

RESEARCH ARTICLE

Determining reference conditions of hemiboreal lakes in Latvia, NE Europe: a palaeolimnological approach

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Received: 28 November 2017; Accepted: 7 May 2018

Abstract – The current status of a lake can be evaluated *via* monitoring, but such data can only provide information about the last few decades to a century at best. In most cases, the natural state of a lake cannot be ascertained. This is even more challenging if the apparent anthropogenic effects on the environment over the last millennia are considered. We used data on fossil algae from five evenly distributed hemiboreal lakes in geographically different regions in Latvia, NE Europe to assess the amount of compositional change or turnover (*i.e.*, the beta-diversity) in the algae datasets for the last 2000 years by using a Detrended Canonical Correspondence Analysis. Our results show that the algae turnover increases towards the present day with distinct shifts during times characterised by extensive and intensive agriculture establishment, and political and economic changes. Because the anthropogenic impact on the landscape and lakes before AD 1200 was relatively minor, we propose that algae composition at that time can be assumed to represent the natural reference conditions for most Latvian lakes.

Keywords: Algae / anthropogenic impact / turnover rates

1 Introduction

Water covers most of the world's surface, but only a tiny portion is freshwater that provides critical ecosystem services to humans (Smol, 2008; O'Reilly *et al.*, 2015). Freshwater ecosystems are considered to be among the most threatened on the planet (IPCC, 2014). The impact of climate and anthropogenic activity are two of the most important factors that affect freshwater lakes in the Northern Hemisphere (Douglas and Smol, 1999; Smol *et al.*, 2005). Extensive climate warming over the last few decades has affected the lake water temperatures (Smith *et al.*, 2015). Increasing thermal stratification of the water bodies can lead to blooms of harmful and toxic cyanobacteria (Paerl and Huisman, 2008; De Senerpont Domis *et al.*, 2013; O'Reilly *et al.*, 2015). Human activities that vary temporally and spatially leave even more pronounced footprints in lakes (Bradshaw *et al.*, 2005;

Battarbee and Bennion, 2011; Weckström *et al.*, 2015; Marzecová *et al.*, 2017). Through eutrophication caused by agricultural activity, soil leaching, over nutrient in-washing of sewage, and manure and fertilizer, biotic processes are changing in the lakes and also affect terrestrial ecosystems (Bellinger and Sigee, 2010; Alliksaar and Heinsalu, 2012; Soinen *et al.*, 2015; Steffen *et al.*, 2015; Mikomägi *et al.*, 2016). It is very likely that, due to the increasing stress from urbanisation and agricultural activity, freshwater ecosystems will continue to face changes in biodiversity and productivity (Schiefer *et al.*, 2013; Douglas and James, 2015; Liu *et al.*, 2016).

Establishing the susceptibility and trophic changes in lake ecosystems is an important management issue on a local and regional scale. To assess the degree of damage to a lake ecosystem, it is necessary to compare present-day conditions with natural or reference conditions. Reference conditions represent a lake ecosystem in the absence of significant anthropogenic impact (Smol, 2008). Commonly used lake monitoring data can provide information about lake status for

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the last few decades to a century at best, but in most circumstances, no one can truly reveal the natural state of a lake. This is even more challenging if the apparent anthropogenic effects on the environment over the last millennia are considered. Over the last decade, lake reference conditions were established for many countries, mainly according to the Water Framework Directive of the European Union (EC, 2000; Heinsalu and Alliksaar, 2009a, b; Hering *et al.*, 2010). In this context, a palaeolimnological approach that employs the algae microfossil record (algal remains that preserve in the lake sediments after their death) has been considered as one of the most influential approaches for determining the past lake ecological status (EC, 2000). This approach provides long-term data (centurial to millennial) that is not achievable using standard monitoring programmes. Furthermore, valuable insight can be gained from sparsely sampled time series and well-positioned isolated samples before and after significant biotic or environmental events or transitions. To the best of our knowledge, a palaeolimnological approach, mainly *via* the algae microfossil record, has not been applied to evaluate the status and reference conditions of freshwater hemiboreal lakes in Latvia, northeastern Europe. Hence, the scientifically validated throughput method used in this study can provide an assessment of water quality and establish general reference conditions for hemiboreal lakes.

This study aims to determine a possible timing of reference conditions for hemiboreal lakes in Latvia, NE Europe using a palaeolimnological approach. We used the algae microfossil record from five freshwater lakes that are evenly distributed in geographically different regions in Latvia to evaluate the algae compositional turnover (beta-diversity) over the last 2000 years – a time from minor to intensive anthropogenic pressure on lake ecosystems. Selected statistical method for the current study, such as a Detrended Canonical Correspondence Analysis (DCCA) has been successfully used to evaluate the phytoplankton communities of lakes (*e.g.*, Smol *et al.*, 2005; Weckström *et al.*, 2015), which can be used in assessment of regime shifts and finding the reference conditions.

2 Study area

2.1 History of human impact on the landscape over the last 2000 years

Palaeovegetation records from the study sites indicate a heavily wooded landscape until 500 BC when the first traces of the continuous record of cereal pollen indicate the establishment of agriculture. However, agriculture during the Iron Age was relatively minor and did not dramatically change the surrounding landscape with few exceptions regarding specific dwellings and cultural aspects (Stivrins *et al.*, 2015a). Agricultural practices varied within and between the Baltic region; at least a 4000-year cultivation history is observed close to settlement centres, but agriculture began much later in peripheral areas.

The first most significant changes in the vegetation and environment during the last 2000 years occurred during the Medieval and post-Medieval period roughly at AD 1200–1850. The Medieval period in the Baltic was dominated by the Crusades, a holy war led by the military orders and bishops that conquered modern-day Latvia, Estonia and western Lithuania

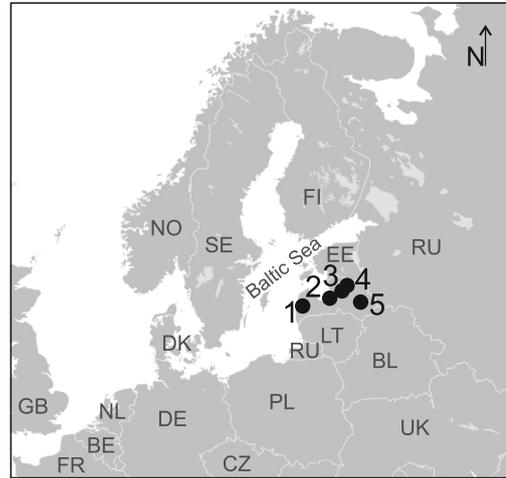


Fig. 1. Location of the study area (Latvia) and the five lakes in the present study: (1) Ķikuru; (2) Lilaste; (3) Āraišu; (4) Trikātas; (5) Lielais Svetiņū.

during the 13th century, with the aim of converting the indigenous pagan tribal societies to Christianity (Brown and Pluskowski, 2014). The conquest of tribal land during the Crusades resulted in changes in the ownership, administration and organisation of the land, and palaeorecords indicate that the landscape changed immediately following the Crusades (Stivrins *et al.*, 2016a), or the century after the Crusades, since the 14th century and later. Overall, this period is characterised by an increase in agriculture and land-use in Latvia that required a vast amount of human labour.

The reduction of the land-use area and a shift from an extensive to an intensive farming economy, which requires less human labour, occurred with the onset of the Industrial Revolution at this region roughly at AD 1850. Industrialization and the accompanying increase in the population density caused increased environmental pressure in many areas due to higher inputs of effluent from industrial and human activity, particularly following construction adjacent to a lake (Stivrins *et al.*, 2016a). Hence, the eastern Baltic has undergone significant social, cultural and economic changes over the last 2000 years from a relatively mute to distinct anthropogenic impact on both the landscape and aquatic ecosystems (Veski *et al.*, 2005; Brown and Pluskowski, 2014; Stivrins *et al.*, 2016a).

2.2 Present environmental conditions, setting and site selection

The study area in Latvia is situated 55–58°N and 20–28°E in northeastern Europe (Fig. 1) in the hemiboreal forest zone, which is characterized by a mixture of hemiboreal coniferous and deciduous tree species such as the Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), birches (*Betula* spp.), alders (*Alnus glutinosa*, *Alnus incana*), mountain elm (*Ulmus glabra*), ash (*Fraxinus excelsior*), lime (*Tilia cordata*) and oak (*Quercus robur*). A combination of a continental (Eurasia) and maritime (Atlantic Ocean) climate is typical for this area and is more continental in the east and more maritime in western Latvia. The average annual air temperature in Latvia is +6°C,

Table 1. Information of the studied lakes.

Lake	Area, ha	Mean/max water depth, m	Elevation m a.s.l.	Coordinates	Related reference
Ķikuru	21.6	2/4.3	38.7	56°48' N; 21°37' E	Stivrins <i>et al.</i> , (2017), but for algae current issue
Lilaste	183.6	2/3.2	0.5	57°10' N; 24°21' E	Grudzinska <i>et al.</i> , (2017)
Āraišu	32.6	4/12.3	120.2	57°15' N; 25°17' E	Stivrins <i>et al.</i> , (2015a)
Trikātas	13	4/4.2	50	57°32' N; 25°42' E	Stivrins <i>et al.</i> , (2016a), but for algae current issue
Lielais Svetiņu	18.8	4/4.3	96.2	56°45' N; 27°08' E	Stivrins <i>et al.</i> , (2015b)

+17°C in July and −4.7°C in January, and the annual precipitation in average reaches 670 mm according to the Ltd. Latvian Environment, Geology and Meteorology Centre data. The present-day topography has primarily been formed as a result of the Weichselian glaciation and the subsequent deglaciation (Zelčs *et al.*, 2011). Overall, Latvia is rather flat with an average altitude of approximately 100 m a.s.l. and the maximum elevation is 312 m a.s.l.

The fossil algae records of the last 2000 years from small to large lakes were selected for the current study (Tab. 1). The selected lakes represent different environmental and geographical localities such as near shore, lowland and upland, which is vital as we determine the overall change in the algal composition of Latvian lakes.

Although our study is based on “one-core data”, it has been assumed as sufficiently representative of trophic state changes of either small or large body of water (Smol, 2008). Smaller lakes’ sediment core records tend to reflect local compositional changes over time, while larger bodies of water might display a uniform picture in general (larger bodies of water experience a broader range of environmental conditions). Responses of communities at large-scale levels are slow and often imprecise, but their ecological relevance is high due to the accumulating effects of disturbances or stresses on the system (Park, 2016). In this context, the advantage of a palaeolimnological approach is that for either a small or a large lake, it indicates conditions that existed before significant anthropogenic effects, which is the primary data necessary to determine the reference conditions or the so-called baseline to compare to the present-day situation.

We used two types of fossil algae remains. In the current study, we use term “diatoms” exclusively for diatoms, but “microscopic Chlorophyta and Cyanophyta” indicates algae other than diatoms. Diatoms are a group of microscopic algae abundant in almost all aquatic habitats that are one of the most common types of phytoplankton. They are unicellular organisms with a silica cell wall. Microscopic Chlorophyta and Cyanophyta have been identified during pollen analysis, and the most common taxa of these groups comprise *Anabaena*, *Aphanizomenon*, *Botryococcus*, *Coelastrum*, *Gloeotrichia*, *Glaucospira*, *Rivularia*, *Pediastrum*, *Staurastrum*, *Scenedesmus* and *Tetraëdron* (Stivrins *et al.*, 2015b). Even though sample preparation methods are different, diatoms and microscopic Chlorophyta and Cyanophyta represent algae living in the lake at the particular time. It is important to note that the algae identified from sediment samples do not reflect the complete taxonomic diversity due to complex taphonomic preservation processes (Stivrins *et al.*, 2018).

Selected sites in the current study are lakes located in geographically different locations. Lake Ķikuru (21.6 ha, 38.7 m a.s.l., max water depth 4.3 m) is located in western Latvia (56°48' N, 21°37' E; Fig. 1). Geologically, the ground consists of Quaternary (Pleistocene) sediments – till and limnoglacial-glaciolacustrine sediments of 4.4–18 m thick. The lake has a flow-through hydrological regime. It is surrounded by open fields and sparse stands of pine and birch (Stivrins *et al.*, 2017). A former dairy is located next to the lake and ejected wastewater into the lake approximately in 1970–1990. The lake is the dystrophic-eutrophic type.

Lake Lilaste (183.6 ha, 0.5 m a.s.l., max water depth 3.2 m) is a drainage lake located on the Coastal Lowland (57°10' N, 24°21' E), approximately 20 km north-east of Riga (the capital of Latvia), and one km east of the Gulf of Riga. Quaternary deposits of 45 m consist of till, glaciolacustrine and marine silt, sand and aeolian sediments. Pine forest and bogs cover the catchment area. Today, treated wastewater from the residential area is discharged into the lake creating anthropogenic stress (Grudzinska *et al.*, 2017). The lake is the mesotrophic-dystrophic type.

Lake Āraišu (32.6 ha, 120.2 m a.s.l., max water depth 12.3 m) is located in central Latvia (57°15' N, 25°17' E), on the western edge of the Vidzeme Upland. The geology is Devonian sandstone overlain by 80 m of till. It has a flow-through hydrological regime. The size of the catchment area is 10 km². An open-air Iron Age lake-dwelling is located in the lake, and a few active and former farms surround the lake. The lake is the eutrophic-hypereutrophic type.

Lake Trikātas (13 ha, 50 m a.s.l., max water depth 6.5 m) is situated in northern Latvia (57°32' N, 25°42' E), in the northern Vidzeme lowland. The lake is located in a 25-m deep valley with an outflow connected to the River Abuls. Quaternary glacial till and alluvial deposits in the Trikātas area overlie Devonian sandstone bedrock. The surrounding landscape comprises a mixture of cultivated land and pasture overlaying sandy and podzolic soils. A former distillery, a dairy, and a working primary school are located next to the lake. The lake is the eutrophic-hypereutrophic type.

Lake Lielais Svetiņu (18.8 ha, 96.2 m a.s.l., max water depth 4.9 m) is located in eastern Latvia (56°46' N, 27°08' E), in the Eastern Latvian Lowland. The bedrock consists of Devonian dolomite covered by Quaternary deposits with a thickness of 5–10 m consisting of sand, silt and clay. Lake Lielais Svetiņu is a drainage lake with a catchment of 12 km², which is predominantly forested but also partly covered by fields. The lake is the mesotrophic-dystrophic type.

3 Materials and methods

3.1 Fieldworks

Fieldworks to obtain the gyttja sediment from the lakes were conducted from the ice-covered surface in Lake Lielais Svetiņu on March 2009, in Lake Trikātas on March 2012, in Lake Āraišu on March 2012, in Lake Ķikuru on March 2013, and in Lake Lilastes on April/March 2012 and 2013 (Stivrins *et al.*, 2015a, 2015b, 2017; Grudzinska *et al.*, 2017). The uppermost unconsolidated sediment was sampled using a Willner-type sampler and subsequent denser sediment using a 10-cm diameter Russian peat sampler that possesses a 1-m-long barrel. In a current study, only sediment covering last 2000 years were included and analysed as it sufficiently covers period revealing prior-, during and post-human situation.

3.2 Chronology

Previously, published original radiocarbon dates from all sites were recalibrated with the IntCal13 calibration dataset (Reimer *et al.*, 2013) with a two σ (95.4%) confidence level and the age-depth models of each sequence were developed using the Bacon 2.2 software package (Blaauw and Christen, 2011) in the R environment (version 3.0.3) (R Core Team, 2014). A load of spheroidal carbonaceous particles (SCP) along the upper sediment sequence was estimated for Lake Ķikuru and followed the methodology of Rose (1990) and Alliksaar (2000). The peak in SCP emission occurred in AD 1982 \pm 10 years (Stivrins *et al.*, 2016b). Information on SCP was already available from Lake Āraišu (Stivrins *et al.*, 2015a) and Lilaste (Grudzinska *et al.*, 2017). Also, microscopic volcanic ash shards – tephra of Askja AD 1875 eruption was used for lakes Āraišu and Trikātas (Stivrins *et al.*, 2016b) in the age-depth modelling.

3.3 Analysed algae

Most of the algal data have been previously published except for Ķikuru and Trikātas, which are presented here for the first time (Tab. 1, Fig. 1). Diatoms from Lake Trikātas were analysed at 16 stratigraphical levels, *i.e.*, 16 samples. The diatom samples were pre-treated according to Battarbee *et al.* (2001). Each subsample had a volume 0.2 cm³ in Lake Trikāta and 0.5 cm³ in Lake Āraišu and Lake Lilaste. At least 400–500 diatom valves were counted and identified for each depth. The diatom taxonomy was based primarily on Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and Witkowski *et al.* (2000). Numbers of diatoms were expressed as percentages. Seven microscopic Chlorophyta and Cyanophyta samples from Lake Ķikuru were identified during a pollen analysis, so seven samples were prepared by routine pollen preparation methods that include digestion of a 1 cm³ subsample with 10% HCl, 10% KOH and acetolysis for 3 min (Berglund and Ralska-Jasiewiczowa, 1986). Afterwards, percentages of microscopic Chlorophyta and Cyanophyta were estimated based on the total sum of algae of each sample (Stivrins *et al.*, 2018) and separately for diatoms according to commonly used approach as described in Battarbee *et al.* (2001). Altogether 23 and 12 samples for diatoms were analysed in Lake Āraišu and

Lake Lilaste, respectively. Microscopic Chlorophyta and Cyanophyta were analysed in Lake Āraišu (36 samples) and Lake Lielais Svetiņu (nine samples).

3.4 Loss-on-ignition

The water quality in freshwater systems is primarily dependent on material loading through hydrological processes within watersheds (Wang *et al.*, 2015). Agricultural and forest clearance activities around the lakes lead to soil erosion amplification that can be recognised as increased mineral matter content in sediment. Hence, to underline timing of increased soil erosion delivering additional nutrients to the lake, mineral matter content was estimated following Heiri *et al.* (2001). A known volume of sediment was combusted at 550 °C for four h to determine the organic matter content and the ignition residue was estimated as the mineral matter content of the sediment. Altogether 157 samples for Lake Ķikuru, 231 samples for Lake Āraišu, 80 samples for Lake Lilaste, 118 samples for Lake Trikātas and 127 samples for Lake Lielais Svetiņu were analysed. Alongside pollen data from studied sites, mineral matter content serves as an independent proxy of environmental changes.

3.5 Statistical analyses

The amount of compositional change or turnover (*i.e.*, the beta-diversity) in the algae datasets for the last 2000 years was estimated by using a DCCA. This is the constrained form of the Detrended Correspondence Analysis that uses age as the external constraint, *i.e.*, environmental data (Smol *et al.*, 2005; Birks, 2007). A DCCA expresses the compositional turnover in standard deviation units (SD), and the turnover is estimated as the difference between the highest and lowest values for each time sequence (Birks, 2007; Birks and Birks, 2008). A complete turnover of species with no species in joint at either end of the gradient would have a gradient length of 4 SD (Hill and Gauch, 1980) or 100% of the total changes in sequence. The percentage data for each site was square-root transformed and detrended by segments with no down-weighting of rare taxa and non-linear rescaling. Importantly, an individual DCCA was performed for each site in the same way for the last 2000 years using CANOCO 5.04 (ter Braak and Šmilauer, 2012).

4 Results

4.1 Chronology

The sediment chronology for all sites indicates a somewhat constant sediment accumulation rate (Fig. 2) with higher sedimentation towards the present day, which is also indicated by the less compacted sediment at the top of the sediment profile. Larger uncertainty bands were observed for Lake Lielais Svetiņu and somewhat for Lake Lilaste. However, the Lake Lilaste age-depth certainty increases with the SCP. The remainder of the sediment sequences has acceptable age-depth models, which have narrower uncertainty bands due to the application of various dating techniques, such as ¹⁴C, SCP and tephrochronology. Age-depth models were constructed for

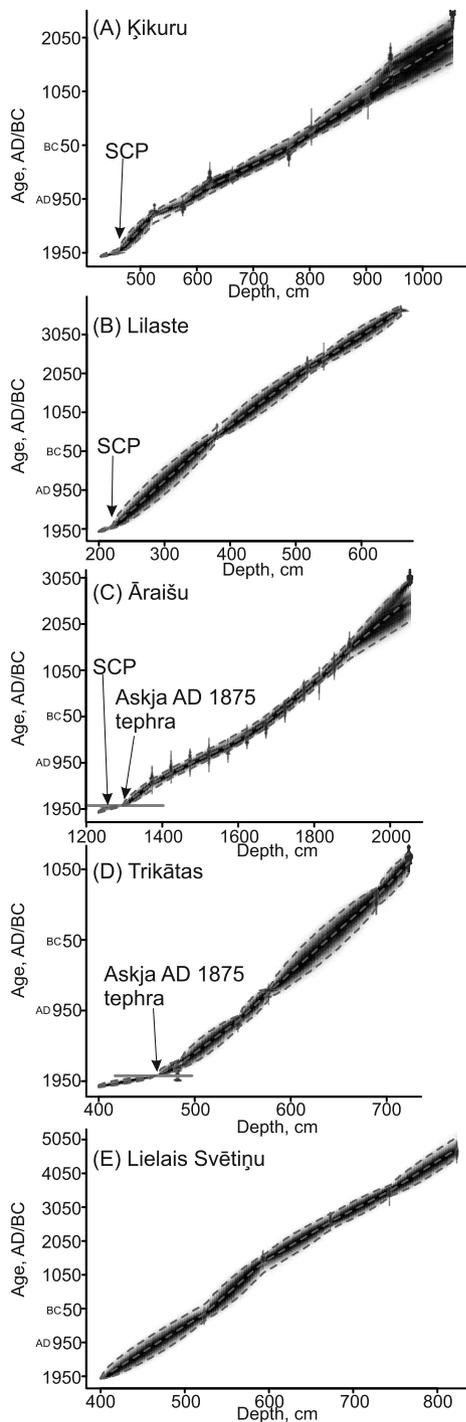


Fig. 2. Age-depth model of (A) Lake Ķikuru, (B) Lake Lilaste, (C) Lake Āraišu, (D) Lake Trikātas and (E) Lake Lielais Svētiņu. The SCP (spheroidal carbonaceous particles) and the tephra of Askja AD 1875 eruption are indicated. Rest of the dates are ^{14}C . The dotted middle curve shows the weighted mean ages of all depths, whereas the greyscale shows uncertainties (a darker shade of grey indicates a more certain section).

longer time spans than the last 2000 years to show that the sediment accumulation rate for these sites was constant and did not abruptly change. However, note that minor changes in the sedimentation rates began at approximately AD 1200 in Lake

Ķikuru, which might be related to human activity in the catchment (*e.g.*, agriculture, soil erosion) to some extent.

4.2 Algae

Majority of the algae results have been previously published (Tab. 1). The present study briefly describes the significant changes (Tab. 2) that can be seen in Figure 3.

4.3 Loss-on-ignition

Mineral matter content varies from site to site, but at least three sites (Ķikuru, Āraišu, Trikātas) reflect the anthropogenic signal, most likely agricultural activities around the lakes (Fig. 4). In Lake Ķikuru more mineral matter derived from AD 600–800 and continuously since AD 1000 onwards, and the maximum values reaching AD 1200–1600. In Lake Āraišu pattern is even more evident – 55% mineral matter content until AD 780 and then abruptly rose up to 70% and stayed until AD 1980s when it dropped back to 55%. Lake Lilaste record has only one distinct shift in values at AD 1700–1950 that might be probably due to its size (larger lake blurs the signal unless it is extensive). Lake Trikātas is another site reflecting the clear human impact that begun at AD 1200 with an interesting pattern – two peaks at AD 1400 and AD 1850, and lower values before, in between and after. Lake Lielais Svētiņu has relatively low mineral matter content in sediment, but an increasing shift is evident at AD 1750.

5 Algae beta-diversity (turnover)

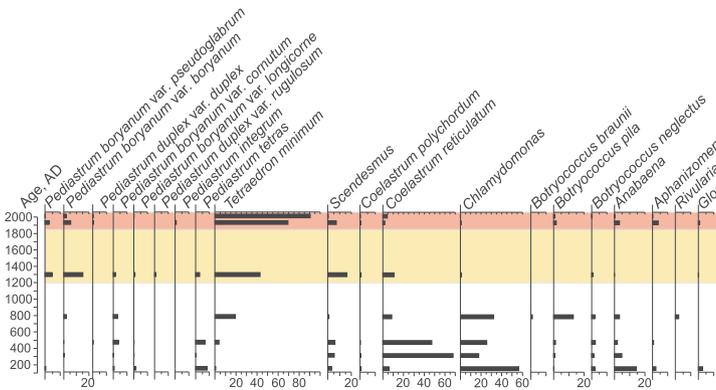
Individual DCCA results of each lake show increasing algae compositional change towards present day (Fig. 4). Lake Ķikuru algae turnover rate increases gradually even at an abrupt mineral matter accumulation at AD 580–700 and since AD 1000 onwards. Soil erosion is pronounced since AD 780 at Lake Āraišu, AD 1200 at Trikātas, AD 1700 at Lilaste and AD 1750 at Lielais Svētiņu (Fig. 4). Distinct diatom turnover rates at Lake Āraišu occur at AD 300 and 1950, and turnover of microscopic Chlorophyta and Cyanophyta increases around AD 1200, 1700 and 1950. Two distinct shifts in diatom turnover appear in Trikātas at AD 1200 and AD 1900. Since AD 1300 turnover rate abruptly increases at Lake Lielais Svētiņu.

The DCCA results indicate that the highest total turnover (SD 2.66) over the last 2000 years was in Lake Trikātas (Tab. 3, Fig. 5) while the rest of the sites had lower turnover indices. The turnover rates of Lake Āraišu indicated comparable turnover of diatoms (SD 1.21) and microscopic Chlorophyta and Cyanophyta (SD 1.24).

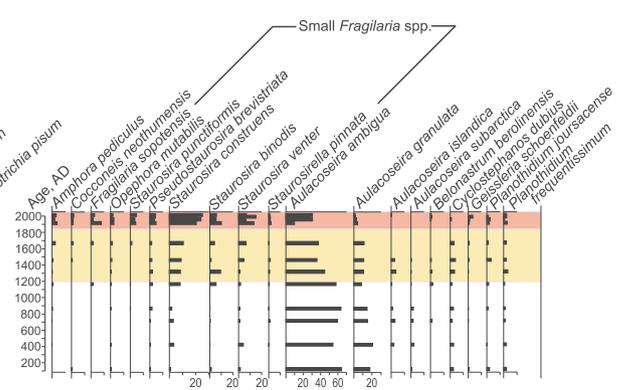
6 Discussion

We demonstrated that the algae composition had changed significantly over the last 2000 years with an average algae turnover as high as SD 1.50–2.00 (Fig. 5, Tab. 3). Smaller and larger turnover indices were noted within a relatively small region in northern Latvia, which suggests that the algae had different sensitivities to local environmental changes in the catchment. These differences can be most likely attributed to

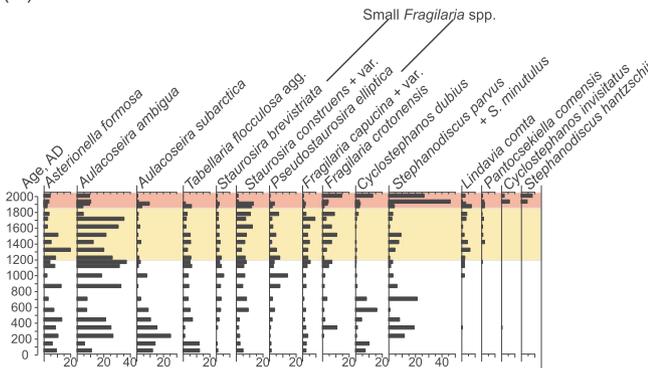
(A) Ķikuru - Chlorophyta & Cyanophyta



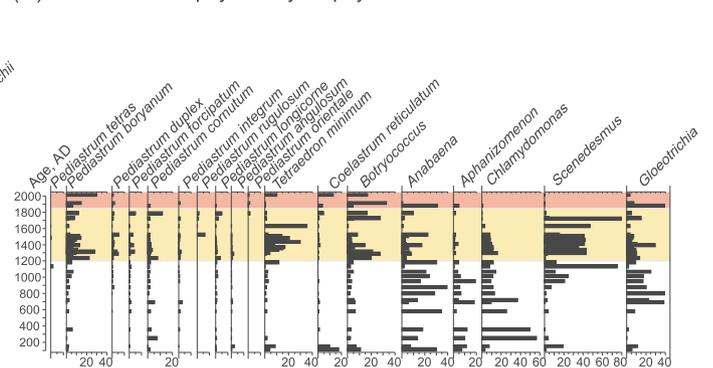
(B) Lilaste - diatoms



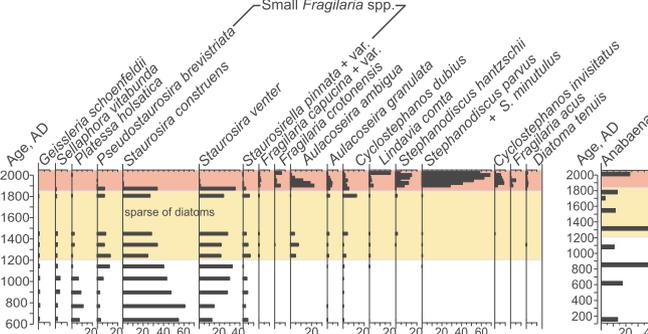
(C) Āraišu - diatoms



(D) Āraišu - Chlorophyta & Cyanophyta



(E) Trikātas - diatoms



(F) Lielais Svētiņu - Chlorophyta & Cyanophyta

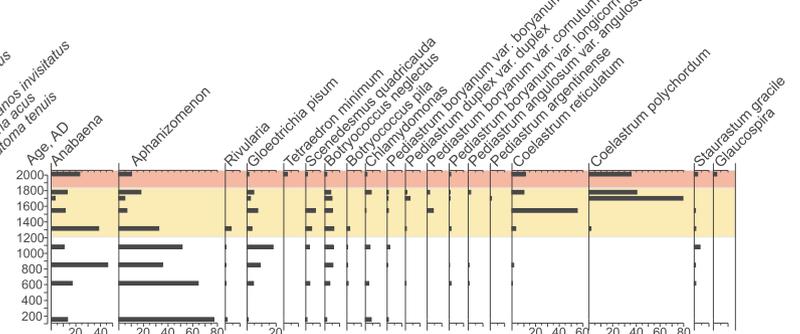


Fig. 3. Diatom and Chlorophyta and Cyanophyta (algae other than diatoms) diagrams of the most common taxa for: (A) Lake Ķikuru (Chlorophyta and Cyanophyta; current study); (B) Lake Lilaste (diatom; Grudzinska *et al.*, 2017); (C) Lake Āraišu (diatom; Stivrins *et al.*, 2015a); (D) Lake Āraišu (Chlorophyta and Cyanophyta; Stivrins *et al.*, 2015a); (E) Lake Trikātas (diatom; current study); Lake Lielais Svētiņu (Chlorophyta and Cyanophyta; Stivrins *et al.*, 2015b).

species competition and different tolerances. General patterns in algae composition as seen individually can be discussed within three time frames which are characterised by a general similarity of the algal composition and cultural aspects. To our knowledge, this is the first time when such an analysis has been carried out for diatoms and microscopic Chlorophyta and Cyanophyta (*i.e.*, recovered during a pollen analysis) at the same time. Our results indicate almost same indices of the total turnover rate meaning they both reflect changes similarly. Increasing microscopic Chlorophyta and Cyanophyta data

availability from Europe and elsewhere over the last decade allow more intensive comparison studies of diatoms and microscopic Chlorophyta and Cyanophyta now.

6.1 The Early, Middle and Late Iron Age (AD 1–1200)

The algal composition was relatively stable during the Early, Middle and Late Iron Age (AD 1–1200) in Lake Trikātas, Lilaste and Lake Lielais Svētiņu suggesting minor environmental stress on the lake ecosystems. Landscape

Table 2. Algae characteristics of study lakes.

Time, AD	Ķikuru	Lilaste	Āraišu	Trikātas	Lielais Svetiņu
1850 – present	Distinct dominance of <i>Tetraëdron minimum</i> suggesting switch in trophic state towards eutrophic conditions with increased nutrient load.	Rapid increase of small <i>Fragilaria</i> spp. and periphytic diatoms (<i>Amphora pediculus</i> , <i>Cocconeis neothumensis</i> , <i>Geissleria schoenfeldii</i>) suggest lake trophic alteration over the last century.	Since 1950s increase of <i>Stephanodiscus parvus</i> shows distinct nutrient loading thus eutrophic to hypertrophic lake conditions.	<i>Stephanodiscus parvus</i> , <i>S. hantzschii</i> and <i>Lindavia comta</i> point to hypertrophic lake that switch from a clear-water to a turbid phytoplankton dominated state of the aquatic ecosystem.	Slight increase of Cyanophyta towards the present-day. <i>Coelastrum</i> and Cyanophyta are the most common algae.
1200 – 1850	Change in algae composition that is evident by increased <i>Tetraëdron minimum</i> and <i>Pediastrum boryanum</i> var. <i>boryanum</i> suppressing previously dominating species.	Gradual increase in small <i>Fragilaria</i> spp. suggests higher turbidity level in the water column.	Significant variations in diatom, green algae and cyanobacteria composition. <i>Aulacoseira ambigua</i> suggests higher turbulence and mixing of the water column.	More abundant planktonic diatom community that switched to more eutrophic conditions. <i>Aulacoseira ambigua</i> , <i>Cyclostephanos dubius</i> and <i>Platessa holsatica</i> were found this period.	Cyanophyta decrease and composition switch in algae by dominance of <i>Coelastrum reticulatum</i> and <i>C. polychordum</i> suggesting additional nutrient loading to the lake.
1 – 1200	Algae composition suggests eutrophic conditions as <i>Coelastrum</i> and <i>Chlamydomonas</i> overwhelmingly dominate.	<i>Aulacoseira ambigua</i> and <i>A. granulata</i> form the most common algae.	Rather stable assemblage of phytoplankton indicating mesoeutrophic conditions until AD 700. Increased amount of Cyanophyta and <i>Stephanodiscus parvus</i> and increase of small <i>Fragilaria</i> spp. indicate in-lake nutrient enrichment since AD 800.	Periphytic diatoms, e.g., <i>Sellaphora vitabunda</i> , <i>Platessa holsatica</i> , suggest a shallow hard-water lake with oligo-/mesotrophic conditions. Although dominance of <i>Staurosira construens</i> and <i>S. venter</i> might show unstable conditions and higher turbidity level.	<i>Aphanizomenon</i> and <i>Anabaena</i> dominates with increased prevalence of <i>Gloeotrichia pisum</i> suggesting Cyanophyta dominance within the lake.

characteristics such as topography and soil type determined by differences in land access for farming and a low human population density certainly could have limited a pronounced impact on the selected lakes. For instance, although eastern Latvia, particularly the vicinity of Lake Lubāns, has been inhabited since the Palaeolithic (Loze, 1972), the continuous presence of natural forests throughout the Iron Age has been suggested around Lake Lielais Svetiņu, which is located only 13 km to the east (Stivrins *et al.*, 2014). This forest-boggy lowland area was not a suitable or first-choice location for extensive agricultural activity, at least not until AD 1300, so no apparent change in algae composition occurred. The anthropogenic impact on the lakes was comparably low for almost the entire Iron Age even for Lake Ķikuru, in which the eutrophic *Coelastrum reticulatum* and *Anabaena*, and the hypereutrophic species *Chlamydomonas* are the most abundant algae (Fig. 4). These species can occur naturally without any effects from human activity (Makohonienko, 2000; Wacnik, 2009; Stivrins *et al.*, 2015b). Indeed, the first pollen results, such as findings of cereal grains of rye and barley, from Lake Ķikuru show a distinct increase in human activity around the lake since 11th/12th century (unpublished results).

Although there is an abrupt increase in mineral matter from ca. AD 580 to AD 700 indicating enlarged soil erosion (Fig. 4), there is no direct evidence for the human activities in the vicinity. Spatially synchronised cooling in some parts of Europe was recorded at AD 536–660 (Büntgen *et al.*, 2016) and it is not excluded that the climate cooling with increased precipitation could drive a soil erosion at Lake Ķikuru, in western Latvia. Lake Āraišu (Fig. 4) was the only lake that experienced a distinct human-induced environmental change already in Late Iron Age, which was associated with the establishment and inhabitation of a lake-dwelling from AD 780 to 1050 (Stivrins *et al.*, 2015a). This was further evidenced by changes in the proportion of the diatom species. A gradual decrease of *Aulacoseira subarctica* and a higher abundance of the planktonic diatom *Aulacoseira ambigua* indicate an increase in nutrient concentrations. In addition, the presence of Cyanophyta and the eutrophic planktonic diatom *Stephanodiscus parvus* indicates in-lake nutrient enrichment from AD 780 to 1100, which suggests eutrophication of the lake ecosystem. An increase of small *Fragilaria* spp. points to unstable conditions caused by increased soil erosion and wind-driven mixing of the water column, which might have been

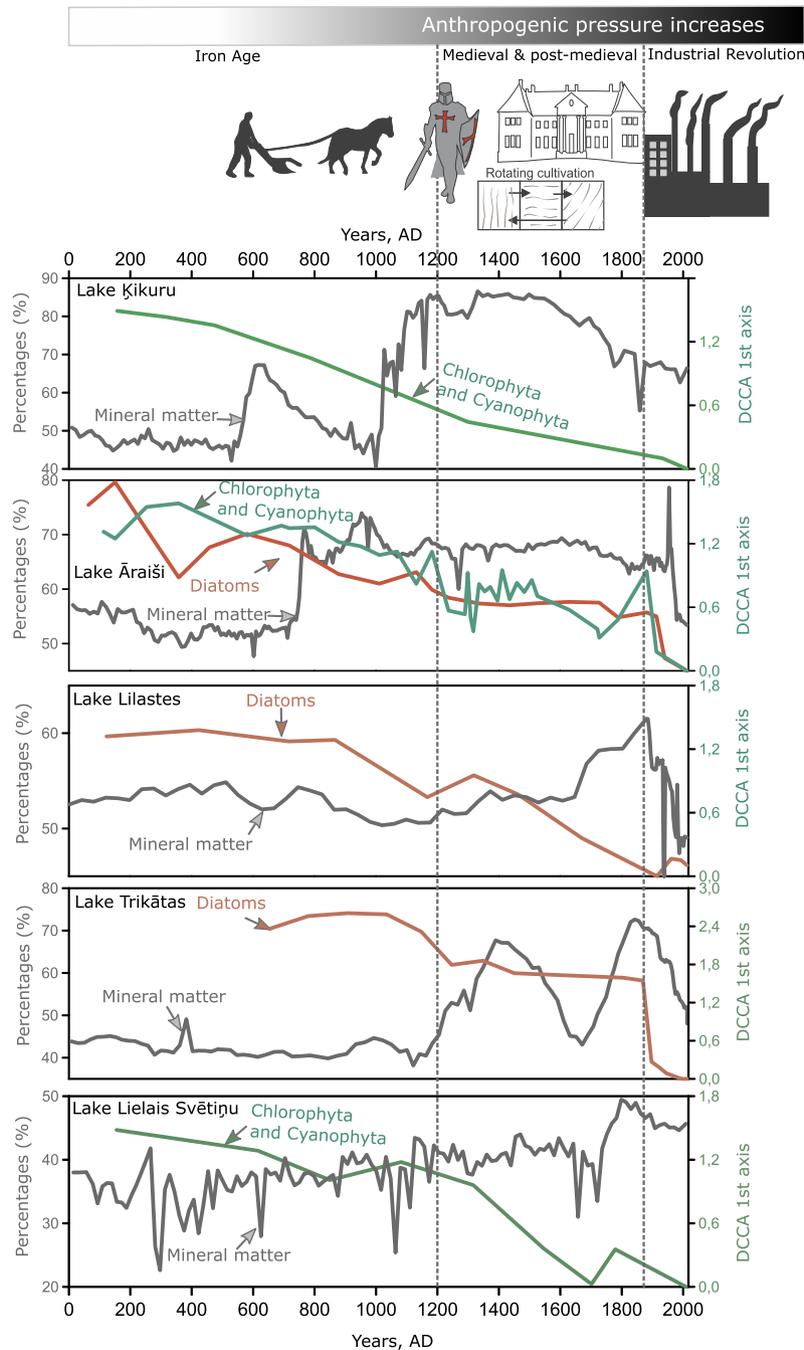


Fig. 4. Compositional algae beta-diversity (1st axis of DCCA) and changes of mineral matter content during the last 2000 years individually for each studied site: (from top) Lake Ķikuru, Lake Āraišu, Lake Lilastes, Lake Trikātas, Lake Lielais Svētiņu. The period division follows the Latvian historical periodisation according to [Graudonis \(2001\)](#) and [Vasks *et al.*, \(1999\)](#).

promoted by clearance of the forest around the lake. Lake eutrophication was most likely a result of intensive arable and pastoral activity, including the rearing of animals within the lake-dwelling ([Stivrins *et al.*, 2015a](#)).

6.2 The Medieval and post-medieval time (AD 1200–1850)

The significant shift in the trophic state of the water is associated with the algal compositional turnover occurring

during the Medieval and post-medieval period of AD 1200–1850. Significant social, political and economic changes occurred during this period that came along with the Christianization and conquest of present-day Latvia in the Crusades and the subsequent Polish-Lithuanian, Russian and Swedish wars and rule, culminating in the economic growth of the Manor time ([Caune and Ose, 2004](#); [Sillasoo and Hiie, 2007](#); [Brown and Pluskowski, 2014](#); [Stivrins *et al.*, 2016a, b](#)). Moreover, technological development such as the rotational crop system increased soil productivity during medieval times;

Table 3. Summary of the detrended canonical correspondence analyses for the five Latvian study sites; algae used in estimation: diatoms and Chlorophyta and Cyanophyta (*i.e.*, algae other than diatoms); the estimated turnover (beta-diversity) was expressed as the standard deviation (SD); number of samples; number of species.

Lake	Algae used	Turnover (SD)	Samples	Species
Ķikuru	Chlorophyta and Cyanophyta	1.56	7	21
Lilaste	Diatoms	1.50	12	85
Āraišu	Diatoms	1.21	22	121
Āraišu	Chlorophyta and Cyanophyta	1.24	36	35
Trikātas	Diatoms	2.66	16	94
Lielais Svētīņu	Chlorophyta and Cyanophyta	1.62	9	29

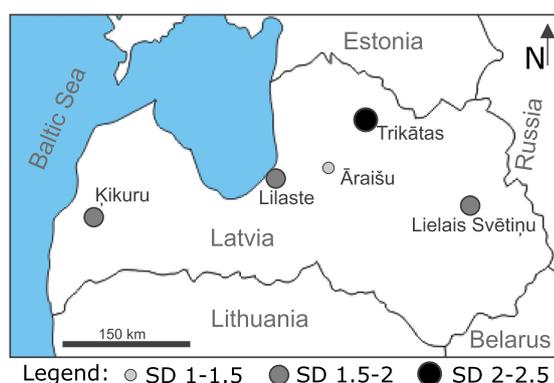


Fig. 5. Total compositional algae beta-diversity during the last 2000 years, expressed in standard deviation (SD) units as estimated by a Detrended Canonical Correspondence Analysis for the five lakes: Ķikuru, Lilaste, Āraišu, Trikātas, and Lielais Svētīņu.

hence, increased food availability allowed the human population and density to grow – increased pressure on the environment. The rotational crop regime became widely accepted and started to replace the previously common slash-and-burn technique due to the disadvantages of the latter. The three-field rotational crop system meant cultivation of winter crops in the first field, summer crops in the second and the third was left fallow and cycled back into a crop field in the next year (Enters *et al.*, 2008). The fallow land was most likely used for grazing, so the soil was enriched by herbivore manure that could readily leach and enter a lake. Manure-enriched water leads to lake eutrophication and is characterised by a prevalence of eutrophic algae, for example, *Coelastrum reticulatum*, *Coelastrum polychordum*, *Gloetrichia pismus*, *Anabaena* and *Aphanizomenon* (Fig. 4) (van Geel *et al.*, 1994; Jankovská and Komárek, 2000). Evidence of such processes can be indirectly assessed by finding fossil coprophilous fungal spores in the lake sediment. These spores are known to indicate the presence of herbivores in the vicinity of the lake (van Geel and Aptroot, 2006). By nature, coprophilous fungi spores do not disperse far from their growth substrate, only 20–100 m on average (Gill *et al.*, 2013). Based on the presence of coprophilous fungi spores the presence of herbivores around the lake during this period has been identified at Lake Āraišu (Stivrins *et al.*, 2015a), Lake Trikātas (unpublished), Lake Lielais Svētīņu (Stivrins *et al.*, 2015b) and Lake Ķikuru (unpublished).

Although the Crusades resulted in significant changes in the organization, ownership and administration of the land, and a shift in the land use patterns, the form and type of agriculture was at first much as it had been during the Late Iron Age (Brown and Pluskowski, 2014; Stivrins *et al.*, 2015a, 2016a). Palaeoecological studies indicate an increase in extensive agricultural land-use a century after the Crusades, *i.e.*, since the 14th century and later (Stivrins *et al.*, 2015a). A rapid increase in the eutrophic algae species, namely, *C. reticulatum* and *C. polychordum*, support an immediate human-induced impact on Lake Lielais Svētīņu during the 16th–17th century (Fig. 4). Similar compositional changes in other lakes support ongoing algae turnover during the time of the Crusades. The abundance of *Staurosira construens* and other small *Fragilaria* spp. since AD 1200 in Lake Lilaste (Figs. 1 and 3) compliment colonisation impact of the Crusades on the environmental conditions and coincide with the foundation of Riga city in AD 1201 (Asaris, 2012). These diatom species suggest a gradual transition to a more dynamic environment (Grudzinska *et al.*, 2017) and might indicate an increased nutrient load from erosive runoff. Similar human-induced activity at all sites appears to fill economic needs, and the development of the Hanseatic League and the manorial system created an increased demand for Baltic timber and agricultural produce (Strods and Zunde, 1999; Stivrins *et al.*, 2016a).

6.3 The industrial revolution (AD 1850 – present)

A distinct shift in algae turnover occurred during the last 150 years since the industrial revolution in approximately AD 1850 (Fig. 3), the time when the use of natural resources multiplied to satisfy the growing demand for the production of goods. Several factors affected the algae composition in the lakes, and all are of anthropogenic origin. First, although this time witnessed the peak of extensive agricultural farming, the subsistence extensive farming system was replaced by a more intensive farming economy that resulted in a reduction of land in use (Petit and Lambin, 2002; Veski *et al.*, 2005; Stivrins *et al.*, 2016b). Second, the development of considerable livestock farming along with agricultural farming (Stivrins *et al.*, 2016a) possibly increased the manure input into the lakes. Third, the establishment of distilleries, brick kilns, dairies and other manufacturers, which might have lacked decent sewage cleaning systems, next to a lake or within the lake

catchment. Notably, during the first years of the manufacture establishment and the Soviet Union occupation period, allowed sewage of different origins directly pass into the lake. High total algae turnover (SD 2.66) has been recorded in Lake Trikātas (Fig. 5) compared with its reference conditions before the intensive human impact indicating a change of more than a half diatom community due to human impact. Thus it could be challenging to restore the water quality to its former status. In Lake Āraišu the first turnover of diatoms occurred around AD 300–400 at the time when the first cereal pollen was detected. Although the human activities were probably of the minor scale, they, however, seem to have influenced aquatic ecosystem. Even though the long-term changes were not as impactful as in Lake Trikātas, a distinct difference from the natural reference conditions is still apparent (SD 1.21–1.24). The status of Lake Āraišu has deteriorated since the 1950s (Fig. 5), as confirmed by the high abundance of eutrophication indicator species such as *S. parvus*, and the appearance of the hypereutrophic diatoms *Stephanodiscus hantzschii* and *Cyclostephanos invisitatus*, which indicate in-lake nutrient enrichment and a distinct deterioration of the water quality (Fig. 4).

7 Conclusions

In this study, we identified algae from five Latvian lake sediment cores and applied a DCCA to estimate the algae turnover rate for the last 2000 years. Our rationale was to determine the lake reference conditions *via* a palaeolimnological approach from Latvian lake sediments, for which such work had not been done. Our results revealed that algae composition has significantly changed over the last 2000 years. The average algae turnover was as high as SD 1.50–2.00, which can be directly linked to the growing anthropogenic pressure towards the present day. Human impact has led to great water deterioration in Lake Trikātas, in which the estimated algae turnover reached SD 2.66, indicating a change of more than a half of diatoms composition, so it would be challenging to restore the water quality to its former status. Our results show that the overall algae turnover increased towards the present day with distinct shifts occurring from AD 1200 to 1850 and AD 1850–onwards – a time of extensive and intensive agriculture establishment and political and economic change. Because of the minor anthropogenic impact on the landscape and lakes before AD 1200, we propose that the algae composition at that time can be assumed to represent the natural reference conditions for most Latvian lakes. The results of this study can be further used in restoration activity and environmental management.

Acknowledgements. The study was supported by the Estonian Science Foundation Grant 9031, IUT 1-8, and Doctoral Studies and Internationalisation Programme DoRa. Special gratitude goes to project EBOR (Finland) and the National basic funding for science project Y5-AZ03-ZF-N-110 “Dabas resursu ilgtspējīga izmantošana klimata pārmaiņu kontekstā” Nr. ZD2010/AZ03 (Latvia). Likewise, we wish to thank Vita Ratniece for providing with additional data for this study.

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Cite this article as: Stivrins N, Grudzinska I, Elmi K, Heinsalu A, Veski S. 2018. Determining reference conditions of hemiboreal lakes in Latvia, NE Europe: a palaeolimnological approach. *Ann. Limnol. - Int. J. Lim.* 54: 22