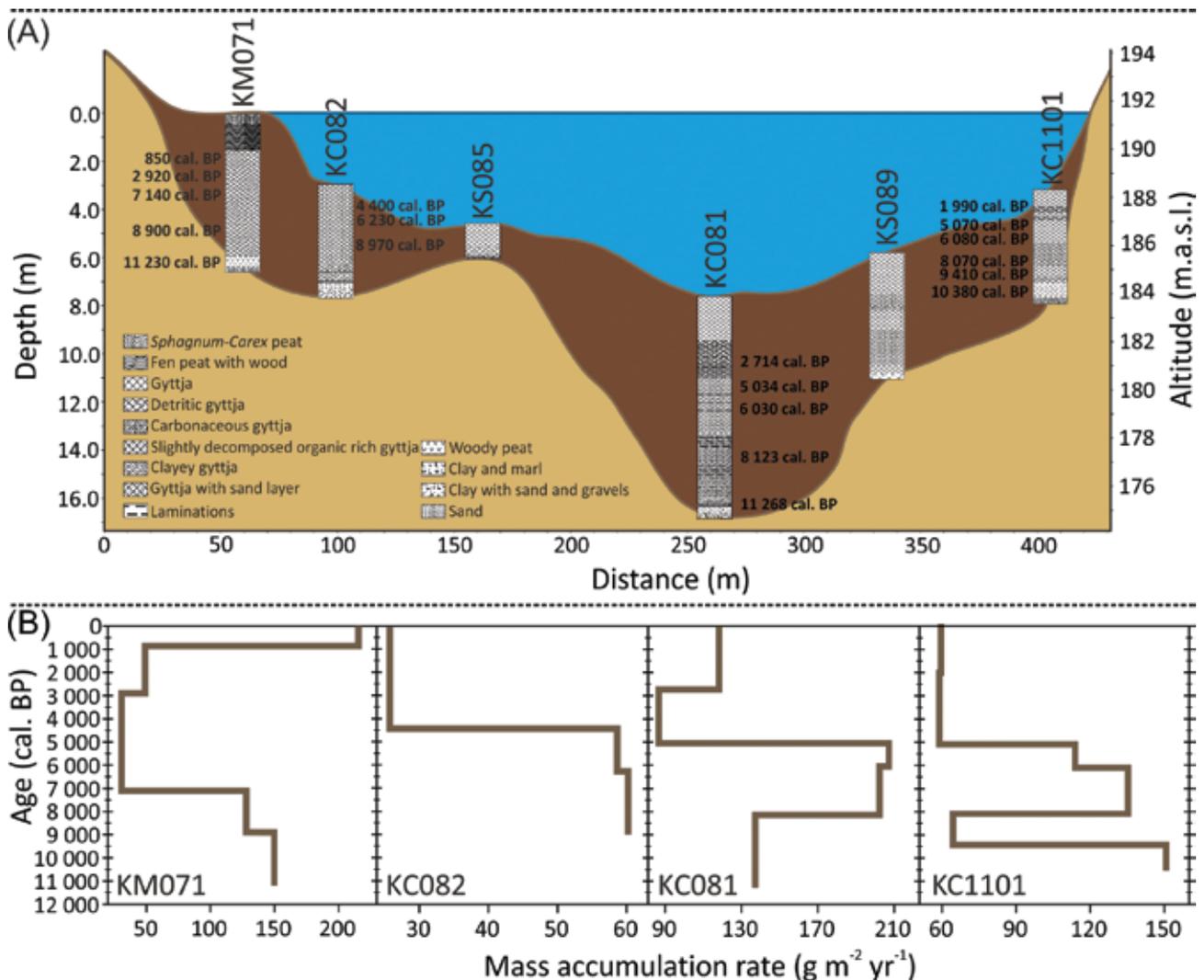


Fig. 2 (A) Cross section of the basin of Lake $\text{K}\ddot{\text{u}}\text{z}\ddot{\text{i}}$ with lithostratigraphy and calibrated dates. Mineral basin is revealed with the help of GPR survey. (B) Mass accumulation rates of dated cores. Compiled by J. Terasmaa, A. Marzecová, E. Vandel.

gravel and sand with silt and clay fractions, covered with a thin layer of peat and followed by gyttja. The central parts of the core KC081 and KC1101 consists of laminated carbonaceous, dark brown detritic gyttja with clay content. The upper parts of sediment cores consist of homogeneous gyttja with no abrupt transitions. The exception is slightly decomposed fen peat covered with *Sphagnum-Carex* peat in the topmost 1.5 m part of core KM071.

The mass accumulation rate (MAR), varies from 26 to 207 g m⁻² yr⁻¹. The lowest MAR values were detected in core KC082 (mean value 48 g m⁻² yr⁻¹) whereas the highest values are in core KC081 (mean value 150 g m⁻² yr⁻¹). The changes in MAR are similar in cores KC081 and KC1101, which are located in the main sedimentation basin. MAR increases during the Middle Holocene (ca 8 000–5 000 cal. BP) and reduces thereafter until ca 2 600 cal. BP, when it increases again (Fig. 2B). MAR changes in core KM071 are almost asynchronous with other cores - very low accumulation in the middle part and high values in the upper part. In their lower parts, cores KM071 and KC082 had some similarities, but the timing was different. Nowadays the location of core KM071 is in the mire, but it has always been a rather shallow and nearshore area.

Sedimentological indicators

The detailed multi-indicator analysis was performed on core KC081 from the deepest part of the lake. Results from the core KM071 are described by Kangur *et al.* (2009). The results of LOI analyses and the CAT scans were compared with changes in grain-size and in several major and trace elements concentrations. The lithology of KC081 is shown in Fig. 2A and selected profiles of lithological variables and chemical elements or their ratios are given in Fig. 3A.

The bottom sediments (920–865 cm; before 11 300 cal. BP), were minerogenic with high concentrations of conservative elements such as Zr (expressed as Zr/Ti ratio) and low water content. The organic sedimentation began at ca. 11 300 cal. BP. The change in sedimentation can be seen in the CAT scan. There was a peak in the sand fraction ca. 850 cm (11 000 cal. BP). From 865–730 cm (up to 9 200 cal. BP), the lithological and geochemical records show pronounced short-term fluctuations. The content of CaCO₃ varied from 2–29%. Between 840–770 cm (10 900 and 9 800 cal. BP), the sand fraction was absent in the grain-size distribution but the content of medium silt was stable. The median grain-size showed a similar trend, showing a temporal peak around 840 cm (10,900 cal. BP). Overall, the period between ca 850–690 cm (11 000–8 500 cal. BP) was characterised by an increased ratio of bromine (Br) to LOI₅₅₀ (Br/LOI₅₅₀) and a

marked variation in redox-sensitive metals (Fe and Mn) as well as sulphur (S) and phosphorus (P). The increase occurred first in the profiles of Fe, S and Fe/Mn ratio. Then, a temporary decrease in S values was followed by an interval with high concentrations of Fe, Mn, S and P but low Fe/Mn ratio (10 000–8 500 cal. BP). In addition, sediments between 740–690 cm (9 300–8 500 cal. BP) are characterised by two peaks – the peak in grain-size distribution (coarse silt) occurring at 730 cm (9 200 cal. BP) and the peak in the organic matter content occurring at 710 cm (8 900 cal. BP). At the same time, the concentrations of Ti and Zr reached their minimum values in the core at about 690 cm (8 500 cal. BP).

At ca. 640 cm (7 900 cal. BP) the grain-size data showed an increase in the clay fraction and a disappearance of the sand fraction while the geochemical data showed an increase in concentration of Ti and high Fe/Mn ratios. Between 640–220 cm (7 900–2 300 cal. BP) the majority of lithological and geochemical indicators stabilised and remained constant. Laminations (Fig. 2A), which in the lower part of the core occurred episodically, were continuous between 360 and 198 cm (4 900–2 000 cal. BP). Nevertheless, during this period of relative stability, several peaks in lithology occurred. The ratio of mineral to organic matter peaked at ca. 354 cm (4 700 cal. BP). Punning *et al.* (2004) demonstrated that this ratio is useful for indicating periods of stability (low value) and instability (high value) in the sedimentary regime of a lake.

Between 220 and 100 cm (2 300–1 000 cal. BP), the sediment was less minerogenic but coarse-grained (Fig. 3A). The content of clay fraction was low and the ratio of mineral to organic matter decreased. The geochemical record was characterised by a decrease in Fe/Mn ratio, low concentrations of Ti and a moderate peak in the ratio of Zr/Ti. In contrast, Si/Al ratio showed a temporary but pronounced increase during this period. Among the trace metals, only Pb showed clear enrichment with two distinctive peaks at 200 and 100 cm (2 100 and 1 000 cal. BP). Between 100 cm and 0 cm, the content of mineral matter increased and fine-grained sediment became predominant. The content of CaCO₃ showed a clear peak at a depth of 170–174 cm (~1 800 cal. BP).

Biological indicators

The samples obtained from the Holocene sedimentary sequence of L. Kūži were generally rich in well-preserved remains of biological indicators (pollen, diatoms, macrofossils). The exception are the samples obtained from the deepest part of the core from 920–860 cm (before 11 200 cal. BP) (Fig. 3). The interval between 860–690 cm (11 200–8 500 cal. BP) contained a large amount of *Betula* and *Pi-*

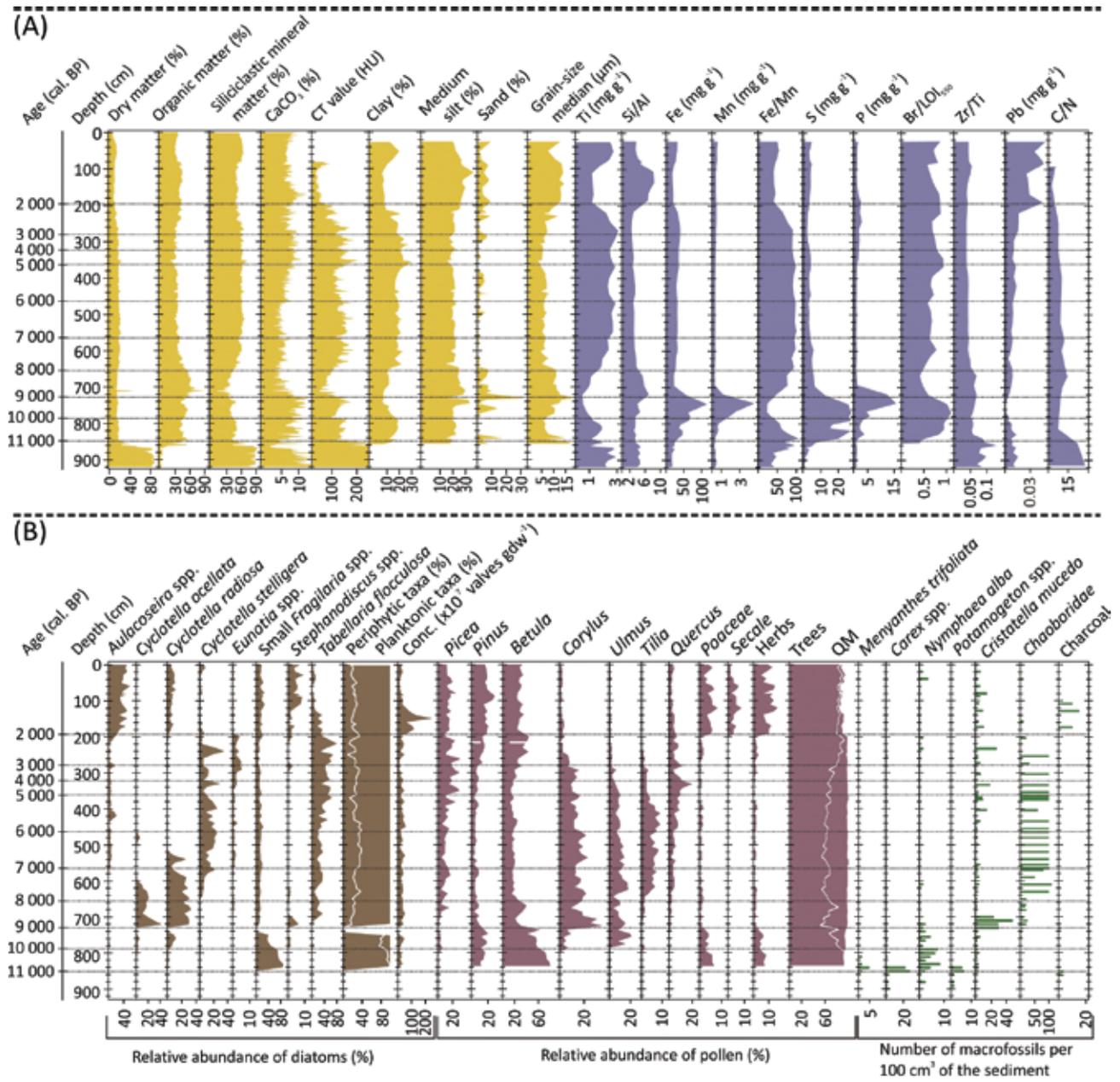


Fig. 3 Lake Kūži sediment core KC081 (A) lithology, grain-size distribution and total concentrations of selected chemical elements and elemental ratios and (B) the relevant diatom and pollen taxa and macrofossils. Dotted lines show calibrated age (BP) at intervals of 1 000 years. Types of counted macrofossils: *Menyanthes trifoliata* - seeds; *Carex* spp. - seeds; *Nymphaea alba* - seed fragments; *Potamogeton* spp. - seeds; *Cristatella mucedo* - statoblasts; Chaoboridae - respiratory horns. Because of some very high values in the lower part of the core, the x-axis is adjusted for some indicators (CaCO₃, CT value). Compiled by J. Terasmaa, L. Puusepp, E. Vandel, A. Marzecová, T. Koff, T. Vaasma, M. Kangur.

nus pollen. High percentages of pollen of herbs and spores of Bryophyta were registered. The beginning of the period (860–840 cm) is dominated by fossil *Betula* seeds, catkin scales and *Carex* seeds, but also seeds of *Menyanthes trifoliata*, *Nymphaea alba* and *Potamogeton* spp. are present in small numbers.

Between 840 and 720 cm (10 900–9 000 cal. BP) *Nymphaea alba* seed fragments dominated among plant macrofossils. Bryozoa *Cristatella mucedo* statoblasts first appeared from 850 cm and were most

abundant in the interval between 740–690 cm (9 300–8 500 cal. BP). Respiratory horns of Chaoboridae (phantom midges) first appeared at 760 cm (9 600 cal. BP) and increased rapidly in numbers. Diatoms first appear abundantly at 850 cm (11 100 cal. BP) and are dominated by periphytic taxa (over 80%; mainly small species of *Fragilaria* and *Achnanthes*). There were no diatoms in the samples obtained from depths of 740 and 730 cm (9 300–9 200 cal. BP) but they reappeared at 720 cm (9 000 cal. BP).

At a depth of 690 cm (8 500 cal. BP) the percentage of *Betula* pollen decreases and the first appearance of *Corylus* and *Ulmus* pollen grains occurs; small quantities of *Tilia* and *Quercus* pollen are also found. Pollen composition changed notably between 385 and 255 cm (5 200–2 600 cal. BP) with an increase of *Picea* pollen, which reaches its maximum postglacial abundance (32%). The proportions of *Alnus*, *Corylus*, *Ulmus*, and *Tilia* pollen grains decrease slightly. From 690 cm (8 500 cal. BP), the most frequent plant macrofossils were a few *Picea* spp., *Betula* spp. and *Salix* spp. remains. *Cristatella mucedo* statoblasts were initially found in low numbers but their abundance slightly increased at 400 cm (5 400 cal. BP). The period from 630 cm to 254 cm (7 800–2 600 cal. BP) was dominated by a large number of respiratory horns of Chaoboridae. Since 9000 cal. BP planktonic diatom taxa were dominant, mainly as a result of the abundance of *Tabellaria flocculosa* and *Cyclotella* species. The interval from 410 to 195 cm (5 500–2 000 cal. BP) was characterised by an increase of the acidophilic periphytic diatom *Eunotia* taxa.

From 195 cm (2 000 cal. BP) the pollen data are dominated by *Betula* and is characterized by a decline in *Picea* and *Corylus* pollen and an increase in *Pinus* pollen. In addition, the occurrence of terrestrial herbs, mainly *Poaceae* and *Secale* was registered. The number of macrofossils, including Chaoboridae, sharply declined, and several charcoal-rich layers were present. At the same time the proportion of *Tabellaria* spp. began to decrease among diatoms, and the more eutrophic *Aulacoseira* spp. (mostly *A. ambigua*) dominated, its percentage rising to 30%. Small *Cyclostephanos dubius*, *Cyclotella radiososa* and *Stephanodiscus* spp. also appeared.

Numerical analysis

The application of principal component analysis (PCA) to each data set allowed us to reduce the data variability and explore the major patterns of change. The amount of variance explained by the PCA axis 1

and PCA axis 2 are presented in Table 2. The variations among the first PCA axes is compared to each other in Fig. 4A to show the main zones of change in the sedimentary record.

DISCUSSION

General pattern of changes and main drivers

The results of current multi-core and multi-indicator research combined with previous studies (Kangur *et al.* 2009; Puusepp, Kangur 2010; Terasmaa *et al.* 2013) have allowed the determination of the main stages in the development of the L. Ҷӯзи (Fig. 3 and 4A).

A combined usage of different, at least partly independent variables (e.g. biological proxies versus grain-size, aquatic versus terrestrial flora) and thorough analysis of all available data allowed us to generalize the interpretation of sedimentary signals and to assess the main drivers of the lake development during the Holocene (Fig. 4B). The discussion is focused on the most pronounced patterns that were synchronous in the majority of indicators (Fig. 4A). The earliest switch (the change in PCA Axis 1 scores from negative to positive values) was detected in macrofossil data (9 500 cal. BP). This change was followed by pollen (9 000 cal. BP), grain-size and geochemistry (8 000 cal. BP) as well as diatoms (7 500 cal. BP). The next substantial change in all indicators started with a shift in pollen (3 000 cal. BP) closely followed by grain-size (2 500 cal. BP) and then by all other variables (2 000 cal. BP).

The evidence from previous studies (Kangur *et al.* 2009; Puusepp, Kangur 2010; Terasmaa *et al.* 2013) indicates that water level in L. Ҷӯзи has been relatively stable during the most of the Holocene. This could be caused by a decrease in the role of climate in controlling the lake's hydrology or by an increase in the importance of indirect or local factors. Therefore, we focus on the whole-lake sedimentation patterns and the differentiation among the relative influences of the local and regional factors.

Table 2. PCA eigenvalues, variances explained by the PCA axes and variables that influence Axis 1 scores

Proxy	Eigenvalue 1 (λ)	Eigenvalue 2 (λ)	Axis 1 (%)	Axis 2 (%)	Variables which strongly influence positive Axis 1 scores	Variables which strongly influence negative Axis 1 scores
Grain size	0.724	0.166	72.4	89.1	Very fine sand, very coarse silt	Very fine silt, clay
Geo-chemistry	0.439	0.243	43.9	68.2	S, P, Mn	Ti, Al, Ce
Diatoms	0.303	0.238	30.3	54.2	<i>Cyclotella radiososa</i> , <i>C. ocellata</i> and periphytic <i>Fragilaria</i> spp.	<i>Tabellaria flocculosa</i> , <i>Cyclotella stelligera</i> , <i>Eunotia</i> spp.
Pollen	0.564	0.236	56.4	80.0	<i>Betula</i> , <i>Poaceae</i> , <i>Pinus</i>	<i>Corylus</i> , <i>Tilia</i> , <i>Alnus</i>
Macro-fossils	0.415	0.169	41.5	58.4	Chaoboridae, <i>Cladocera</i> , <i>Salix</i>	<i>Carex</i> seeds, <i>Nymphaea</i> seeds, <i>Potamogeton</i> spp.

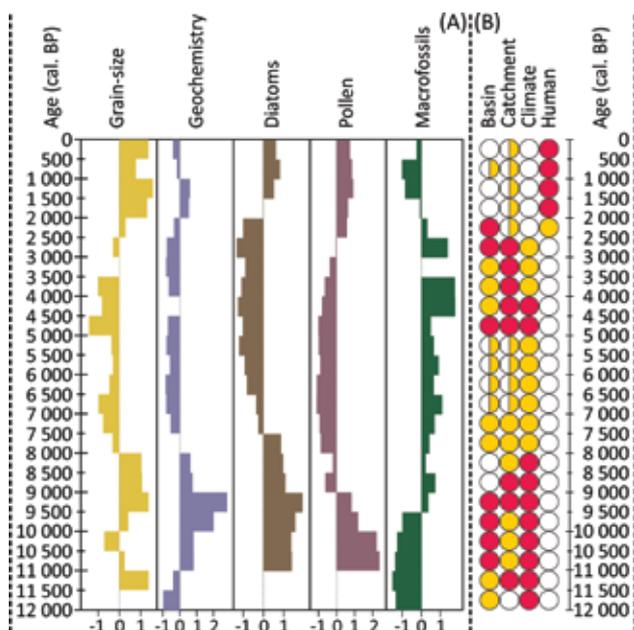


Fig. 4 Summary of main changes in Holocene sedimentary history. (A) Results of PCA showing axis 1 sample scores for grain-size, geochemistry, diatoms, pollen and macrofossils throughout the Holocene averaged on 500 yr time-window (age in cal. BP). (B) Impact of main drivers affecting the sedimentary signal based on qualitative interpretation of indicators. The points indicate different levels of impact: no detectable impact (*white*), moderate impact (*yellow*), strong impact (*red*). A combined color indicates that impact of the certain driver on the sedimentary signal was mediated by another control mechanism (e.g. human influence is mediated through changes in catchment). Compiled by J. Terasmaa, L. Puusepp, E. Vandel, T. Koff, T. Vaasma.

Lake basin development

According to the findings from the main core (KC081), the water level changed and lake volume varied in L. Kūži most markedly at the beginning of the Holocene (ca 11 200–9 000 cal. BP). When the lake was formed, minerogenic sedimentation was the dominant process, as indicated by the high sediment density and low organic content (<2%). The organogenic sedimentation began with the formation of a peat layer at 11 300 cal. BP (Fig. 2A). Peat layers with similar ^{14}C ages were also found in the bottom of other cores, although, at present, these layers are situated at different absolute altitudes (Fig. 2A). As suggested by Terasmaa *et al.* (2013), the peat layer formed due to a block of dead ice covered with sediment and meltwater that allowed the growth of mosses and herbaceous plants. The new whole-basin sedimentation model based on the GPR survey supports the earlier reconstruction. It indicates that with the melting and break-up of the ice block, a lake with two sub-basins was formed, starting the lacustrine sedimentation. These processes coincided with an increase in the lake depth, moving the basal peat layers to the bottom of the lake basin.

Between 11 200–10 500 cal. BP, the large number and variety of macrofossils and the high proportion of coarser sediments reflects an unstable sedimentary environment with possible erosional events, suggesting a shallow depth and fluctuating lake levels. Between 10 000–9 000 cal. BP, the absence of sand and helophyte macrofossils and the disappearance of *Nymphaea* seeds in core KC081 indicates water level rise in L. Kūži (the maximum lake depth around 5 m). During this period, the lake basin achieved its current shape. The sedimentary signal in the period from 9 000 cal. BP to 8 000 cal. BP was not affected by lake basin development, suggesting that other controls were more important (Fig. 5).

The absence of macrofossils of helophytes and floating leaved plants since 8 000 cal. BP suggests stable conditions with high water levels. A variety of indicators, such as the high number of respiratory horns of phantom midge pupae (*Chaoboridae*), the appearance of laminations and the high Fe/Mn ratio, are indicative of the anoxic conditions in the bottom waters (Engstrom, Wright 1984; Zolitschka 2007; Sweetman, Smol 2006; Terasmaa *et al.* 2013). The lake reached its known maximum water depth (up to 11 m) between 8 000 and 7 000 cal. BP, and the lake level became stable. After the stabilisation, lake levels do not seem to have influenced the sedimentary signal until 5 000 cal. BP, although the gradual infilling of the lake basin by sediments continuously decreased the lake depth.

After 5 000 cal. BP, the sedimentary signal in L. Kūži changed and the MAR in the main sub-basin significantly decreased (Fig. 2B). Two possible causes (local and regional) could have occurred, and it is rather difficult to separate the prevalent influence. Due to the configuration of the lake basin, the steep sloped sub-basin became filled with sediments by 5 000 cal. BP (Fig. 2A). The area of accumulation broadened rapidly as a result of shallower slopes and flatter topography. This created a larger area of accumulation, reduced the sediment focusing to the deepest part of the lake and decreased sedimentation rates. During the infilling of a lake basin, deposits were distributed over a continuously increasing area (Terasmaa 2005; Terasmaa 2011). If we assume a constant annual rate of in-lake production, this implies the deposition of a thinner sediment layer each year (Davis, Ford 1982). The regional cause of this change is discussed in the section about the climatic signal.

Between 3 000 cal. BP and 2 000 cal. BP, the density of the sediment decreased, and the grain-size became coarser (increase in medium silt and sand), which is also reflected in the geochemistry (Fig. 3A). The declining trend in Ti profile is likely to have been caused by a decrease in the clay fraction (Boyle 2001). The coarsening in grain-size could possibly in-

dicating a shift in the zone of accumulation area (Punning *et al.* 2006); although the changes could also be caused by the enhanced erosion from the catchment (Oldfield *et al.* 2003). After 2 000 cal. BP, human impact (as discussed later) is the main driver affecting the sedimentary signal with changes in the lake basin appearing through lake level lowering.

Changes in catchment erosion and vegetation pattern

In the beginning of the Holocene the high percentages of dry and mineral matter in the sediment show a significant degree of surface runoff from the surrounding drainage area. The high concentrations of conservative elements (high Zr/Ti ratio), the presence of rock-forming elements (Ca, Mg; data not shown) and the high C/N ratio indicate a supply of coarser, poorly weathered soils from a recently deglaciated catchment (Engstrom, Wright 1984; Oldfield *et al.* 2003; Panizzo *et al.* 2008). After 11 200 cal. BP, organic matter content increased substantially (Fig. 3A) as the terrestrial and aquatic vegetation gradually started to develop. The diatom flora was dominated by periphytic taxa, primarily in the form of *Fragilaria* spp (Fig. 3B). Many such species are usually regarded as being pioneers in the post-glacial period (Bigler *et al.* 2002; Rühland, Smol 2005), which is also often associated with a considerable degree of erosion from the catchment (Ampel *et al.* 2008). The importance of catchment vegetation on the lake water balance of small lakes has been indicated also in hydrological modelling by Vainu, Terasmaa (2014) which showed that difference between forested and unforested catchment area can cause up to an 18% change in the water budget.

The diatom data indicate changes in the lake environment between 9 300–9 200 cal. BP. There were only a few diatom valves in the sediment (Fig. 3B), possibly because of the physical degradation and breaking of frustules during sedimentation caused by interactions with coarse-grained minerogenic matter (Flower 1993; Ryves *et al.* 2006). Due to the catchment topography (Fig. 1B), it is possible that to the north of the lake basin, a dammed body of water filled up with melt water that broke through at some point (ca 9 300 cal. BP) and flowed into L. Kõõzi. The increased flow from catchment area might have caused a washout of waterlogged soils, as suggested by the unusually high abundance of Fe, Mn and S and P (Terasmaa *et al.* 2013). The inflow event is also supported by outcrop studies near the lake (sudden deposition of older deluvial coarse sediments) (Koff, Terasmaa 2011). The increased Br/LOI₅₀ ratio suggests that between 11 000–9 000 cal. BP the lake received an increased proportion of allochthonous organics (Panizzo *et al.* 2008).

The decrease in abundance of diatom species *Fragilaria* spp. simultaneously with changes in the terrestrial vegetation and lithology after 9 000 cal. BP suggest a smaller input of nutrients because the development of the catchment vegetation and decreasing erosion. At the same time the proportion of broad-leaved trees and *Picea* had increased and *Betula* had decreased. Catchment stabilization is the direct result of the gradual immigration of the trees.

The sediment record from 8 000 cal. BP to 5 000 cal. BP is characterized by a stable lake-catchment system (lake with a high water level surrounded by forest) with low perturbation by erosional fluxes.

According to the pollen analyses, spruce became increasingly dominant among the terrestrial vegetation around 5 000 cal. BP (Fig. 3B). After that, the diatom taxa changed in favour of acidophilous (*Eunotia* spp., *Tabellaria flocculosa*; Fig. 3B). It has been suggested that spruce expansion on a lake catchment leads to lake water acidification due to the higher production of humic acids. This affects soil formation processes and through it also influences lake water causing an increase of acidophilous diatom species (Fallu *et al.* 2005; Köster, Pienitz 2006). A positive correlation between acidophilous diatom taxa and *Picea* pollen was also described by Puusepp, Kangur (2010) in L. Kõõzi. These conditions prevailed until ca. 2 000 cal. BP. After 2 000 cal. BP changes in catchment are mainly caused by human impact.

Climatic signal

Around 11 000–10 000 cal. BP, the dominance of periphytic diatoms together with geochemical evidence of near-bottom anoxia (high Fe/Mn ratio) suggests a period of prolonged ice cover that reduced the abundance of planktonic flora and led to oxygen depletion in the bottom of the lake (Smol 1988; Bigler *et al.* 2002). From 10 000 cal. BP to 8 500 cal. BP, a warm and humid climate was confirmed by the rise in the relative abundances of *Ulmus* and *Corylus* pollen and the presence of *Cristatella mucedo* statoblast. *Cristatella mucedo* do not thrive in lakes with low water temperatures (Økland, Økland 2000) and they do not appear before 9 000 cal. BP.

Several authors (Seppä, Poska 2004; Heikkilä, Seppä 2010) have shown that there was a cooler period between ca 8 600–8 000 cal. BP in the region of eastern Latvia, Estonia and southern Finland. Also, the disappearance of warm water species (e.g. *Cristatella mucedo*) in core KC081 points to a colder environment at the beginning of the Middle Holocene (8 500 cal. BP). After 8 000 cal. BP, the climatic signal (increase in broad-leaved tree pollen) suggests warmer conditions and coincides with the Holocene thermal maximum (Renssen *et al.* 2009; Heikkilä, Seppä 2010). The changes in sedimentation

and geochemical patterns in L. Ķūži provide indirect evidence that supports the previous regional climate reconstructions.

Local factors (related to the lake basin) which are possibly responsible for the changes in the sedimentary signals (Fig. 3) and MAR (Fig. 2B) around 5 000 cal. BP, are described in the lake basin development section. The regional factor behind the decrease in MAR can be the short-term climatic cooling associated with lower primary production. The beginning of the cooling trend in Latvia is also described by Heikkilä, Seppä (2010), mostly based on the gradual decline of pollen proportions of *Tilia*, *Corylus*, *Ulmus* and *Alnus* and the expansion of *Picea* after 5 500 cal. BP. From 4 000 cal. BP to 2 500 cal. BP peaks in sediment density and changes in pollen composition (decrease in *Quercus*, *Ulmus* and *Tilia*) are signs of the cold anomalies described between 3 800–3 000 cal. BP by Seppä *et al.* (2009).

Human impact

In Latvia, the lake ecosystems became affected by farming in the Late Bronze and Iron Ages (Vasks *et al.* 1999; Stankevica *et al.* 2015). In L. Ķūži, the pronounced changes occurred in most of the sedimentary indicators around 2 000 cal. BP. The sediment record registers a disappearance of laminations and remains of *Chaoboridae*, an increase in grain-size median as well as decline in Ti concentrations. After 2 000 cal. BP, the relative decrease in tree pollen and the increase in the pollen of herbs (*Poaceae*, *Secale*, and *Rumex*) suggests an onset of agriculture in the lake catchment. The change in the pollen record also coincides with changes in the diatom assemblages. The dominance of *Aulacoseira* spp. (mostly *A. ambigua* and *A. granulata*) suggests higher turbulence and mixing of the water column. The appearance of these heavily silicified diatom species that require turbulence to remain in suspension in the photic zone is often connected with deforestation and increasing cultivated area around the lake, which led to higher wind exposure of the open-water area (Bradbury *et al.* 2002; Andrén *et al.* 2015). The greater exposure of a catchment to wind can lead to an increased input of sand and a higher median grain-size (Fig. 3A). Evidence connected with charcoal fragments found in the upper part of the sediment sequence represent a clear sign of forest clearance by fire. All this suggests notable changes in the L. Ķūži catchment due to the increasing presence of humans. Simultaneously, the decrease in oligo-mesotrophic diatom indicator species (*Tabellaria* spp. and *Cyclotella stelligera*) and their replacement by taxa that live under more eutrophic conditions (*Aulacoseira* spp., *Stephanodiscus* spp., *Cyclostephanos dubius*) as well as the 3.5 times increase in absolute diatom productivity

(reflected also in high Si/Al ratio) indicate a change in lake trophic conditions and an increase in aquatic productivity (Fig. 3). In addition, the step-wise increases in Pb concentrations at ca. 2 100 and 1 000 cal. BP suggest that the sediments of L. Ķūži became influenced by the atmospheric Pb deposition, possibly caused by a spread of lead smelting (Renberg *et al.* 2001).

According to core KM071, obtained from the mire at the edge of L. Ķūži, at around 700 cal. BP the water level was below the surface of the sediment at this location, thereby implying that the water level was up to 1.5 m lower than it is today (Kangur *et al.* 2009). A possible reason for this reduction in water level is given by Terasmaa *et al.* (2013) who interpreted it as evidence for a man-made regulation system for drainage of agricultural land. Grain-size and lithological changes at 100 cm depth in core KC081 support water level lowering. We can assume that a depth of around 100 cm represents an age of around 700 cal. BP. As a result of a smaller area of accumulation and of the reworking of previously accumulated material, the clay and Ti curves both show a recent rapid increase (Fig. 3A). Of course, we must also consider the possibility that some material may have been carried away through outflow from the previously closed lake. During the subsequent decades, the effect of the drainage system diminished and the water level began to rise.

CONCLUSIONS

The multi-indicator sedimentary record of L. Ķūži in central Latvia provides reliable information about the environmental changes that took place in this region of the Baltic. We found that the comparison of a number of independent paleoindicators can significantly improve the accuracy of the interpretation of paleolimnological data. The use of different indicators helps to separate possible coincidental causes of the changes in the sedimentary signals. The GPR survey combined with multi-core analysis was crucial for understanding the formation of lake basin, which was an important driver of sedimentation changes, especially in the early Holocene. Thanks to multi-indicator and multi-core analysis, it was possible to define the major drivers of sedimentation and track the influence of the lake basin (genesis and shape), catchment properties (size and vegetation structure), climate and human activities. Results suggest that the significance of climate, which is widely considered to be the main driver of lake ecosystem changes, lessens over time. The lake basin, catchment properties and anthropogenic impact can during certain periods be more dominant for changes in sedimentary signals than the climate.

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