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Reconstruction of the Holocene palaeoenvironmental conditions accordingly to the multiproxy sedimentary records from Lake Pilvelis, Latvia

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ABSTRACT

Reconstruction of the Holocene palaeoenvironment conditions in Southeastern Latvia is based on multiproxy records from Lake Pilvelis: pollen, plant macrofossil and microfossil analysis; loss-on-ignition (LOI) measurements; ^{14}C dating; humic substances content; humification index; and elemental composition of gyttja organic mass. The data complex obtained in the result of multiproxy studies of sediments in Lake Pilvelis indicates significant changes in the depositional environment during the lake development. Data from Lake Pilvelis show that the start of organic-rich sediments formation before approximately 9750 cal BP, when birch–pine forest dominated in the surrounding landscape. Diagrams and data sets show six remarkable comparatively short cooling periods during the Holocene, which are related to changes in temperature and water level and influenced values and variability of remains. The investigation recognized the 8.4 ka BP and 4.6 ka BP cold events, while other cooling events can be recognised conditionally. During the events of 4.0 ka BP, the water level decreased extremely and the climate was probably drier, indicated by the comparison of records from Lake Pilvelis, Mazais Svetinu Bog and Lake Razna. A comparison of pollen data from Lake Pilvelis with Lake Kurjanovas, Mazais Svetinu Bog and Lake Razna shows some similarities, revealing features of cooler climatic conditions approximately at the time characterised by an increase of *Betula* and herb pollen.

1. Introduction

Sediment sequences from small lakes without or with limited inflow/outflow of rivers and springs function as archives for studying long-term fluctuations of environmental conditions, palaeoclimate, the history of vegetation in the lakes, and their catchment areas and human impact on them. Sediment accumulation process has been ongoing continually since the formation of these lakes. Therefore, they contain continuous records about the history of these lakes and their surroundings (Meyers, 2003). These insights can be used in forecasting an ecosystem's potential future (Wetzel, 2001).

In eutrophic water bodies, which are common in the North Temperate Zone, primary production, such as algae and aquatic macrophytes, dominates because of increasing nutrient inputs instead of mineralization processes in lakes (Cooke et al., 2005). Intensive sedimentation takes place in relatively small lakes in particular, resulting in development of thick organogenic sediment layers of sapropel, gyttja or dy (terminology is dependent more on historical traditions and differences in the sediment composition) (Hansen, 1959). Gyttja or sapropel is a prospective material for diverse applications (Stankevica and Klavins, 2013). In Latvia, the classification is made only for the term 'sapropel' to identify organic limnic sediments as valuable resource with a wide range of possible uses in agriculture, balneology and industry, but the term 'gyttja' usually is used to define organic rich lake sediments in limnology and for past climate studies. Sapropel type classification (Stankevica and Klavins, 2013) has been used in the current study to identify differences in analysed sediment samples with aim to

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distinguish environmental changes during the Lake Pilvelis development.

Organogenic lake sediments formed from the remains of aquatic plants, plankton and benthic organisms were transformed through the activity of bacteria and mixed with mineral components supplied from the lake basin (Kurzo et al., 2004). Analysis of lake sediment composition is widely used for paleolimnological, paleoclimatic (Sümegi et al., 2008; Heikkila and Seppa, 2010; Grimm et al., 2011) and environmental pollution studies (Klavins et al., 2011; Tylmann et al., 2011). Multiproxy analysis of sediment composition is of great importance in understanding the transformation processes of organic matter during sedimentary phases and is also helpful in reconstructions of palaeoenvironment conditions and palaeoclimatic changes.

Reconstruction of Holocene palaeoenvironment conditions and vegetation in the territory of Latvia has mainly been conducted using pollen analysis from sediment sequences (Danilans, 1957; Seglins, 2001a, 2001b). However, as Seglins (2001c) and Ozola (2013) have pointed out, it is not possible to detect exact geographic locations of the studied sites, and information about macrofossils and algae is also missing, along the age dating, in a great number of pollen diagrams from studies until the 1980s. Multidisciplinary studies of the Holocene palaeoenvironment started only during last years (Stankevica et al., 2012; Ozola, 2013; Kalnina et al., 2014; Stivrins et al., 2014).

Latgale Upland region was chosen for the study because of a great number of lakes (more than 600), which are of glacial origin, formed instantly after the retreat of the glacier 14–15 thousand calendar years ago (Zelcs and Markots, 2004; Heikkila and Seppa, 2010; Veski et al., 2012; Stivrins et al., 2014). During geological mapping, 6–8 m thick layers of gyttja were found in many lakes of Latgale Upland (Murnieks et al., 2004), including Raznava Hilly Area (Markots, 1997). Glaciolimnic clays and sand has been covered by limnic sediments containing organic material in these lakes, and therefore contain records of environmental condition changes since the beginning of the Holocene. Reconstruction of past palaeoenvironment conditions in Lake Pilvelis not only provides important data about the history of the ecosystem of the lake in the past and about the long-term dynamics of the plant and algae community there, but also helps to understand and predict the development and behaviour of the lake ecosystem. Proxies, including biological parameters, give important information about the development of the lake, dimensional distribution of layers, and properties of sediments. The aim of this study is to analyse and reconstruct the Holocene palaeoenvironmental conditions in Raznavas Hilly Area using the multiproxy records of sediments from Lake Pilvelis.

2. Study area

Lake Pilvelis (Fig. 1) is a small overgrowing lake of a glacial origin at the elevation 156 m asl., situated in the western part of Raznavas Hilly Area, northwest Latgale Upland, in the Eastern part of Latvia. The area of the lake is 8.7 ha. The average water depth is 0.90 m, and maximum 1.00 m. There are no inflow–outflow streams in the lake. Gyttja fills more than 90% of the lake's depression, with an average thickness of 4.50 m, maximum 5.90 m. The total amount of gyttja deposits in Lake Pilvelis is 360,000 m^3 (Geo-Konsultants, 1998). The Lake Pilvelis shore is formed by an approximately 30 m wide reed (*Phragmites*) marsh belt. The lake catchment basin occupies 138.5 ha and is boggy, covered by mixed forest.

Initially, the lake was formed from the discharge of water from the former ice-dammed lake responsible for the modern geomorphology of the area. It is located inside a relatively broad glacial depression occupied by the Rāzna glacier tongue during the earliest deglaciation phases of the Latgale Upland (Zelcs and Markots, 2004; Zelčs et al., 2011). After the melting of the local glacier during the Late Glacial period, individual lakes were formed in the midst of hummocky, morphologically higher-situated hills. The area around Lake Pilvelis is classified as small-sized morainic-hilly relief, where hummocky hills exceed 10 m relative height. Their elevation above sea level exceeds 160–170 m. This area is one of the highest parts of Latgale Upland formed on the Devonian bedrock uplift, where approximately 40 m thick glacigenic till represented by glaciofluvial sand and gravel interlayers cover the dolostones of the Upper Devonian Daugava Formation (Murnieks et al., 2004). These Pleistocene deposits are overlaid by the Holocene lake sediments, including gyttja (Geo-Konsultants, 1998). Westward from the lake, between till and glaciofluvial sediments, a glacier contact slope is located (Meirons, 1975; Zelcs and Markots, 2004).

3. Materials and methods

3.1. Coring and sampling

Sampling points were selected corresponding to the lake characteristics and preliminary data for gyttja layers in the given location. Coring was done from ice at the western part of Lake Pilvelis (56°39′45.21″ N, 27°17′31.40″ E). Sediment coring was carried out by a 10 cm diameter Russian-type peat sampler with a 1.0 m long camera. The sediment thickness reached 400 cm (Fig. 2), of which 390 cm was gyttja. Water depth of the lake was 70 cm. Five parallel overlapping sediment cores were documented according to the protocol for collecting, handling and (Givelet et al., 2004), packed into film-wrapped 1 m plastic semi-tubes and transported to the laboratory for physical, chemical and palaeobotanical analyses. Gyttja monoliths were subsampled with interval 5 cm and 40 subsamples were analysed using each method to get multiproxy data. In total, 240 gyttja samples were analysed.

3.2. Chronology

The lithostratigraphy chronology was based on ^{14}C radiocarbon dates from three 10-cm-thick bulk samples (Table 1). Gyttja samples were dated by means of the conventional liquid scintillation method at the Institute of Geology, Tallinn University of Technology (Tln), Estonia. Radiocarbon dates were converted to calendar years using the Clam 2.1 calibration dataset (Blaauw, 2010) and R2.15.1 programme deposition model (R Development Core Team, 2012) with a 95% confidence level. The ages in the text refer to calendar years before present (cal BP; 0 = AD 1950). For the chronological subdivision of the Holocene, recommendations of the Working Group of INTIMATE (Walker et al., 2012) were used.

Table 1
Radiocarbon dating of Lake Pilvelis sediments.

No	Depth, cm	Laboratory reference	^{14}C yr BP	δ^{13}C, ‰	Model age (cal BP)	Calibrated age (cal BP) 95%	Material dated
1	180–190	Tln3394	4947 ± 60	−30.6	5278	5588–5761	Bulk gyttja
2	240–250	Tln3395	5292 ± 55	−30.4	6520	5931–6207	Bulk gyttja
3	390–400	Tln3396	8983 ± 85	−20.2	9980	9882–10,273	Bulk gyttja

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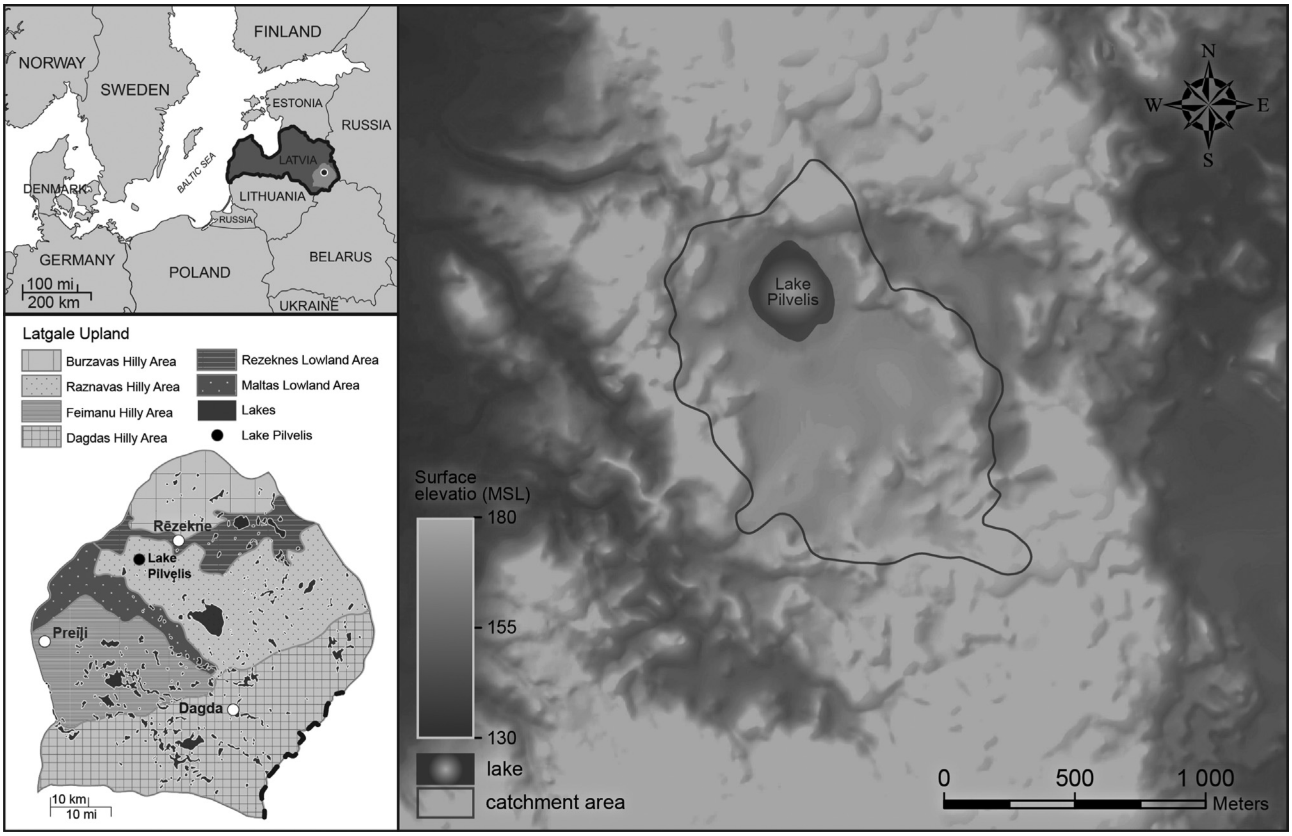


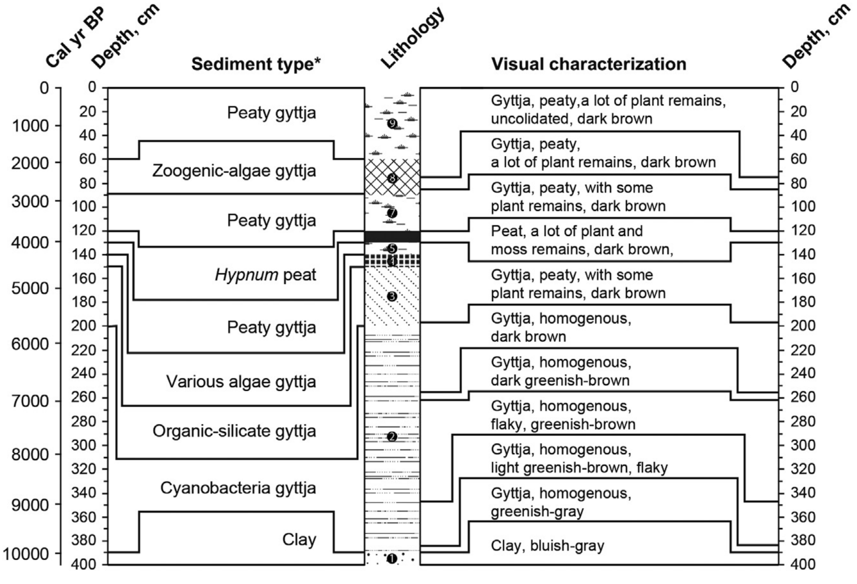
Fig. 1. Location of the study area and Lake Pilvelis basin.

3.3. Loss-on-ignition (LOI)

This method was applied in order to estimate the moisture, organic matter, carbonates and mineral matter content in the sediments (Heiri et al., 2001). At first, the moisture of sediments was determined after drying it at 105 °C. The content of the organic and carbonate matter was analysed by incinerating the samples sequentially at 550 °C for 4 h and at 900 °C for 2 h.

3.4. Pollen analysis

Sediment samples for pollen analysis were prepared according to Bennett and Willis (2001). At least 400 pollen grains were counted per sample (except aquatic plant pollen and spores). The basic sum (100%) for pollen percentage calculations was based on the sum of all pollen, except the aquatic plant pollen (Berglund and Ralska-Jasiewiczowa, 1986). For the



* defined using Sapropel type classification (Stankevica un Klavins, 2013)

Fig. 2. Lithostratigraphy of Lake Pilvelis sediments.

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processing of pollen data, the TILIA 1.7.16 software was used (Grimm, 2012).

3.5. Macrofossil analysis

The samples for macrofossil analysis (approximately 50 cm^3) were washed through 0.25 mm sieves with a gentle spray of water. The residue was washed gently off the sieve into a container and kept cold until analysis commenced. Small quantities of the residue were suspended in a Petri dish and examined systematically under a stereomicroscope Stemi 2000-C at about 10–40× magnifications until the entire sample was examined. Remains of interest were picked out, sorted, identified by comparison with atlases (Cappers et al., 2006; Katz et al., 1965; Sloka, 1978; Velichkevich and Zastawniak, 2006, 2008) and herbarium collection reference materials (Laboratory of Quaternary Environment of the Faculty of Geography and Earth Sciences at the University of Latvia; the Latvian Museum of Natural History), counted, and tabulated (Birks, 1980). A macrofossil diagram was compiled using the TILIA 1.7.16 software (Grimm, 2012).

3.6. Microfossil analysis

Microfossil analyses were carried out for 40 lake sediment samples. Remains of vascular plants, algae and aquatic animals, fungi and moss were identified. 10 ml of water was added to 1 cm^3 of the sample and vortexed for 15 min to destroy sample colloidal structure. Motic DM-B1 Digital Microscope with the 400–1000 times magnification was used to analyse the organic matter composition. For the identification of organic remains, atlases of algae, freshwater and mire plants (Katz et al., 1977; Bellinger and Sigee, 2011; Linne von Berg and Melkonian, 2012) were used. The results were processed and visualised using the TILIA 1.7.16 software (Grimm, 2012).

3.7. Elemental analysis of C, H, N, O

The carbon, hydrogen, nitrogen and sulphur concentrations in the gyttja samples were carried out using an Elemental Analyzer Model EA-1108 (Carlo Erba Instruments) with the combustion-gas chromatography technique. The instrument was calibrated using cystine (Sigma–Aldrich Inc.).

3.8. Humification index

0.5 g of air-dried and finely ground gyttja was treated with 100 ml of 8% NaOH and simmered at 95 °C for 1 h. The suspension was filtered, diluted 100 times, and the light transmission at 540 nm was measured (Blackford and Chambers, 1993).

3.9. Humic substances

0.5 g of air-dried and finely ground gyttja was treated in N_2 with 25 ml of 2% NaOH for 24 h, stirring. The suspension was filtered, diluted 100 times, and the absorption at 410 nm was measured. Calculation of the content of humic substances was made using a calibration method as recommended by the International Humic Substances Society (Tan, 2005).

4. Results and interpretation

The multiproxy data obtained in the study have been described below, compared and analysed with the aim to determine the characteristics helping to reconstruct the palaeoenvironment of Lake Pilvelis and its surroundings. For the Holocene subdivisions, we used the Holocene boundary set proposed by the INQUA group of researchers (Walker et al., 2012) and based on the data of the global stratotype Greenland NGRIP1 ice drill, determining the Early to Middle Holocene boundary at 8200 cal. BP and the Middle to Late Holocene boundary at 4200 cal. BP. The characteristic features found by researchers in the Baltic region were taken in account (Veski et al., 2004; Kangur et al., 2009; Heikkila and Seppa, 2010; Veski et al., 2012; Stivrins et al., 2014). As a result of the data analysis, we identified cold and dry events, which are marked in diagrams to draw attention to the lake level fluctuations and palaeoenvironment changes during the Holocene. The dark grey lines in the diagrams mark the levels where certain characteristics of possible climate cooling have been detected. The levels marked with a light grey line contain features pointing to drier climatic conditions, but with insufficient evidence of cooling.

4.1. Lithostratigraphy and chronology

The studied sediment sequence from Lake Pilvelis contains both mineral and organogenic sediments. Organic sediments have been subdivided into eight lithostratigraphic units according to the investigation data (Fig. 2). The type of gyttja was determined using Sapropel type classification (Stankevica and Klavins, 2013). The type of sediments was estimated using microfossil data, where amount of algae, aquatic animals and vascular plant remains were taken into account. Organogenic sediments have been subdivided as Cyanobacteria, various algae, peaty and zoogenic algae gyttja types. Ash content (sum of mineral matter and carbonates) in this sediments does not exceed 30%, carbonates – less than 8%, and Fe – less than 5% (Stankevica et al., 2012). The sediments with ash content ranges from 30 to 65%, carbonates – less than 8%, and Fe – less than 5% have been determined as the organic-silicate sapropel type, belonging to the clastic sediment class.

The basal part of the lake sediment section (390–400 cm) consists of bluish-grey clay with high amount of ash content (81–92%) and is covered by organic-rich sediments. Gyttja rich in Cyanobacteria remains started to accumulate since around 9800 cal BP until 5700 cal BP (Table 1) at the depth from 390 to 200 cm, i.e. the middle part of the Early Holocene. The average organic matter content was 85%; carbonate evenly decreased towards from 1.37% to 0.4% and then sharply increased to 1.27% at 250 cm and to 3.51% at 240 cm in the very upper part (Fig. 3). The ^{14}C dating at a depth of 240 cm yielded an age of 5930–6200 cal BP (Table 1), i.e. the cold event at the Middle Holocene. At the depth from 200 cm to 150 cm, the organic matter content decreased by approximately 66.7%, and carbonates increased about 1%. The numerical age of sediments at a depth of 180 cm yielded an age interval of 5600–5760 cal BP. The sediment sequence from 150 to 140 cm, accumulated 4550–4290 cal BP, was composed of various algae gyttja. Further, continuous peaty gyttja accumulation took place in the depth interval from 140 to 0 cm, with two interlayers: peat from 130 to 120 cm and zoogenic-algae gyttja from 90 to 60 cm layers. An exception is a 10 cm thick dark-brown *Hypnum* peat rich in plant and moss remains interlayer formed at the depth interval of

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120–130 cm accumulated during 4020–3740 cal BP (Fig. 2), with average mineral matter content of 18%.

4.2. Pollen analysis

Six statistically significant local pollen assemblage zones (LPAZ) were established (Table 2 and Fig. 4) in the sediment sequence of Lake Pilvelis on the basis of changes in pollen composition and fluctuations of curves, supported by sediment composition characteristics and radiocarbon dating results.

Table 2

Description of the local pollen assemblage zones (LPAZ) subdivided according palynological studies of Lake Pilvelis sediments.

Depth (cm)	Age (cal BP)	LPAZ	LPAZ description	Vegetation type in area
00–80	2550 – before present	P_P-6	***Betula* – *Pinus* – *Poaceae*.** Decrease of broad-leaved and *Corylus* pollen and increase of *Betula* (from 29 to 42.2%), *Pinus* (26.3%) and *Picea* pollen values point on climate deterioration and significant changes in vegetation composition, The prevalence of *Poaceae* is increased, reaching 2.6% and decreasing for Cyperaceae. The zone ends with the increase of herbaceous – Asteraceae, Solanaceae and Apiaceae. Values of cultivated land plants as *Secale cereale* in the zone reach about 1.5%.	Birch-pine forest with meadows and agricultural area
80–160	4800–2550	P_P-5	***Alnus* – *Quercus* – *Fraxinus*.** Warmth demanding tree pollen still have quite high values, however with tendency to decrease upwards zone. *Corylus*, *Ulmus* and *Tilia* in range 3–5%, while their maximum values reaches *Quercus* (8.9%) and *Fraxinus* (6.1%). In the middle of the zone *Fagus* and *Carpinus* appears reaching up to 0.5%. *Alnus* pollen curve is fluctuating (15–29.4%), but *Betula*, *Pinus* and *Picea* pollen curve has tendency increase, indicating changes in forst composition. Amount of herb pollen is fluctuating. Decreased Poaceae amount, but Cyperaceae, *Artemisia*, *Ranunculus* and *Apiaceae* is increased. Number of the aquatic plants is decreased for Nymphaceae and *Potamogeton*, the same trend is for *Equisetum* and *Sphagnum*.	Mixed forest with significant presence of oak and ash.
160–231	6340–2550	P_P-4	***Tilia* – *Corylus* – *Alnus* – *Picea*.** Broad-leaved tree pollen reaches their maximum. Constant values retain *Tilia* and *Quercus* in range 4–7.3%. *Ulmus* varies from 10.6% to 14.1%. *Carpinus* pollen appears in small amount and *Fraxinus* increased at the end of the zone, *Corylus* pollen the average incidence in whole zone is 17.8%, but *Alnus* 22%. Increased *Picea*, reaching 15.6%, but amount of *Betula*-decreased. Throughout zone Ericaceae pollen increase. At the end of zone number of herb pollen including Poaceae and Cyperaceae decreased, indicating more dense forest development around lake. Increase amount of *Potamogeton*. *Equisetum* and *Sphagnum*.	Broad-leaved forest with spruce
231–310	8090–6340	P_P-3	***Ulmus* – *Corylus* – *Alnus*.** Gradual increase in broadleaved tree pollen *Ulmus* (to 5.8%), *Tilia* (to 5.2%) and *Quercus* pollen (1.2%–6.2%) and increase in *Corylus* (18.5%) and *Alnus* indicate development of warmth demanding vegetation of climatic optimum. Amount of *Betula* reaches 27%, *Picea* pollen remains in a range of 2.4%–5.3%, while *Pinus* values are reduced by 9%.	Broad-leaved forests with alder, hazel, areas of meadows slightly decrease
310–360	9280–8090	P_P-2	***Pinus* – *Ulmus*.** Significant changes took place in pollen composition of this zone. Increases *Pinus* to 29.2%. *Picea* retains a stable incidence with 6%, appears and increases *Ulmus* to 9%, *Alnus* varies from 1.5 to 4.7% and *Corylus* from 7 to 17.7%. *Betula* decreases in the upper part of the zone to 25%. Appears Ericaceae and Linaceae. Cyperaceae pollen up to 3%, Poaceae over 1.7%, having a constant pollen curve and reaching the highest values. Ruderal herbs represented by *Artemisia*, an average of 2.4%, *Plantago* –0.5%. Sum of herb pollen reaches up to 20%, point on open area around the lake. The spores are represented by Polypodiaceae, *Sphagnum* and *Equisetum*.	Pine-birch forests with elm and hazel, wide areas of meadows, partly overflowing
360–400 …	–9280	P_P-1	***Betula* – *Pinus*.** *Betula* tree pollen is dominating and reaches 66%, *Corylus* average is around 5%. Shrubs represent *Salix* with the average 1–3%. Coniferous are represented by *Pinus* (20%) and *Picea* (1–5%). Herb pollen reaches 15–20%, mainly is represented by grass Poaceae –6.4% and sedge Cyperaceae –1.3%, pointing on the partly open landscape. The aquatic plant pollen is mostly represented by Nymphaceae and Potamogetonaceae.	Area surrounded by birch forest stands with some coniferous and wide areas of meadows

The pollen analysis results reflect regional vegetation changes and indicate that the organic-rich deposits were accumulated Lake Pilvelis since the Early Holocene, before 9800 cal BP, and have been continuing until today. During this time, different types of gyttja with larger or smaller admixtures of mineral matter have been deposited. The sediments contain pollen, which characterises the changes in vegetation composition in the surroundings of the lake. Proportions between the tree and shrub or arboreal (AP) and herb or nonarboreal (NAP) pollen indicate that a partly opened, mosaic-type meadow-forest landscape with birch forest and some coniferous stands existed around the lake during the Early Holocene. The pollen spectra, showing some decrease in the warmth-demanding plant pollen content and increase of birch before the start of broad-leaved forest distribution during the Holocene Thermal Maximum, indicate a slight climate cooling. It is supported by some decrease in the quantities of warmth-demanding plant pollen and increase in number of corroded and re-deposited pollen along to slight increase of mineral matter in sediments, which probably is related to the lakeshore.

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4.3. Plant macrofossils

The macrofossil diagram for Lake Pilvelis was divided into six plant macrofossil zones (PMAZ) (Table 3 and Fig. 5). The variety of plant species in the lake is poor: 23 plant forms were established, although species were not detected for 4 forms of plants.

Table 3
Description of the local plant macrofossil zones (PMAZ) of Lake Pilvelis sediments.

Depth (cm), age (cal BP)	LPMA	Description and vegetation type
00–90 cm 2855 – present	P_{MA}-5	***Potamogeton* – *Nymphaea alba* – *Characeae*** Dominant species – *Potamogeton natans*, *Nymphaea alba* and Characeae. *Daphnia* and *Bryozoa* occurred in small amounts. Total number of macrophytes species is increasing for aquatic plants remains.
90–180 cm 5278–2855 cal BP	P_{MA}-4	***Betula* – *Picea* – *Characeae*** Small amount of *Characeae* oogonia, *Potamogeton pussillus* and *Typha* sp. seeds. Rapidly increases amount of *Daphnia* ephippia. Increases *Picea* needles and seeds, and remains of aquatic plants, also *Hypnum* leaves especially in the interval 110–130 cm.
180–240 cm 6520–5278 cal BP	P_{MA}-3	***Betula*** Dominate *Betula sect. Albae* nutlets. Small amount of aquatic and telmatic plants, aquatic animals. Some *Cristatella mucedo* statoblasts. Increased amount of *Hypnum* leaves.
240–320 cm 8296–6520 cal BP	P_{MA}-2	***Najas flexilis* – *Characeae* – *Potamogeton pussillus*** Large amount of *Characeae* oogonias, *Potamogeton pussillus* and especially *Najas flexilis* seeds. Unequally increases *Cristatella mucedo*. Seeds of coastal plants were not found.
320–400 cm 9737–8296 cal BP	P_{MA}-1	***Najas marina* – *Najas flexilis* – *Typha* – *Carex*** *Najas marina*, *Najas flexilis* and *Typha*, *Carex* and *Characeae* oogonia regularly occurred. High amount of *Betula sect. albae* and bryozoans *Cristatella mucedo*. Tree-plant leaves and fragments of twigs, aquatic plant remains were in little amount. Seldom *Carex* nutlets and *Characeae* oogonia, often *Betula sect. Albae* nutlets. Chitin fragments of zooplankton and several *Hypnum* leaves and culms in the very lower part of section (390–400 cm).

Plant macrofossil data (Fig. 5) shows that the lake vegetation was poor at the basal part of the lake sediment section (4–3.9 m). The quantities of aquatic plant remains slightly increased in course of the P_{MA}-1 zone (Fig. 5), and the remains of washed-in birch leaves and fragments of twigs were dominant. In the sediments that had accumulated during the Holocene Thermal Maximum (P_{MA}-2), the quantities of *Potamogeton pusillus* and *Najas flexilis* aquatic plant remains increased. There were also remains of *Cristatella mucedo*. This is supported by the disappearance of coastal plants. At the depth interval of 240–180 cm (P_{MA}-3), accumulated before 5300–6300 cal BP, there was a significant increase of washed-in *Betula* nutlets. This and the lack of aquatic plants may indicate the water level rising, while the remains of *Hypnum* moss indicates the intensive bogging-up processes in the surrounding territories.

In the upper layers (P_{MA}-4), the washed-in spruce needles and seeds indicated that spruce was growing in the surrounding territories. The increasing quantities of aquatic plant remains may represent a decreasing water level. The increasing number of macrophyte species and the total quantity of aquatic plant remains (P_{MA}-5) suggested that the water level was slightly rising and became rich in nutrients. The extinction of *Najas flexilis* was caused by eutrophication and acidification of lakes (Ellenberg, 1992, 2009).

4.4. Microfossils

Seven microfossil zones (MIZ) were established (Table 4 and Fig. 6), based on visual and statistical evaluations of the algae, total aquatic animals and total vascular plant remains. Microfossils are represented by four algae groups: cyanobacteria, green algae, diatoms and desmidiales, vascular plants, aquatic animals, fungi and moss. The genus of algae and aquatic animals was detected.

Table 4
Description of microfossil zones (MIZ) of Lake Pilvelis sediments.

Depth (cm), age (cal BP)	BCZ	Description and vegetation type
00–90 cm 2855–before present	P_{MI}-7	***Higher plants* – *Anabaena* – *Aquatic animals*** Higher plants are increased in upper part of the zone from 23% to 64% with the tendency to extend in upper layers. Average *Anabaena* amount increases to 21%. Amount of aquatic animals increases, reaching in average 20%. Found *Scenedesmus*, *Pediastrum* and *Tetraedron* remains in small amounts, *Botryoccoccus* disappears in upper part of the zone.
90–140 cm 4290–2855 cal BP	P_{MI}-6	***Higher plants* – *Aquatic animals*** In upper part of the zone *Lyngbya* disappears. *Anabaena* decreased from 26 to 7%. Increased amount of green algae remains up to 3% and these are still mainly represented by *Botryoccoccu*. *Scenedesmus*, *Pediastrum* and *Tetraedron* remains appear in very small amount. Aquatic animals are mainly presented by *Cladocera* with average 8%, increased *Spongilla* to 6%. Distribution of *Insecta* chitin is irregular. Higher plants average amount decreased, reaching 30%.
140–200 cm 5709–4290 cal BP	P_{MI}-5	***Higher plants* – *Anabaena*** Average total of higher plants remains is 40%. Cyanobacteria mainly represented by *Anabaena*, the average incidence in all zone is 30%. *Lyngbya* decreased average to 3%. Green algae represented by small amount of *Botryoccoccus*. Detritus still decreased (average to 20%). Aquatic animals decreased in upper part from 10 to 4%, appears *Spongilla* remains.
200–240 cm 6520–5709 cal BP	P_{MI}-4	***Anabaena* – *Lyngbya*** *Lyngbya* is continuing to decrease till 15%, but *Anabaena* increased from 18 to 25%. Increased detritus (30%) and remains of total vascular plants (average 25%). Small amount of *Chlorogloea*. *Scenedesmus* decreases until 3%. Total amount of green algae decreased. Insignificant increase of aquatic animals. Detritus decreases to 30–25%.
240–320 cm 8296–6520 cal BP	P_{MI}-3	***Lyngbya* – *Anabaena*** Still dominates *Lyngbya*, but gradually decreasing in upper part of the zone from 60% to 33%. Increased *Anabaena* –10%. *Chlorogloea* decreased. *Scenedesmus* varies from 5 to 8%. Detritus increased in upper layer of the zone to 33%.
320–390 cm 9737–8296 cal BP	P_{MI}-2	***Lyngbya* – *Scenedesmus*** Dominates *Cyanobakteria*, bentic blue-green algae *Lyngbya* gradually increased from 1% to over 60% in upper part of the zone. Detritus decreased from 80% to 20%. Small amount of plankton blue-green algae: *Chlorogloea* and in the end of the zone some *Microcystis* remains. *Anabaena* shows irregular distribution. Green algae remains are represented by *Scenedesmus* (1–10%) and small amount of *Tetraedron* and *Pediastrum*. Small amount of aquatic animals and higher plants.
390–400 cm … -9737 cal BP	P_{BC}-1	***Diatom* – *Desmidia* – *Spongilla*** High amount of *Diatom* and *Spongilla*. Some *Desmidia* remains.

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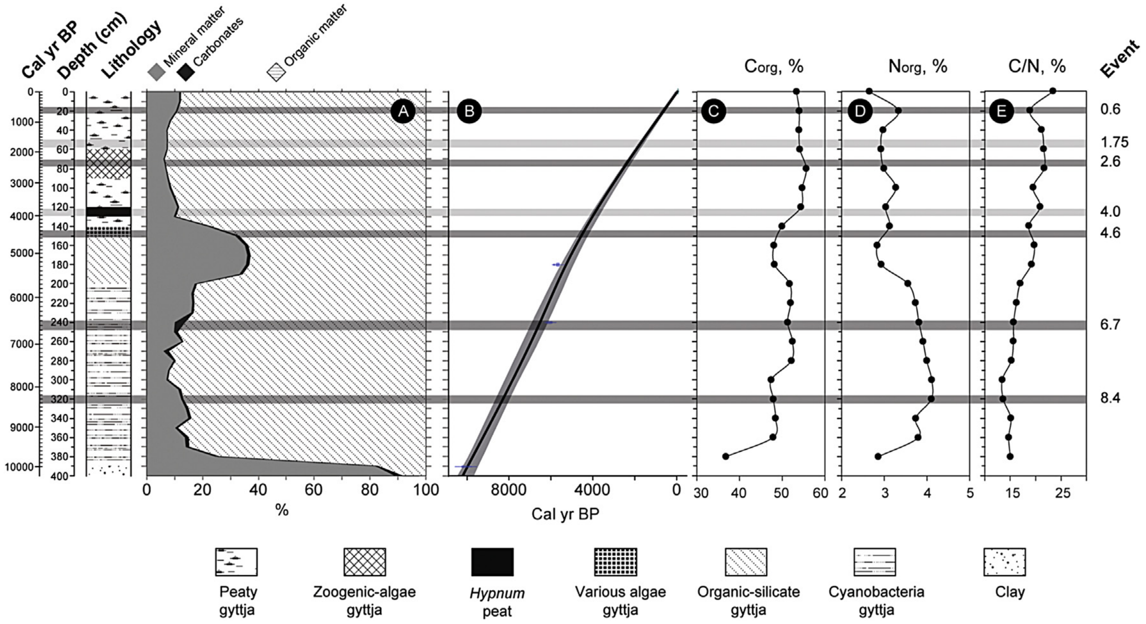

Fig. 3. Lake Pilvelis sediments: (A) changes in mineral matter, carbonate and organic matter content, (B) age–depth model, (C–E) elemental composition.

The data shows that intensive eutrophication started in Lake Pilvelis with massive development of the cyanobacteria *Lyngbya* since 9700 cal BP. The *Lyngbya* population dominated and achieved their maximum of 72% during the cooling period known as the 8.2 ka cold event. It was established that the sediment sequence in Lake Pilvelis was deposited over a period from 8500 to 8200 cal BP. Since 6550 cal BP, the *Lyngbya* population decreased, while the cyanobacteria *Anabaena* and vascular plant population increased and dominated until the present day, with some variations.

4.5. Elemental composition

The organic matter of gyttja in Lake Pilvelis is characterised by low content of carbon (36.8–55.6%) and high content of oxygen (34.7–55.0%), nitrogen (2.7–4.1%) and hydrogen (5.3–7.1), as well as a relatively high variability of gyttja elemental composition. The elemental composition of gyttja organic matter cannot be used as a typology parameter, as different gyttja types have no significant differences in elemental composition (Braks, 1971). The total organic carbon (TOC), the total organic nitrogen (TON) and the C/N atomic ratio are effective parameters in conjunction with other organic proxies discussed in this paper (Fig. 3).

Algae do not have cell walls consisting of cellulose and lignin, but contain cytoplasm with nitrogen-rich proteins. Thus, the sediments formed from algae have higher organic nitrogen amounts, while the sediments formed from residues of vascular plants have higher organic carbon amounts. The transformation of organic nitrogen and carbon in lake sediments is mainly the result of microbial processes. The role of fauna from the bottom of the lake in the transformation of nitrogen and carbon is unknown and is only likely significant in the upper sediment layers (~3 cm). The most intensive mineralization processes take place in the uppermost sediment layers (pelogen), especially considering the presence of oxygen. Eutrophication results in a reduced intensity of

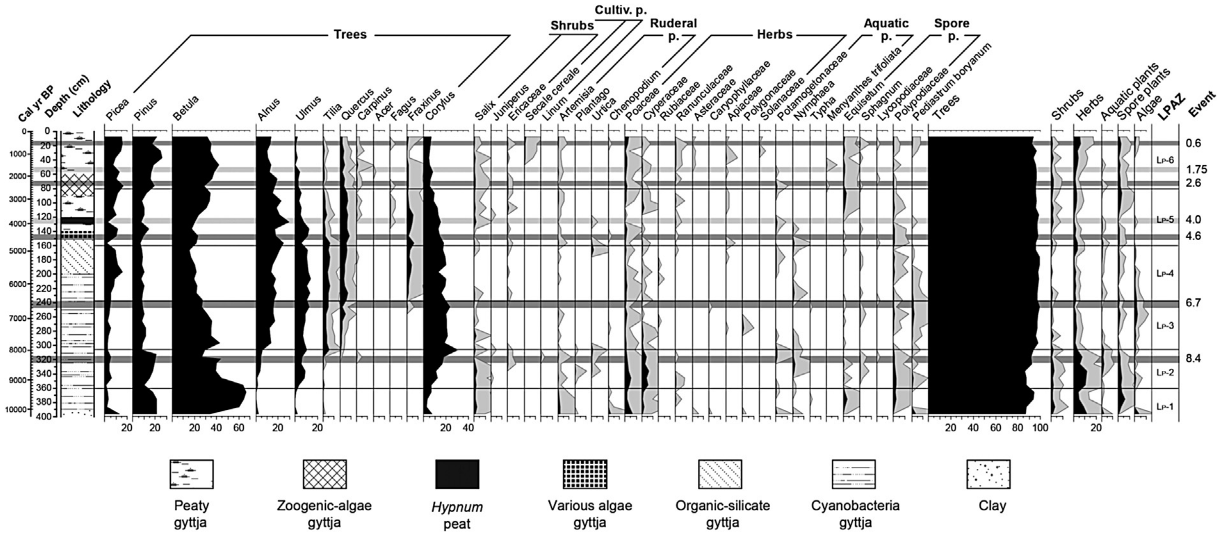

Fig. 4. Pollen percentage diagram of Lake Pilvelis sediment section.

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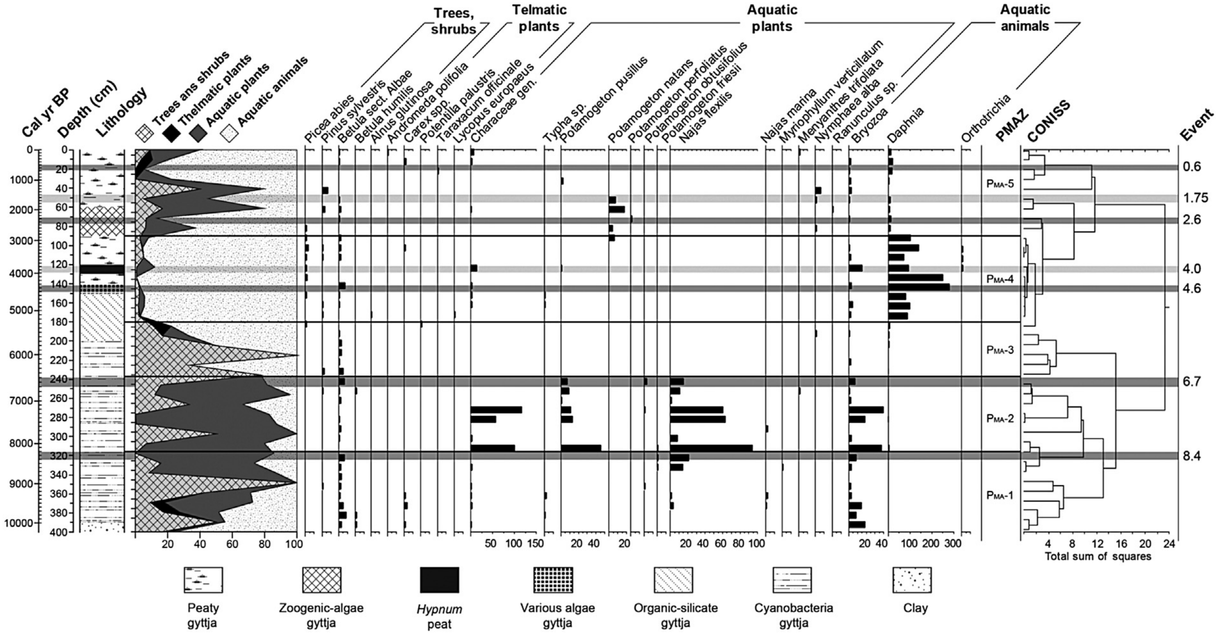

Fig. 5. Plant macrofossil diagram of Lake Pilvelis sediment section.

mineralization process, especially affecting the C/N ratios. The organic nitrogen amount was increasing with the depth of the sediments, while the organic carbon concentrations had the highest value in the upper (less mineralized) sediment layers (Fig. 3). These data have good correlation with the concentration of humic substances and percentage of higher vegetation (Fig. 7).

The C/N atomic ratios at the depth of 400–200 cm were ~15, indicating the residues of algae as the main contributing source of organic matter, whereas in the upper layers the C/N ratio reached 23, indicating, according to Meyers and Teranes (2001), higher vegetation as the major source of organic matter. The C/N ratio coincides with the indicators of lake genesis and demonstrates impacts of lake eutrophication and overgrowth with macrophytes on the composition of sediments.

4.6. Humification index and humic substances content

Humification index as a proxy is usually used to depict the degree of decomposition of the remains of vascular plants. A more intensive humification process occurs in aerobic conditions. Therefore, it is strongly influenced by the activity of microorganisms, conditions of wetness, temperature, pH values, and the type of peat-forming plants (Zhong et al., 2011). However, decay and humification of organic matter continues even in anaerobic conditions, even if this process goes on very slowly, releasing methane (Chambers et al., 2010b). In reconstructions of palaeoenvironment, humification degree is usually used as a parameter of climate wetness and temperature during of peat deposition, but it is rarely used for lacustrine sediments (Zhong et al., 2011). However, it is an

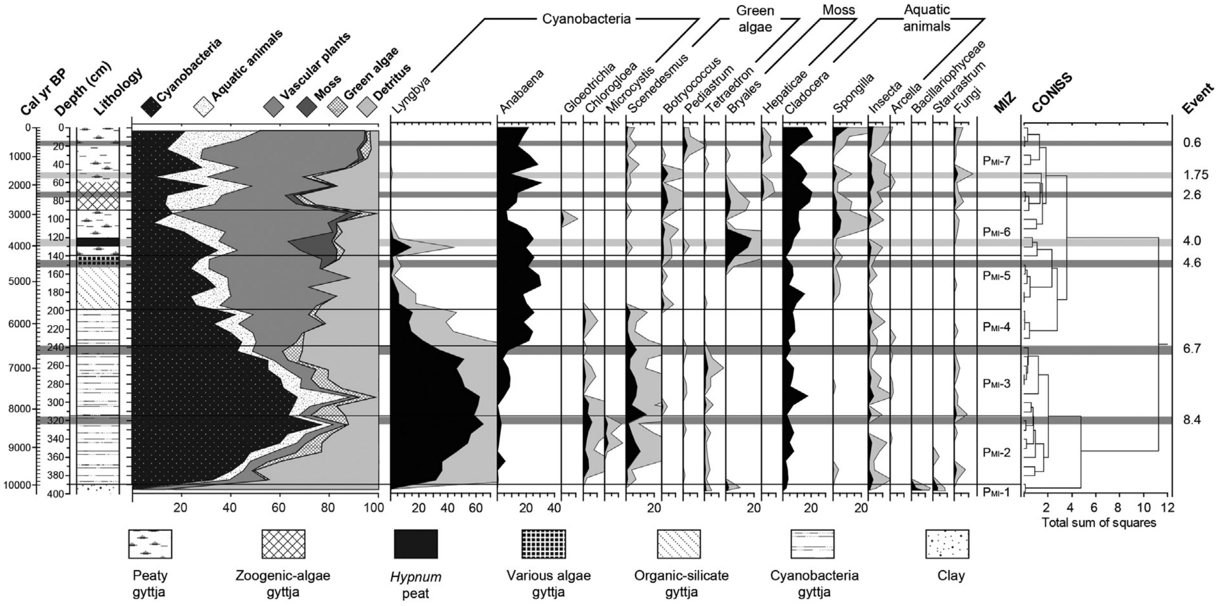

Fig. 6. Microfossils determined in Lake Pilvelis sediment section.

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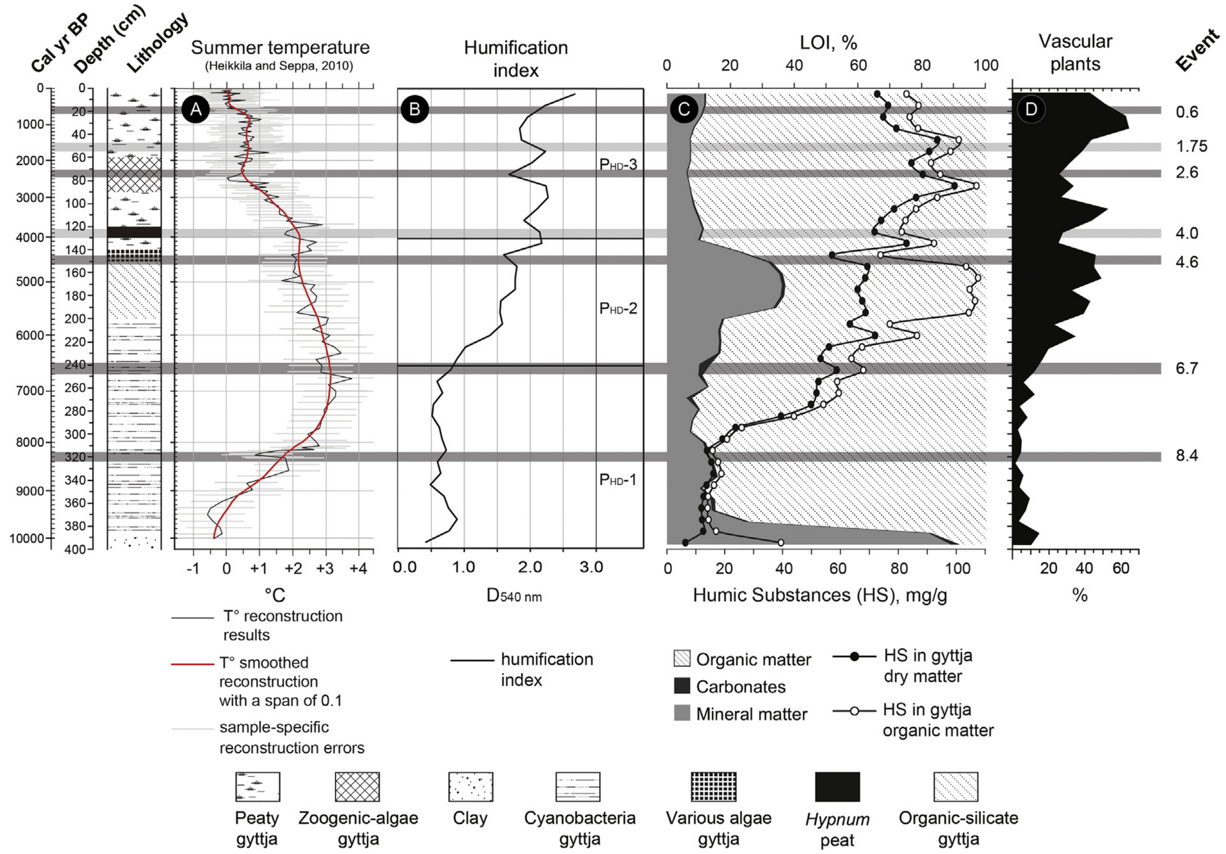

Fig. 7. (A) Reconstructed summer temperature anomalies at the location of Lake Kurjanovas during the Holocene (Heikkila and Seppa, 2010); (B) gyttja humification degree in Lake Pilvelis; (C) LOI data: the content of humic substances in dry matter and organic matter; (D) distribution of vascular plant remains.

important data source about climate changes in the past and gives additional information for the environment reconstruction. Therefore humification index (as used for peat) has been used in study of gyttja, which is a sedimentary sequence formed by alternation between lacustrine sediments with high ash content, such as clay and sand, and fen peat.

As the humification index of sediments corresponds to the quantity of vascular plants, and lacustrine sediments often are represented by different algae remains, the changes in humification degree of sediments from Lake Pilvelis (Fig. 7) allowed division into three zones taking in consideration microfossil composition and mineral matter content. The P_{HD}-1 zone reflects the development of Lake Pilvelis until around 6600 cal BP. At that time, large amounts of algae, mainly cyanobacteria, accumulated in the lake, while the remains of vascular plants were present in low amounts. The P_{HD}-2 zone corresponds to the development of Lake Pilvelis from 6600 to 4300 cal BP, when the humification of gyttja increased, along with the quantities of mineral matter and vascular plants. The P_{HD}-3 zone (4300 cal BP until present) corresponds to the sediment interval containing high quantities of vascular plant and *Hypnum* remains. This part of sediments is more humificated, and this can be attributed to peaty gyttja, whose properties are similar to fen peat. The humification index of sediments fluctuates in the frame of the zone, reflecting some climatic changes.

Humic substances are formed during the humification (decay) process of organic matter. They are biogenic, heterogenic organic substances, containing up to 70% of the organic carbon in soils and more than 90% in peat (Šīre, 2010). Distribution of humic substances (Fig. 7C), humification index (Fig. 7B) and content of vascular plants (Fig. 7D) in paleolimnological investigations can provide information about aerobic conditions, water temperature and water level in the lake. Comparison of reconstructed summer temperatures anomalies from Lake Kurjanovas (Fig. 7A) during the Holocene (Heikkila and Seppa, 2010) and parameters obtained from Lake Pilvelis sediment studies: humification index (Fig. 7B), LOI data and humic substances content in dry matter and organic matter (Fig. 7C), amount of vascular plant remains (Fig. 7D) indicate climatic events during the Holocene.

The data obtained shows that fluctuations of sediment humification index and amount of humic substances coincide with climatic changes in this region. In the interval recognised as the 8.2 ka cold event (8500–8100 cal BP), humification and the content of humic substances decreased due to a rapid drop in the quantity of vascular plants during the cold event. The other cooling event can be indicated around 6600 to 6400 cal BP, when the content of humic substances decreased, while the humification degree increased. At that time, the water level in the lake rose, causing disappearance of aquatic plants (Fig. 5) and increase of carbonates (Fig. 7C). The total quantity of vascular plants was not affected, suggesting that the resources were mainly terrestrial plants. As the lake had a run-off hydrological regime, the humic substances could be washed out. Since 6400 to approximately 5000 cal BP, the water level in Lake Pilvelis was high. Humification of sediments was low, while the content of humic substances was high, suggesting that the high water level inhibited decay of organic matter, vascular plant remains, and high volume of mineral matter in the sediments, providing notable inputs from the catchment area. The 4.0 ka event was characterised by cold and dry climate. Humification increased, while the amount of vascular plants as well as humic substances decreased. The 2.6 ka event for Lake Pilvelis is marked with

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decrease in the quantity of vascular plants, humic substances and humification, pointing to cold and wet conditions at that time. The cold event around 1750–1500 cal BP corresponds to cold and dry conditions. Since 1750 cal BP to present, the water level in lake has risen and also the humification degree has increased, whereas the quantity of vascular plants and humic substances diminished. Consequently, the lake is filled with sediments to such an extent that the rising water level does not influence the process of humification. At the same time, decrease in the quantity of vascular plants results in reduced consumption of oxygen, and its excess is available for microorganisms that are responsible for humification processes.

5. Characteristics of lake ecosystem dynamics in Southeastern Latvia

5.1. Before 9700 cal BP (First part of the Early Holocene): sediment interval (400–390 cm), pollen zone P_P-1, plant macrofossil zone P_M-1, microfossil zone P_{BC}-1, sediment type: clay

Light bluish-grey clay lying in the basis of the studied sediment section in the depth interval 400–390 cm consists of 81.91% mineral matter, 1.8% carbonates, and 16.29% organic matter. These values indicate low biota productivity in the Lake Pilvelis and intensive shore erosion in the catchment area.

Sediment in this interval is poor in aquatic plant macroremains (Fig. 5) containing small amounts of *Bryozoa* chitin fragments and *Carex*, *Betula* sect. *Albae* nutlets transported from the lake catchment area, as well as Characeae oogonia. This sediment layer is poor with microfossils represented by diatoms (*Fragilaria* spp.), desmidians (*Staurastrum* spp.) and *Spongilla* spiculas (Fig. 6). This data suggests that Lake Pilvelis was a shallow oligotrophic water basin with transparent alkaline water.

5.2. 9700–8200 cal BP (Second part of the Early Holocene): sediment interval (390–320 cm), pollen zones P_P-1 and P_P-2, plant macrofossil zone P_M-1, microfossil zone P_{BC}-2, sediment type: cyanobacteria gyttja

The next stage in the history of Lake Pilvelis started approximately 9700 cal BP, and it was characterised by a rapid decrease of mineral matter (14.83% in average), drop in the carbonate content (1.02%), and increase of organic matter, reaching 84.15%. The presence of *Najas marina* and *Najas flexilis* macrofossils indicates the beginning of eutrophication processes in the lake at this depth interval. Increase in the vascular plants, diversity of cyanobacteria genus, and sharp increase in the distribution of the benthic filamentous cyanobacteria *Lyngbya* point on significant decline in the water level (Korde, 1960). The presence of *Typha* sp. (Hannon and Gaillard, 1997) and pikes of *Insecta* (Ayieko et al., 2010) and *Cladocera* (Nevalainen et al., 2011) indicates development of a littoral zone under warmer climate conditions, when, according to sediment studies from Lake Kurjanova by Heikkila and Seppa (2010), temperatures were ~0.5 C° below the reconstructed modern temperatures. Similar changes in lake water levels approximately in this time span of the Early Holocene were also fixed in Lake Razna, Eastern Latvia (Zeimule et al., 2014), Lake Ķūžu, Central Latvia (Kangur et al., 2009), Lake Petrašiūnai and Lake Juodonys (Stančikaite et al., 2009), Briaunis paleolake, Eastern Lithuania (Gryguc et al., 2013) and Lake Sloboda, Central Belarus (Zuhovickaja et al., 1998). These lakes also are of glacigenic origin, distributed in hilly areas, and have limited inflow conditions.

During 9200–9000 cal BP, the water level of the lake increased. At that time, the quantity of *Lyngbya* remains stopped rising, the values of *Cladocera* and *Insecta* decreased, there was a short peak of rise for the planktonic cyanobacteria *Anabaena*, and the quantities of aquatic plants and green algae *Scenedesmus* sp. increased. The values of tree and shrub macrofossils, in turn, decreased from 52% to 10% and were represented only by *Betula* sect. *Albae*. Mineral matter (13.66–14.01%) and organic matter (84.87–85.01%) were variable in this period. Carbonates increased from 1.12 to 1.33%, and humic substances from 14.10 to 14.29 mg/g, suggesting a rising input of terrigenous matter from the catchment into the lake.

The cold episode known as the 8.2 ka BP cold event and the most extreme cold event after the Younger Dryas has been detected in different sedimentary environments. This event concurred with the Bond event 5b and continued approximately from 8.6 (8.3) to 8.1 ka BP (Wanner et al., 2011). It is also recognisable in the data characterising the sediments of Lake Pilvelis dated 8400–8200 cal BP. Slight decreases of mineral matter from 13.99% to 12.36% and carbonates from 0.95 to 0.90%, and humic substances from 18.85 to 15.81 mg/g, increased organic nitrogen, and the C/N ratio dropping lower than 15 show increased algae remain distribution in the sediment organic mass. A typical peak of the benthic cyanobacteria *Lyngbya* increase reached a maximum of 78%, and other cyanobacteria genera increased likewise. This can be explained by the remarkable ability of Cyanobacteria to adapt to and survive in extremely cold conditions (Zakhia et al., 2008). Green algae, which usually are found in warm, nutrient-rich waters, disappeared; only some *Scenedesmus* remains were found in this depth interval. *Cladocera* decreased, and *Insecta* disappeared completely. Detritus was found in reduced quantities, suggesting decrease in runoff from the lake catchment area. The macrofossil data shows a rapid decrease in trees and shrubs, as well as *Bryozoa*. At the end of the cold event, the *Najas flexilis* aquatic plants started to develop gradually. All these data indicates an anomalous decrease in temperature without significant changes in the lake water level. Bond et al. (1997) established that the cold event took place because of the Holocene ice-rafting event, which was a cause of the ocean surface cooling that may have been brought about by a rather substantial change in the North Atlantic surface circulation (Wanner et al., 2011). The characteristics of the cold event have also been noticed in several other lake sediment studies in Latvia. Ozola (2013) found that, in the sediments of Ancient Lake Burtnieks corresponding to this time, algae disappeared, and the amount of spherical particles increased with the supply of minerals. Usually these data are supported by the results of pollen analyses showing that the values of the thermophilous tree species pollen sharply fluctuated or declined, whereas *Betula*, *Pinus* and *Picea* increased between 8300 and 8100 cal BP (Stivrins et al., 2014). A comparison of pollen data from Lake Pilvelis, Lake Kurjanovas, Lake Razna and Mazais Svetinu Bog shows some similarities in the position and character of pollen curves (Fig. 8). The pollen curves from these sites reveal features of cooler events approximately at the time characterised by an increase of *Betula* and decrease of warmth-demanding *Ulmus*, *Tilia*, and *Quercus*.

5.3. 8200–3800 cal BP (the Middle Holocene or the Holocene Thermal Maximum): sediment interval (320–130 cm), pollen zones P_P-1 and P_P-2, plant macrofossil zone P_M-2, microfossil zone P_{BC}-3, sediment type: cyanobacteria, organic silica and peaty gyttja

After the level of 8200 cal BP Lake Pilvelis pollen diagram (Fig. 4) shows a rapid increase of *Corylus* pollen from 15 up to 30%, as well as increase in *Ulmus*, *Quercus* un *Tilia* pollen values. This feature is characteristic also in pollen diagrams from other lakes in Southeastern Latvia (Fig. 8). The predominance of aquatic plant remains like *Najas flexilis*, *Characeae*, and *Potamogeton pusillus* during the period from 8200 cal BP until 7000 cal BP suggests water level rise and depth was more than 3 m in Lake Pilvelis (Hannon and Gaillard,

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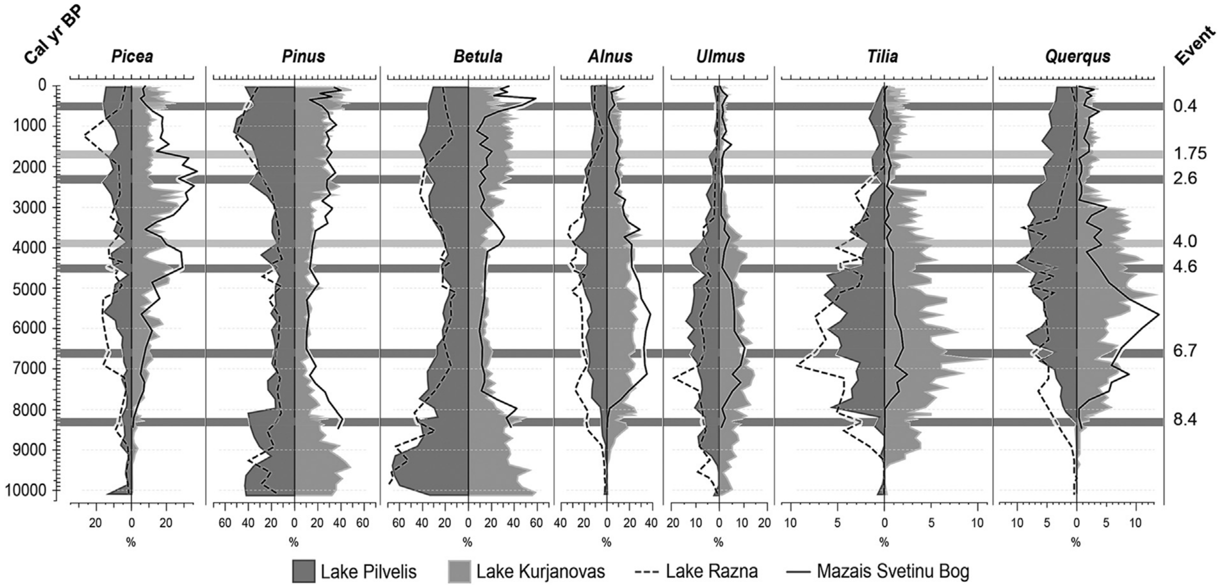

Fig. 8. Comparison of *Picea*, *Pinus*, *Alnus*, *Betula*, *Ulmus*, *Tilia* and *Quercus* pollen curves from Lake Pilvelis, Lake Kurjanovas (Heikkila and Seppa, 2010), Lake Razna (Zeimule et al., 2014) and Mazais Svetinu Bog (Stivrins et al., 2014). These lakes are situated in Southeastern Latvia.

1997). Coexistence of *Najas flexilis* and *P. pusillus* has been established in the sediments of the Holocene Thermal Maximum and Subboreal chronozone in Poland (Galka et al., 2012). The data from Lake Pilvelis concurs with the study results from Lake Ķūži located in Central Latvia, where the water level rose during the period from 8000 to 7000 cal BP. This occurred due to significant erosion of the surrounding slopes (Terasmaa et al., 2013). Rapid increase of humic substances in the sediment organic mass took place in Lake Pilvelis: from 15.81 to 67.92 mg/g, along with a rise of the C/N ratio. Decrease of cyanobacteria and increase in the amounts of green algae and vascular plant remains indicate the start of lake overgrowth. Tree and shrub macrofossils were represented mainly by *Betula* sect. *Albae*. In the gyttja microfossil composition *Lyngbya* is still present, decreasing from 72% to 43%. This and gradual decrease of *Chlorogloea*, disappearance of *Microcystis*, increase of *Anabaena* (from 4 to 10%), presence of green algae represented by *Scenedesmus* sp. and *Tetraedron* sp. indicate reduced water transparency, alkalinity and increasing water temperature at a stable water level.

The period between 8200 and 7000 cal BP for Lake Pilvelis was marked by significant quantities of *Cristatella mucedo* statoblasts. This species of bryozoa indicates a relatively higher water temperature, small wave action, medium or high levels of calcium, medium level of magnesium, slightly acidic water and medium water colour (Økland and Økland, 2000). From 7000 cal BP to 6600 cal BP, the quantity of all aquatic plants, *Bryozoa*, *Lyngbya* and green algae decreased. During the period from 6600 cal BP to 5300 cal BP, the macrofossils of aquatic and telmatic plant remains and *Bryozoa* almost disappeared, while the values of mineral matter increased from 10.09 to 36.00%, humic substances in sediment organic mass to 108 mg/g, and the planktonic cyanobacteria *Anabaena* from 8 to 22%, pointing to a significant water level rise in Lake Pilvelis.

Similar water level changes have been determined approximately at the same time period in Lake Ķūžu (Terasmaa et al., 2013) and Lake Juusa (Punning et al., 2005), as well as in Lake Sloboda (Zuhovickaja et al., 1998). Changes of this kind in the lake biota communities could be induced not only by water level rise but also by cold temperature anomalies during around 6600 to 6400 cal BP. This has been demonstrated by a pollen-based reconstruction of summer temperatures in a study of Lake Kurjanovas sediments (Heikkila and Seppa, 2010). The study results show that the decrease of temperature for almost 1 °C happened around 6650 to 6400 cal BP. As this occurred in the period of Holocene Thermal Maximum, with the mean anomaly of +3.0 C° (Wanner et al., 2011), this drop was not marked as a negative temperature anomaly in the areas of Scandinavia. The rise in the water level in Lake Pilvelis during the same time does not provide for a strong evidence of temperature decrease in summers. Since 5300 cal BP, the C/N ratio increased to 20, humification and humic substances in organic matter rose from 77 to 107 mg/g, and the green algae *Botrycoccus* appeared. Ji et al. (2010) have found abundant *Botrycoccus* fossils in organic-rich dark mudstones and carbonaceous mudstones formed from ancient mud. They noted that *Botryococcus* is rarely found at the depth greater than 100 cm, as it is autotrophic algae, which needs sufficient sunlight and calm, clear water (Ji et al., 2010). The mentioned facts and point to possible bogging-up processes in the surrounding areas of Lake Pilvelis and minor lake surface reduction, as well as water level decrease, reaching the minimum approximately around 4000 cal BP.

The Holocene Thermal Maximum in the Baltic region took place around 8000–4500 cal BP (Seppa and Poska, 2004). Significant changes in the vegetation development are also estimated to have taken place approximately 4500 cal BP in Seda Mire, North Vidzeme Lowland, where there were more favourable conditions for mire overgrowth by forest, which is clearly noticeable by the preserved wood layer covering the wood peat layer in peat profiles (Kalnina et al., 2009, 2014). Our study data to the Holocene Thermal Maximum conditions starting after the 8.2 ka event and ending before the 4.0 ka event, which is slightly different from that of the aforementioned study, but accords with the Middle Holocene boundary discussed in Walker et al. (2012). Pollen studies from Southeastern Latvia determined that before 4000 cal BP *Betula* pollen was minor, but warmth-demanding tree pollen were abundant. After 4000 cal BP in all studied sites, the amount of *Betula* pollen starts to slightly increase, but *Quercus*, *Tilia*, *Ulmus* and *Alnus* decrease. The 4.0 event coincides with the Bond event 3 and is indicated by negative temperature anomalies in Greenland, North America, Africa and Antarctica (Wanner et al., 2011). Probably this was the reason of the extreme water level decrease in Lake Pilvelis under cold and dry climate conditions, when *Hypnum* peat with *Lyngbya* started to form and covered the layer of peaty gyttja. According to this study results, the conditions are comparable with the 4.0 event which took place in Lake Pilvelis during 4000–3800 cal BP. It is indicated by the sharply reduced content of humic substances from 103 to 74 mg/g, lower humification, decrease in the quantity of vascular plant remains to 22% (almost twice), and disappearance of *Insecta*, while the values of *Lyngbya* increased from 2 to 16%, reaching the maximum, and moss *Bryales*, mainly represented by *Hypnum*, rose from 6 to 20%.

5.4. 3800 cal BP – present (Late Holocene): sediment interval (130–0 cm), P_P-5 and P_P-6, plant macrofossil zones P_M-4 and P_M-5, microfossil zones P_{BC}-6 and P_{BC}-7, sediment type: peaty and zoogenic-algae gyttja, Bryales peat

The high values of *Anabaena* and *Cladocera* and decrease in *Bryales* remains suggest that the water level in Lake Pilvelis slightly rose since 3800 cal BP, followed by water level decrease around 3000 cal BP, indicated by a drop of *Anabaena* and sharp growth in the values of vascular plants. According to Stivrins et al. (2014), the short dry event is also recorded in Lake Mazais Svetins located in the Rezekne region, and it is detected in many wetlands in Latvia during that time (Kalnina et al., 2014, Fig. 3).

The next cold event (conditionally comparable to Bond event 2) can be recognised in the sediments of Lake Pilvelis approximately before 2600–2400 cal BP, when the water level in the lake rose again and zoogenic-algae gyttja accumulated. The composition of gyttja is characterised by increase and stable values of *Anabaena* and Bryales, decrease in green algae, and disappearance of *Scenedesmus*, showing lower temperatures and higher humidity. Colder and wetter conditions have also been reconstructed for Lake Ruila in Estonia (Seppa and Poska, 2004). Similar features have been recognised in many sediment records in continental Europe, showing increased wetness, generally corresponding to the Blitt-Sernander Subboreal–Subatlantic transition (Chambers et al., 2010a). The humification degree of sediments in Lake Pilvelis sharply decreased and humic substances were reduced to 93 mg/g during this cold event.

Significant climate amelioration took place after the cold event approximately before 2400–1750 cal BP, which is indicated by increase in *Anabaena* from 15 to 30% and in vascular plants and *Insecta*, appearance of *Scenedesmus* and *Hepaticae*, decrease in Bryales, and increase in aquatic plants (*Potamogeton natans*, Characeae). For a period since that time until present, increase in the values of mineral matter (7.05–11.66) and carbonates (0.23–0.55%) in the sediment composition was determined, which can probably be explained by human presence and activities in the area.

Records from the sediments dated 1750–1500 cal BP or 360–610 AD indicate some drop in water level by decrease of *Anabaena* (8%) and disappearance of green algae, except *Botryococcus*, usually increasing during dry conditions in the studied profile. The humification degree decreased, while the values of humic substances increased, which can be explained by significant spread of vascular plants due to dry conditions.

The results from the uppermost part of the section do not allow proper characterisation of changes in climate and sedimentation conditions of Lake Pilvelis. During the period of 1500–1000 cal BP, some weakly-expressed climate amelioration took place, indicated by an increase of *Anabaena* and green algae and particularly by the appearance of *Scenedesmus*, suggesting higher water level.

The historical data indicate that climate deterioration took place during 700–500 cal BP or 1350–1850 AD. In this study, the key evidences suggesting climate deterioration are the drop in the quantity of aquatic animals, including *Cladocera*, *Insecta* and *Spongilla*, disappearance of green algae, and decrease in *Anabaena*.

The data complex obtained from multiproxy studies of sediments from Lake Pilvelis indicates significant changes in the depositional environment during the lake development. Diagrams and data sets show six remarkable comparatively short cooling periods during the Holocene, which are related to changes in temperature and water level, and influenced values and variability of remains.

The investigation data allow recognition of the 8.4 ka BP and 4.6 ka BP cold events, while other cooling events can be recognised conditionally. These events are characterised by decrease in temperature and have different humidity and lake water level. Cooling is usually associated with higher or increased water level. However, during the events of 1.75 ka BP and 4.0 ka BP, the water level decreased and the climate was probably drier.

6. Conclusions

Changes in lithology, organic matter content and composition, as well as macrofossils and pollen data in the sediment profile of Lake Pilvelis represent not only local changes in the lake catchment area but also those in the lake development during the Holocene in Southeastern Latvia. The multiproxy records from the sediments of Lake Pilvelis indicate significant changes in the composition of sediments during the development of the lake caused by water level changes and climatic cold events. Since 9700 cal BP, Lake Pilvelis started to accumulate organogenic sediments – gyttja, rich in remains of benthic cyanobacteria *Lyngbya*. The higher *Lyngbya* population was fixed during the 8.2 ka event (in Lake Pilvelis: 8500–8200 cal BP). In the beginning of the Middle Holocene, the *Lyngbya* population started to decrease and the quantities of aquatic plants grew higher, pointing to a decrease in the water level. Around 6500 cal BP, the water level in the lake sharply increased, intensive erosion of shores started, and the summer temperatures probably fell. This was the reason for the disappearance of aquatic plants and increase of the benthic cyanobacteria *Anabaena* to. Since around 5300 cal BP, the water level in the lake started to decline. A lower water level in the lake was also estimated during the 4.2 ka event in the period of 4000–3800 cal BP, when *Hypnum* peat with *Lyngbya* formed, covering the peaty gyttja layer. Since the Late Holocene, 3800 cal BP, the water level in Lake Pilvelis has been variable. Another cold event is clearly reflected by the data derived from gyttja deposited during approximately 2400–2200 cal BP. As indicated by *Anabaena*, there were cold and wet conditions during this event.

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