VILNIUS UNIVERSITY
NATURE RESEARCH CENTRE

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The influence of natural and anthropogenic factors on the development of Lateglacial and Holocene (a)biotic palaeoenvironment in the southeastern flank of the Last Scandinavian Glaciation

DOCTORAL DISSERTATION

Natural Sciences,
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GAMTOS TYRIMŲ CENTRAS

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Gamtinių ir antropogeninių veiksnių įtaka vėlyvojo ledynmečio ir holoceno (a)biotinės aplinkos raidai paskutinio Skandinavijos ledyno pietrytiniame pakraštyje

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CONTENTS

LIST OF ABBREVIATIONS

(a)biotic – biotic and abiotic
a.s.l. – above sea level
AMS – Accelerator Mass Spectrometry
AP – Arboreal Pollen
BCE/CE – Before the Common Era/ Common Era
cal yr BP – calibrated years before present
ChEAZ – chemical element assemblage zone
CONISS – Constrained cluster analysis (Constrained Incremental Sums of Squares cluster analysis)
EDS – Energy Dispersive Spectrometry
HTM – Holocene Thermal Maximum
ICS – International Commission on Stratigraphy
Ka – thousand years
LG – Lateglacial
LGM – Last Glacial Maximum
LOI – loss-on-ignition
MSus – magnetic susceptibility (mass)
NAP – Non-Arboreal Pollen
NGRIP – North European GReenland Ice core Project
NMDS – Non-metric Multidimensional scaling technique
NRC – The State Scientific Research Institute Nature Research Centre
OAC – Open Access Center
PCA – Principal Component Analysis
QM – Quarcetum Mixtum
SEM – Scanning Electron Microscopy
yr b2k – before two thousand years

LIST OF ORIGINAL PUBLICATIONS

Doctoral dissertation is based on the following co-authored original publications which are in the Clarivate Analytics Web of Science and other peer review process publications.

I. Edvardsson, J., Stančikaitė, M., Miras, Y., Corona, C., Gryguc, G., **Gedminienė, L.,** Mažeika, J., Stoffel, M. 2018. Late-Holocene vegetation dynamics in response to a changing climate and anthropogenic influences–Insights from stratigraphic records and subfossil trees from southeast Lithuania. *Quaternary Science Reviews*, 185, 91–101. (IF 4.641, Q1).

II. Stančikaitė, M., **Gedminienė, L.,** Edvardsson, J., Stoffel, M., Corona, C., Gryguc, G., Uogintas, D., Zinkutė, R., Skuratovič, Ž., Taraškevičius, R. 2019. Holocene vegetation and hydroclimatic dynamics in SE Lithuania–Implications from a multi-proxy study of the Čepkeliai bog. *Quaternary International*, 501(A), 219–239. (IF 1.952, Q2).

III. Stančikaite, M., Simniškytė, A., Skuratovič, Ž., **Gedminienė, L.,** Kazakauskas, V., Uogintas, D. 2019. Reconstruction of the Mid- to Late- Holocene history of vegetation and land-use in Petrešiūnai, north-east Lithuania: implications from palaeobotanical and archaeological data. *Quaternary International,* 516, 5–20. (IF 1.952, Q2).

IV. **Gedminienė, L.,** Šiliauskas, L., Skuratovič, Ž., Taraškevičius, R., Zinkutė, R., Kazbaris, M., Ežerinskis, Ž., Šapolaitė, J., Gastevičienė, N., Šeirienė, V., Stančikaitė M. 2019. The Lateglacial-Early Holocene dynamics of the sedimentation environment based on the multi-proxy abiotic study of Lieporiai palaeolake, Northern Lithuania. *Baltica*, 32 (1), 91–106. (IF 0.5, Q4).

V. Spiridonov, A., Balakauskas, L., Stankevič, R., Kluczynska, G., **Gedminienė, L.**, Stančikaitė, M. 2019. Holocene vegetation patterns in southern Lithuania indicate astronomical forcing on the millennial and centennial time scales. *Scientific reports, 9* (1), 1–15. (IF 4.525, Q1).

THE AUTHOR‘S CONTRIBUTION

In Papers I-V the analyses were proceeded and the results published by multiple authors:

I. Collaboration in project planning and accomplishment: EJ (Edvardsson Johannes), SM (Stančikaitė Miglė), MY (Miras Yannick), CC (Corona Christophe), SMar (Stoffel Markus); fieldwork: EJ, SM, MY, CC, KG

((Kluczynska) Gryguc Gražyna), MJ (Mažeika Jonas), SMar; description of sediment lithology, palynological and macrobotanical studies: SM, KG, **GL (Gedminienė Laura);** MSus measurement, LOI: **GL**; radiocarbon datings: MJ, age-depth modeling and calculation of sedimentation ratios: MJ, **GL;** tree ring records: EJ, MY, CC, SMar; data interpretation and statistical treatment: SM, EJ; compilation of diagrams, figures and tables: EJ, SM, MY, CC, KG, **GL**, SMar; writing the article: EJ, SM, MY, CC, KG, **GL**, MJ, SMar.

II. Project planning and accomplishment: SM, **GL**, EJ, SMar, CC, KG; fieldwork: SM, EJ, SMar, CC, KG; description of sediment lithology: **GL**, SM; palaeobotanical studies and analysis: KG, **GL**, SM; geochemical analysis: **GL**, TR (Taraškevičius Ričardas), ZR (Zinkutė Rimantė); MSus, LOI analyses: **GL**; radiocarbon dating: SŽ (Skuratovoč Žana); age-depth modeling and calculation of sedimentation ratios: SŽ, **GL**; tree replication based on the results published: EJ, SMar, CC; principal component analysis: UD; interpretation of data and result compilation: SM, **GL**; compilation of diagrams, figures and tables: **GL**, UD; writing the article: all authors.

III. Project planning, fieldwork, description of sediment lithology: SM, SA (Simniškytė Andra); archaeological data and situation reconstruction: SA; palaeobotanical studies and analysis: SM; MSus analyses: **GL**; radiocarbon dating: SŽ; age-depth modeling and calculation of sedimentation ratios: SŽ, **GL**; principal component analysis: UD; interpretation of data and result compilation: SM, SA, **GL**; compilation of diagrams, figures and tables: SM, SA, **GL**, UD, KV (Kazakauskas Vaidotas); writing the article: all authors.

IV. Project planning, fieldwork: SM, ŠV (Šeirienė Vaida); project accomplishment **GL**, SM; chemical element content determination: **GL**, TR; SEM: ŠL (Šiliauskas Laurynas), **GL**; grain size determination: KM (Kazbaris Mindaugas); dating: EŽ (Ežerinskis Žilvinas), ŠJ (Šapolaitė Justina); chronological scale modeling: SŽ; comparison of MSus, LOI, chemical element content, grain size data and modeling **GL**; chironomid analysis: GN (Gastevičienė Neringa); writing the article: **GL**, SM, SŽ, ZR.

V. Research design and accomplishment: SA (Spiridonov Andrej), BL (Balakauskas Lauras), SM; contributed the analytical tools and comparative data and/or discussed the manuscript in progress: SA, KG, **GL,** SM; data analysis SA, SR (Stankevič Robertas); writing the article: SA, BL and SM.

APROBATION OF THE RESULTS

The key results of the research presented at the proceedings of the international conferences:

1. Spiridonov, A., Balakauskas, L., Stankevič, R., Kluczynska, G., **Gedminienė, L.**, Stančikaitė, M. 2019. A case of astronomical forcing – evidence from the south-east Baltics. 20th Congress of the International Union for Quaternary Research (INQUA), Dublin, Ireland.
2. Dietze, E., Theuerkauf, M., the **CEL Holocene fire team**. 2018. Holocene fires in the central European lowlands and the role of humans. EGU General Assembly, Vienna. Geophysical Research Abstract book, vol. 20, EGU2018–9629.
3. Stančikaitė, M., Simniškytė, A., Skuratovič, **Gedminienė, L.,** Uogintas, D. 2018. Holocene human-nature interaction in NE Lithuania: an example of the vegetation and land-use history in the surroundings of Petrešiūnai Hillfort. EGU General Assembly, Vienna. Geophysical Research Abstract book, vol. 20, EGU2018–19075–1.
4. **Gedminienė, L.,** Gastevičienė, N., Stančikaitė, M., Šiliauskas, L., Šeirienė, V., Kisielienė. D. 2017. Lateglacial and Early Holocene (a)biotic environment in response to climatic shifts: an example from Lieporiai Lake, Northern Lithuania. INQUA Peribaltic Working Group Meeting and Excursion, Finland. Excursion guide and Abstract book, 165–166.
5. **Gedminienė, L.,** Stančikaitė, M., Taraškevičius, R., Gryguc, G., Zinkutė, R., Mažeika, J. 2016. Holocene history of environmental dynamics: multi proxy approach from the Čepkeliai Highmoor, SE Lithuania. INQUA Peribaltic Working group meeting & International field symposium, Poland. Abstract book, 39.
6. **Gedminienė, L.,** Gudaitienė, G. 2016. Chemical and physical composition of disturbed and less disturbed soil of the Dūkšteliai 1 site. 22 nd Annual Meeting of the EAA, Vilnius. Abstract book, 290**.**
7. **Gedminienė, L.,** Gudaitienė, G., Zinkutė, R., Taraškevičius, R., Stančikaitė, M. 2015. Anthropogenic impact or natural environmental change: new data based on palaeobotanical and geochemical analysis of Dūkštelis lake sediments. INQUA Peribaltic Working group meeting & International field symposium, Netherlands. Abstract book: Quaternary Geology and Modern Questions, 55–57.
8. **Gedminienė, L.,** Rimkutė, G., Stančikaitė, M. 2014. Post-glacial environmental changes and the earliest human inhabitance of the Lake Dukštelis area, Eastern Lithuania. INQUA Peribaltic Working group

meeting & International field symposium "Late Quaternary terrestrial processes, sediments, and history: from glacial to postglacial environments", Latvia. Excursion guide and Abstract book, 106–108.

RELATED PUBLICATIONS (NOT INCLUDED IN THIS DISSERTATION)

VI. Dietze, E., Theuerkauf, M., Bloom, K., Brauer, A., Dörfler, W., Feeser, I., Feurdean, A., **Gedminienė, L.**, Giesecke, T., Jahns, S., Kołaczek, M., K., Kołaczek, P., Lamentowicz, M., Latałowa, M., Marcisz, K., Obremska, M., Pędziszewska, A., Poska, A., Rehfeld, K., Stančikaitė, M., Stivrins, N., Musznicka, J., S., Szal, M., Vassiljev, J., Veski, S., Wacnik, A., Weisbrodt, D., Wiethold J., Vannière, B., Słowiński, M. 2018. Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. *Quaternary Science Reviews*, 201, 44–56. (IF 4.797, Q1).

VII. Taraškevičius, R., Motiejūnaitė, J., Zinkutė, R., Eigminienė, A., **Gedminienė, L.**, Stankevičius, Ž. 2017. Similarities and differences in geochemical distribution patterns in epiphytic lichens and topsoils from kindergarten grounds in Vilnius. *Journal of Geochemical Exploration*, 183, 152–165. (IF 2.464, Q2).

VIII. Taraškevičius, R., Zinkutė, R., **Gedminienė, L.**, Stankevičius, Ž. 2017. Hair geochemical composition of children from Vilnius kindergartens as an indicator of environmental conditions. *Environmental Geochemistry and Health*, 1–24. (IF 2.994, Q1–Q2).

IX. Šeirienė, V., Šinkūnas, P., Stančikaitė, M., Kisieliene, D., **Gedminienė, L.** 2019. Late Middle Pleistocene interglacial sediments from Buivydžiai site, eastern Lithuania: A problem of chronostratigraphic correlation. *Quaternary International*, 534, 18–29. (IF 2.199, Q2).

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SCIENTIFIC PROBLEMS

Attention to palaeoenvironmental studies is rapidly growing in the world. The characterization of the history of natural environmental change is exclusively relevant in order to understand current fluctuations of climate in the chronological perspective and with the help of changing patterns to predict possible scenarios of climate changes that would ensure a safe environment for future human generations.

The characteristics of the environmental situation of the LG and Holocene indicated in the marginal area of the Last Scandinavian Glaciation during the recent years are significantly different from those accepted for many years. For example, in North and North-eastern Europe, a delayed GI-1 warming (Veski et al., 2015) and a delayed natural environment response to the warming in the beginning of the Holocene (Wohlfarth et al., 2007; Stančikaitė et al., 2008a, 2015; Lauterbach et al., 2011) are fixed. In the northernmost part of Europe, particularly early onset of HTM appears (Väliranta et al., 2015). On the other hand, the recordings of the development of palaeoenvironmental constituents show an adequately synchronous response to the *"Preboreal Oscillations"* of the Early Holocene climate that are incident to the western part of Europe (Björck et al., 1997; Bond et al., 2001; Wanner et al., 2008), "*8.2 Ka*" cooling (Seppä, Poska, 2004; Veski et al., 2004, 2015; Gałka et al., 2014), HTM, and Late Holocene cooling (Seppä, Poska, 2004). Sedimentation environment during the Holocene has been quite actively researched in the region over the recent decades (Stivrins et al., 2014; Veski et al., 2004, 2012, 2015; Heikkilä, Seppä, 2010; Šeirienė et al., 2009; Gaidamavičius et al., 2011; Gryguc et al., 2013; Kabailienė et al., 2015); however, studies discussing abiotic environment investigations remain rather scarce. It is clear that chronostratigraphically constrained geochemical studies of sediments of lakes and bogs representing this period, and the analysis of the results obtained in the context of globally and locally recorded fluctuations in environmental conditions (Goslar et al., 1999; Engstrom, Wright 1984; Koinig et al., 2003; Kylander et al., 2013a, Stančikaitė et al., 2015), vegetation cover and sedimentation regime required additional attention in the territory of Lithuania and surrounding territories in particular.

In order to fill up the existing gap, the impact of global and local factors, such as solar cycles, climate change or human activity, geological-geomorphological situation, etc., on the (a)biotic environment components has been evaluated. The territorial and chronological definition of previously unrecorded changes of palaeoenvironmental situation was of primary importance. The analysed time-frame includes the LG and the Holocene. The results of the multi-proxy studies that were primarily based on palynological and geochemical data allowed us to identify a long-term history of terrestrial and aquatic vegetation and a long-term chemical variation of the sediments in the context of natural and anthropogenic, local and global factors first of all. Solutions dealing with different aspects of this problem were presented by the Author and her Colleagues in five main (**Papers I-V**) and four additional (**Papers VI-IX**) publications.

The cyclicities which can be observed in the past solar activity patterns belong to one of many natural, globally captured processes which have a major influence on centennial, millennial, etc. climate cycles and changes in the environment (**Paper V**).

Although the complex studies performed in the recent decades in the Baltic region were focused on the LG vegetation dynamics and ecosystem changes (Šeirienė et al., 2006; Heikkilä et al., 2009; Stančikaitė et al., 2008a, 2015; Veski et al., 2012; Balakauskas et al., 2013; Amon et al., 2014; Druzhinina et al., 2015; Stivrins et al., 2015), the majority of them were based on the analysis of the biotic proxy data exclusively. While analyzing the palaeoenvironmental history of this period the Author has also invoked abiotic parameters. The conducted assessment has enabled to describe the response of the abiotic environment to the natural external factors of different scale (**Paper IV**).

The Holocene palaeoenvironment history has been quite actively analyzed in the region over the recent decade (Stivrins et al., 2014; Veski et al., 2004, 2012, 2015; Heikkilä, Seppä, 2010; Šeirienė et al., 2009; Gaidamavičius et al., 2011; Gryguc et al., 2013; Kabailienė et al., 2015); however, studies discussing abiotic environment investigations remain rather scarce. It is clear that chronostratigraphically constrained geochemical data and in particular the analysis of the results obtained in the context of globally and locally recorded environmental fluctuations in the region (Goslar et al., 1999; Engstrom, Wright 1984; Koinig et al., 2003; Kylander et al., 2013a) and in the territory of Lithuania (Stančikaitė et al., 2015) required additional attention, and the Author emphasized it in the studies performed (**Papers II** and **III**).

When analyzing the environmental history and the relationship of the identified fluctuations in external conditions with local and global factors it is essential to evaluate the potential impact of human activity on the palaeoenvironment. A particularly strong influence was fixed when the development of agriculture and animal husbandry was introduced (Maldre, Luik, 2009; Simniškytė, 2013; Daugnora, Girininkas, 1998; Girininkas, 2002; Poska, Saarse, 2006) in the region. Willing to assess such fluctuations, the impact of expected human activity on the biotic and abiotic environment should be modeled taking into account the context of global climate warming, the background values of the region and its' individual parts and geological-geomorphological situation. The carried out analysis of the (a)biotic environmental parameters and the analysis of the collected information in the context of global and local factors, taking into account the history of human impact fixed in the region, are presented in two publications (**Papers I** and **III**).

THE AIM OF THE RESEARCH AND OBJECTIVES

To determine the influence of natural (astronomical, global, regional, and local) and anthropogenic factors on the development of the (a)biotic palaeoenvironment in the SE flank of the Last Scandinavian Glaciation based on high-resolution multi-proxy records of the LG and Holocene age.

Objectives:

1. To construct the chronologically defined scale of sediment columns using the properties of ^{14}C isotopes.
2. To reconstruct the chronologically defined history of LG and Holocene vegetation changes in the context of natural and anthropogenic factors.
3. To identify the chronologically defined dynamics of the abiotic parameters evaluating the peculiarities of chemical element accumulation under the influence of various factors first of all.
4. To evaluate the interdependence of recorded changes in biotic and the abiotic environmental parameters.
5. To assess the changes fixed in the (a)biotic environment in relation to various-scale natural (astronomical, global, regional, and local) and anthropogenic factors.

THE NOVELTY AND RELEVANCE OF THE RESEARCH

For the first time the high-resolution abiotic proxy records including geochemical data have been used in order to describe the dynamics of the LG and Holocene palaeoenvironmental history and to assess the nature of the captured fluctuations in the context of various-scale external factors.

The complex studies of the terrestrial and aquatic vegetation history and interpretation of the obtained results by taking into account their dynamics in the context of natural (astronomical, global, regional, and local) and anthropogenic processes allowed to identify the stages of the biotic palaeoenvironment that had not been captured before in the region.

The results obtained were synchronized in regard to the NGRIP chronological scale and a new chronostratigraphical subdivision of the Holocene geological period.

1. BRIEF LITERATURE REVIEW

The multi-proxy investigations conducted in various parts of Europe throughout the last decades have provided new insights into environmental and climate dynamics during the LG and Holocene. Some regions which are located in the transitional climatic, vegetation, etc. zones are especially sensitive to the influence of natural and anthropogenic factors, and sediments accumulated in such zones perfectly reflect various aspects of the palaeoenvironmental history. The SE flank of the Last Scandinavian Glaciation, including the Eastern Baltic, could be indicated as one of such areas, thus a number of investigations conducted there throughout the last decades is great. While reconstructing the tendency of the local and regional vegetation dynamics, much attention was paid to palaeobotanical research in the countries around the region: in Estonia (Amon et al., 2012, 2010), Latvia (Stivrins et al., 2014; Heikkilä et al., 2009; Heikkilä, Seppä, 2010; Kalnina, 2004), Poland (Kołaczek et al., 2015; Gałka, Tobolski, 2012; Karasiewicz et al., 2019; Apolinarska et al., 2012), Kaliningrad Oblast (Druzhinina et al., 2015), E part of the Baltic region (Veski et al., 2012, 2004), and Lithuania (Stančikaitė et al., 2015, 2008a, 2008b, 2002; Gaidamavičius et al., 2011; Šeirienė et al., 2006). The dynamic of the biotic environment was assessed according to the stratigraphical and palaeogeographical aspects (Heikkilä et al., 2009; Salonen et al. 2012). While studying the long-term changes in the geochemical composition of sediments, a lot of attention is dedicated to the classification of chemical elements and their associations (Koinig et al., 2003; Rydberg, Martinez-Cortizas 2014). In the studies of sediments, some elements are interpreted as indicators of climate, hydrological state, temperature, evaporation, and trophicity of a basin (Koinig et al., 2003; Naeher et al., 2013; Kylander et al., 2013b; Dypvik, Harris, 2001). Although these results generally reflect a sequence of development of the natural environment in a particular territory or a sediment basin, only part of studies on geochemical elements considered changes of climate and vegetation in the regional context (Pawłowski et al., 2016; Apolinarska et al., 2012; Koinig et al., 2003). The above-mentioned data sets together with chironomidae and $\delta^{18}O$ and $\delta^{13}C$ isotopes data were used for quantitative palaeoclimate reconstructions, i.e. reconstruction of LG and Holocene summer and winter temperatures (Nazarova et al., 2017; Veski et al., 2015; Kołaczek et al., 2015; Mirosłav-Grabowska, 2015; Veski et al. 2015; Seppä, Poska, 2004; Heikkilä, Seppä, 2010; Davis et al., 2003; Zernitskaya, Kalicki, 2008; Novik et al. 2010) in the region.

2. MATERIAL AND METHODS

2.1. Study sites

The study area is located in the E Baltic region of Europe (Fig.1). The main relief of land surface of this territory is mainly a combination of moderate lowlands and highlands formed by the Pleistocene Glaciations (Guobytė, Satkūnas, 2011; Stančikaitė et al., 2008a, 2008b; Satkūnas et al., 2009). During Late Weichselian Glaciation and Holocene, the territory took the current shape with various forms of dominating Quaternary sediments (i.e. moraine uphills, glaciofluvial plains, glaciolimnic lowlands, etc.) varying from about 10–30 to 200–300 m a.s.l. The study sites are located within the area of the marginal formations of the Middle Lithuanian Phase (Lieporiai, N Lithuania) and the marginal area of the surface affected by the Baltic (Pomeranian) Stage of the South Lithuanian Phase (Petrešiūnai, NE Lithuania, and Čepkeliai, SE Lithuania) (Guobytė, Satkūnas, 2011). The chosen area of the studies which includes part of the Eastern Baltic region is attributed to the transitional zone between the marine and continental climate, and the junction of boreo-nemoral vegetation communities (Ozenda, Borel, 2000). A brief description of the studied sites is given in Table 1 and shown in Fig.1.

Table 1. The study sites description.

Site	**Čepkeliai peat bog (Čepkeliai)**	**Lieporiai palaeolake (Lieporiai)**	**Lake Petrešiūnai (Petrešiūnai)**
Location of the coring point	54° 00′ 48″ N, 24° 37′ 01″ E	55° 54′ 04″ N, 23° 14′ 12″ E	55° 50′ 52″ N, 25° 42′ 10″ E
Altitude, m a.s.l.	128.5–134.4	122	107
Site size	5858 ha	8 ha	1.5 ha
Discussed interval of sediment sequence, cm	100–210 and 200–1200	40–200	121–813
Maximum lake depth, m	-	-	4-5
Annual temperature	+6.2 °C	+6 °C	+6.1 °C–+6.7 °C
January average temperature	-5.4 °C	-7 °C	-4.8 °C–-3.8 °C
July average temperature	+17.7 °C	+18 °C	+18 °C
Annual precipitation mm yr^{-1}	673	592	600

Site	Čepkeliai peat bog (Čepkeliai)	Lieporiai palaeolake (Lieporiai)	Lake Petrešiūnai (Petrešiūnai)
Landscape, geomorphology	Wetland complex is lying in the glaciolacustrine plain stretching along the marginal formations of the Late Weichselian Glaciation. Hummocky moraines and till plains of Late Weichselian Grūda Stage border the area from SE, and continental dunes of Late Pleistocene age extend from W and NW	Small glaciofluvial depression surrounded by the hills of the end moraine crossing the marginal formations of the Late Weichselian Glaciation of the Middle Lithuanian Phase (Baltic Stage)	Shallow eutrophic lake of thermokarst origin situated in the palaeo-incision of glaciofluvial origin formed by the Late Weichselian Glaciation (Baltic Stage). The territory of the lake is surrounded by glacial moraines, glaciofluvial ridges, and hills from N and NW and glaciolacustrine sediments from S
Underlying deposits	The peat layer is underlain by the sediments of glaciolacustrine origin - silty and clayey sand predominantly	Calcareous gyttja is underlain by glaciolacustrine sediments with admixture of glaciofluvial coarse-grained sand or gravel. Representation of Devonian carbon-enriched deposits close to the present surface	Gyttja underlain by glaciofluvial origin sediments
Hydrology (outflow/inflow)	Mostly fed by groundwater and in situ rainfall. Excess drains to the Musteika (inflow of the Grūda) and Lynupis (inflow of the Ūla) rivers and numerous streams. Belongs to Katra, Ūla and Grūda basins	Mostly fed by groundwater and in situ rainfall. Outflow feeds Šventupis the River, which discharges into Bubiai Dam and also drains to the Švendrelis River which belongs to the upper reaches the Lielupis drainage basin	Mostly fed by groundwater and in situ rainfall. Its outflow Vargupys River connects with the Audra River and Lake Sartai. Belongs to the very northern part of the Šventoji River basin
Vegetation	Raised bog common species: various colored *Sphagnum* (i.e. *magellanicum*, *cuspidatum*), *Vaccinium*, *Ledum*, *Andromeda*, *Calluna vulgaris, Eriophorum*, *Calla palustris* on the periphery; lowland sedge bogs common species Carex, Cyperaceae, *Alnus glutinosa* with *Caltha palustris*; march area surrounded by dry *Pinus-Betula* forests	Herbs and grasses predominate. The territory is forested with *Populus, Populus tremula, Betula pendula, Betula pubescens, Alnus glutinosa, Alnus incana* growing in uncultivated lowlands, *Tilia cordata* growing by the roads. Surrounding grasslands currently converted to agricultural lands	Boggy area, surrounded by *Betula pubescens* and *Alnus glutinosa* forests, grasslands currently converted to agricultural lands

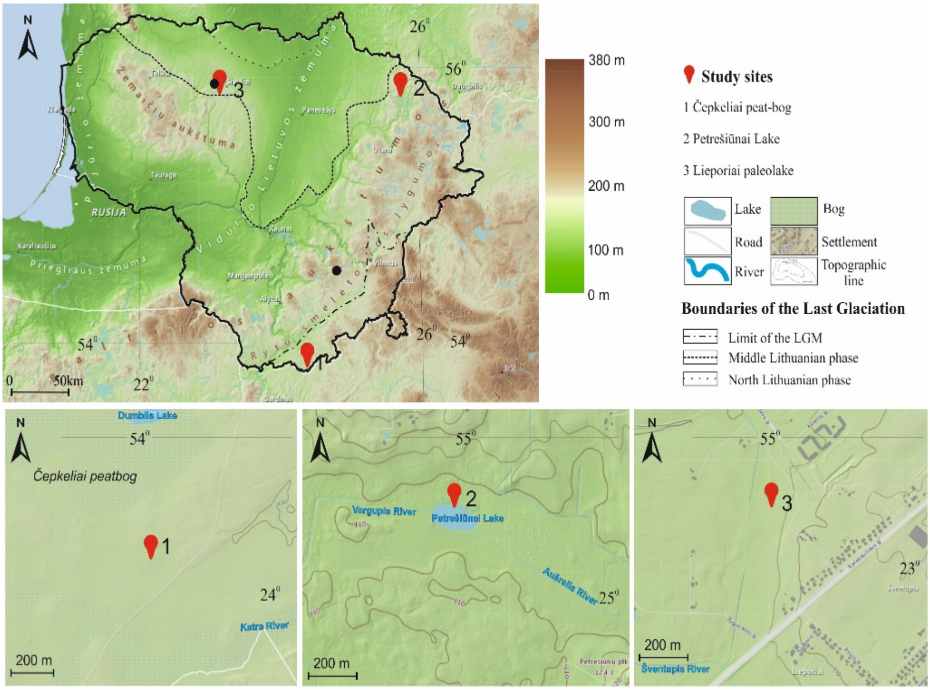

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Figure 1. Location of the study sites.

2.1.1. Sediment sampling

The coring methods, sampling strategy, lithological profiles, and analytical methods applied are shown in Table 2 and described in **Papers I**, **II** and **V** (Čepkeliai), **Paper III** (Petrešiūnai), and **Paper IV** (Lieporiai).

2.2. Analytical methods

Most multi-proxy studies for sediment sequences were carried out at the NRC in Vilnius, Lithuania. In addition, the facilities of the OAC of the NRC have been involved. More details are given in publications (**Papers I-V**).

The pollen investigations (**Papers I-V**) and analysis of the assemblages of chemical elements (**Papers II** and **IV**) could be interpreted as the study methods of primary importance. To obtain additional information, multi-proxy analyses (i.e. MSus, LOI, grain-size determination, macro-botanical, ^{14}C and AMS dating) were performed. The analyses applied and the number of samples analyzed are shown in Table 2.

Table 2. Analytical methods and the number of samples analyzed.

	Papers	Čepkeliai	Petrešiūnai	Lieporiai
Radiocarbon (^{14}C, AMS) dating	**I – V**	16	6	5
Pollen analysis	**I – V**	149	86	33
Geochemical analysis	**II, IV**	76	-	48
Charcoal	**III**	149	86	33
LOI	**I, II, IV**	182	-	41
MSus	**I – IV**	550	335	81
Plant macrofossils analysis	**I, II**	231	-	-
Grain size determination	**IV**	-	-	26
SEM	**IV**	-	-	5
Publications		**I, II, V**	**III**	**IV**

2.2.1. Pollen analysis

The standard chemical procedures were used when preparing samples for pollen analysis in case of Čepkeliai and Petrešiūnai (**Papers I, II** and **III**) (Erdtman, 1936; Grichuk, 1940). While the preparation of Lieporiai samples (**Paper IV**) that included the combined pretreatment of the sediments with cold 40% and/or hot 70% HF acid (Berglund, Ralska-Jasiewiczowa, 1986; Bennett, Willis, 2001) was performed at the Tallinn University of Technology, Institute of Geology. To determine the concentration of pollen, *Lycopodium clavatum* tablets were added (Stockmarr, 1971). Pollen identification relies on Moore et al. (1991), Faegri, Iversen (1989) and PalDat – an online palynological database (2000 onwards, www.paldat.org). In the construction of the cumulative pollen percentage diagram, taxa are grouped according to the presumed ecological requirements (Ermolli, 2000; Berglund, Ralska-Jasiewiczowa, 1986) (**Papers I, II** and **III**). In order to describe the changing landscape utilization practices, particular species were grouped following Behre (1981) and taking into account suggestions provided by Berglund and Ralska-Jasiewiczowa (1986), Gaillard, Berglund (1988), Veski (1998), Poska et al. (2004), and Stančikaitė et al. (2008a, 2013) (**Paper III**). The results are presented in percentages of the total sum of AP and NAP taxa. According to pollen data, the main vegetation stages recovering regional and local environmental history were constructed.

2.2.2. Geochemical analysis

The samples for geochemical analysis were prepared and analyzed using the standard procedures previously described by Zinkutė et al. (2015). The material was analyzed by EDXRF equipment Spectro Xepos using the Turboquant for the pressed pellet calibration procedure (Schramm, Heckel,

1998) elaborated by the manufacturers. The elements playing the leading role in the description of the palaeoecological regime, i.e. Ca, Mg, Sr, Rb, Al, K, As, Fe, Ti, Mn, P, S, Si, Zr, Na, Zn, Cu, Cl, were selected for further analysis (**Papers II** and **IV**). Variation of elemental contents (natural logarithms of parts per million) was evaluated dividing the elements according to the possible origin. Elemental ratios (i.e. Si/Ti, Rb/Ti, Ca/Mg, Rb/Si) were calculated, because element contents may be affected by sediment enrichment with the dominant constituent, i.e. organic matter (Kylander et al., 2013b), carbonates, Si, etc. (Dypvik, Harris, 2001).

2.2.3. Other methods

^{14}C dating

^{14}C dating was performed at the Laboratory of Nuclear Geophysics and Radioecology at the OAC of the NRC (**Papers I** and **II**, lab. code Vs-); at the Kiev Radiocarbon Laboratory, Kiev, Ukraine (**Paper III**, lab. code Ki-); at the Center for Physical Sciences and Technology, Vilnius, Lithuania (**Paper IV**, lab. code FTMC-). ^{14}C ages were obtained using both liquid scintillation spectrometry and AMS techniques and were used for the determination of the sediments' chronology and calculation of sedimentation rate. The uncertainty of results was reported at 1σ level. The ^{14}C dates were converted to calendar years using the radiocarbon calibration program OxCal 4.3.2 (Ramsey, 2017) with the IntCal2013 (Reimer et al., 2013) and expressed at the given 2σ confidence level. The chronologies were based on age-depth models, constructed applying the P_Sequence function in the OxCal 4.3.2 software. The mean value of the modeled age was used for the sedimentation rate calculation (**Papers II-IV**). The sedimentation rate value, expressed as cm yr^{-1}, was calculated at 1 cm depth intervals according to the mean values of the probability distribution of the modeled age (mean) for each depth. OxCal software (Ramsey, 2008; Ramsey, Lee, 2013) was used to construct P_Sequence age-depth models.

Loss-on-ignition

The content of organic matter, carbonates and ignition residue (LOI, **Papers I, II and IV**) were determined applying the standard procedure and expressed in percentages of gross weight (Dean, 1974; Bengtsson, Enell, 1986).

Magnetic susceptibility measurements

MSus was measured using MFK1-B kappa bridge (AGICO) equipment (**Papers I, II, III** and **IV**). The measured MSus values were recalculated considering sediment weight and expressed in SI units (10^{-9} m^3/kg) using standard methods (Sandgren, Snowball, 2002; Blumentritt, Lascu, 2015).

Plant macrofossil analysis

Macrofossil survey (**Papers I** and **II**) was carried out following the standard wet sieving procedure (Grigas, 1986; Berggren, 1969, 1981; Cappers et al., 2006).

Grain size determination

The composition of the untreated fine-grained (<0.2 mm) sediment fraction of Lieporiai core (**Paper IV**) was evaluated applying a Fritsch Laser Particle Sizer "Analysette 22". The differentiation of grain size follows Udden and Wentworth scale (Blott, Pye, 2001).

Scanning electron microscopy

The high-resolution micro-images of the selected Lieporiai sediment subsamples were taken using SEM Quanta 250 equipment. Alongside, chemical composition and structure of the selected elements were evaluated (**Paper IV**). The procedure was performed using the Energy Dispersive Spectrometry (EDS) detector X-Max, the INCA x-stream digital pulse processor, and the INCA Energy EDS software.

Statistical methods and visualizations

Statistical methods applied are shown in Table 3. The PCA was performed for the evaluation of interrelations between various proxies (**Papers II** and **III**). All numerical data, including palaeobotanical, geochemical, physical, lithological, and palaeomagnetic were processed and diagrams were constructed applying Tilia and Tilia graph software (2.0.060 version, Copyright 1991-2016 Eric C. Grimm) and CorelDRAW Graphics Suite 2017. The CONISS cluster analysis was performed (Grimm, 1987) establishing the litho-, bio-, and chemo- zones (**Papers I-IV**). Statistical analysis of the pollen data based on the conclusions of **Paper V**. NMDS technique was used to randomly re-arrange palynological samples to recurrence plots according to their similarity and chosen metrics (**Paper V**).

Table 3. Statistical methods applied.

	Papers	Čepkeliai	Petrešiūnai	Lieporiai
CONISS, PCA	**II, III** and **IV**	CONISS, PCA for vegetation and geochemistry	CONISS, PCA between pollen groups	CONISS
NMDS	**V**	Pollen data and astronomical forces	-	-
Publications		**I, II, V**	**III**	**IV**

3. RESULTS

This chapter combines the results of chronostratigraphical, lithostratigraphical, palaeobotanical and geochemical analyses that play the leading role allowing comparison of the data and reconstruction of LG and Holocene (a)biotic palaeoenvironmental history (Papers I-V).

3.1. Chronology and accumulation rate

The interpretation of the environmental history on the regional scale is based on local reconstructions and independently generated radiocarbon-based age-depth models (Fig. 2). The obtained data proves the uninterrupted sediment formation between 12 000 and 600 cal yr BP in Čepkeliai (**Papers I** and **II**). A high sedimentation rate (up to 0.2 cm yr^{-1}) indicated during the beginning of the Early Holocene and several peaks were superimposed upon the low curve during the Middle Holocene. The chronology of the Petrešiūnai sediment sequence proves the deposition of the investigated sediment sequence between 9 000 and 500 cal yr BP (**Paper III**). The culmination of sedimentation rate (1.7 cm yr^{-1}) noted between 800–500 cal yr BP. The formation of the investigated sediment sequence started before 14 000 cal yr BP, when the highest sedimentation rate recorded, throughout the LG-Early Holocene in Lieporiai (**Paper IV**) (Fig. 2).

In the presented radiocarbon age-depth profiles (Fig. 2), markers indicate the median values of modeled data, x-axis error bars running through the markers represent calibrated 2σ age ranges. Radiocarbon ages are expressed in cal yr BP.

LG chronology is based on the so-called *Event Stratigraphy* (Lowe et al., 2008) and the formal subdivision of the Holocene follows ICS (http://www.stratigraphy.org/index.php/ics-news-and-meetings/125-formal-subdivision-of-the-holocene-series-epoch) and Walker et al. (2009, 2012):

Late Holocene (after 4 250 yr b2k) / Meghalayan Stage/Age
Middle Holocene (~8 326–4 250 yr b2k) / Northgrippian Stage/Age
Early Holocene (~11 700–8 326 yr b2k) / Greenlandian Stage/Age
GS-1 (~12 896±138–11 700±69 cal yr BP)
GI-1a (~13 099±143–12 896±138 cal yr BP)
GI-1b (~13 311±149–13 099±143 cal yr BP)
GI-1c (~13 954 ±165–13 311±149cal yr BP)
GI-1d (~14 075±169–13 954 ±165 cal yr BP)
GI-1e (~14 650–14 075±169 cal yr BP)
GS-2 and older (>14 650 cal yr BP)

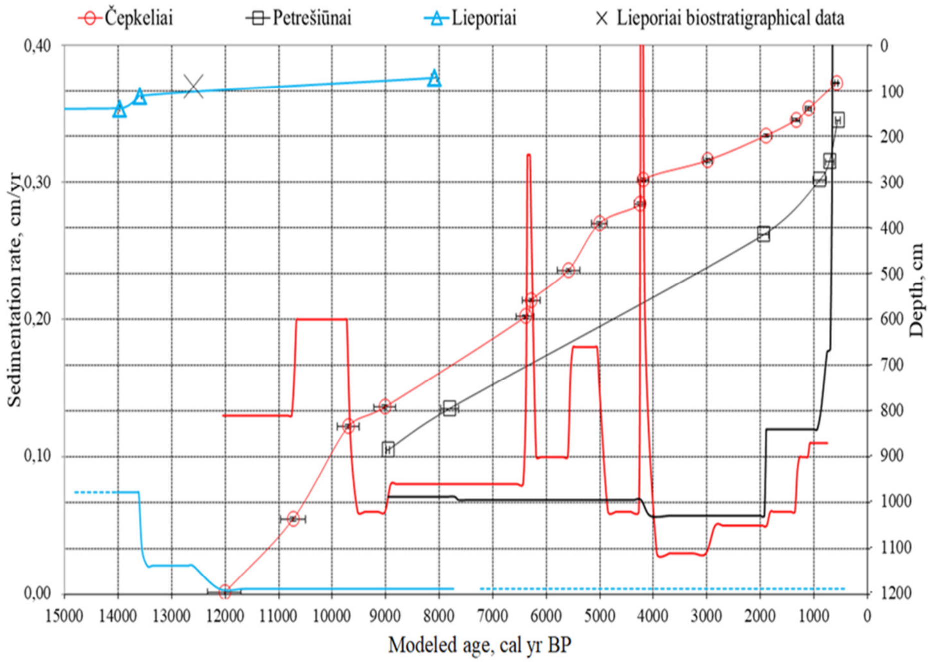

Figure 2. Combined age-depth models, developed by linear interpolation between calibrated (cal yr BP) midpoints, and sedimentation rates.

3.2. Lithology

The studied sequences consist of sediments with different percentages of organic matter (LOI) and MSus values (Table 4). Čepkeliai (**Papers I** and **II**) and Petrešiūnai (**Paper III**) sediments consist of peat, peaty gyttja, and gyttja mainly and therefore contain a higher percentage of organic matter. In Lieporiai, a high participation of terrigenous matter is noted in the lowermost part of the sequence consisting of sand and gravel while deposition of silty sediments with a low percentage of organic matter recorded upwards (**Paper IV**). The highest MSus values are determined during the LG and the earliest stages of the Early Holocene. Most negative MSus values positively associate with increased organic matter values. The summarized results of LOI and MSus are plotted on the modeled age scale in Fig. 3.

Table 4. Lithostratigraphy of the studied sites.

Depth, cm	Age interval, cal yr BP	Sediment description	LOI, organic %	MSus*10^{-9}, m^3/kg
Čepkeliai				
100–207	Younger than 2 000	*Sphagnum* peat, poorly decomposed, brown	93–98	-8.2–-5.42
207–385	2 000–5 000	*Sphagnum* peat, medium decomposed, brown	91–97	-8.54–-5.47
385–411	5 000–5 100	*Pinus*– cotton peat, poorly decomposed, brown	95–97	-8.56–-7.24
411–600	5 100–6 900	Sphagnum peat, medium decomposed, brown- dark brown	91–100	-9.34–-6.77
600–700	6 900–8 000	Gyttja, brown	91–97	-8.11–-4.55
700–800	8 000–9 200	Gyttja, greenish-brown	90–100	-8.63–-6.98
800–1034	9 200–10 900	Gyttja, greenish, dark brown	64–93	-8.17–2.21
1034–1050	10 900–11 000	Gyttja, greenish, dark brown, with white layers	82–85	-0.34–4.85
1050–1100	11 000–11 400	Gyttja, light greenish	74–85	0–50.59
1100–1200	11 400–12 000	Gyttja, calcareous, light greenish, silty and darker at the bottom	54–71	0–35.87
Petrešiūnai				
121–250	500–700	Peat, poorly decomposed light grey	-	0.12–78.85
250–300	700–1 000	Gyttja, enriched with peat, poorly decomposed, light grey	-	15.3–137.4
300–526	1 000–3 500	Gyttja, enriched with shells, light brown	-	4.25–84.40
526–800	3 500–7 900	Gyttja, light brown	-	2.46–52.73
800–900	7 900–9 000	Gyttja, light grey	-	22.6–131.1
Lieporiai				
44-55	Younger than 8 000	Peat, black, on the topmost of the layer slightly enriched with darker well-decomposed peat.	76–77	-2.2–1.67
55-68		Peat, clayish and silty, enriched with shells on the bottom part	76–80	-3.81–-1.47
68-80	8 000–10 200	Silt, coarse, dark brownish, enriched with gyttja and with a lot of shells	11–15	-5.56–2.37
80-90	10 200-12 600	Silt with very fine and fine-grained sand, dark brownish	8–10	10.19–44.2
90-108	12 600–13 400	Silt with up to 10% of clay, enriched with light and fluffy carbonaceous detrital mud	5–11	1.75–20.83
108-118	13 400–13 700	Silt with very fine-grained sand, dark brownish, that contains frequent shells	3–8	21–31.8
118-126	13 700–13 800	Silt with very fine-grained sand, dark brownish, consists sporadic shells	2.5–2.7	32.07–36.37
126-160	13 800–older than 14 000	Silt with very fine-grained sand, greyish green	0.8–7.4	22.89–53.42
160-165		Sand, various grained	0.6–1.5	16.5–26.9
165-200		Sand and gravel, coarse-grained, with the till in the bottom	0.5–1.5	17.7–150

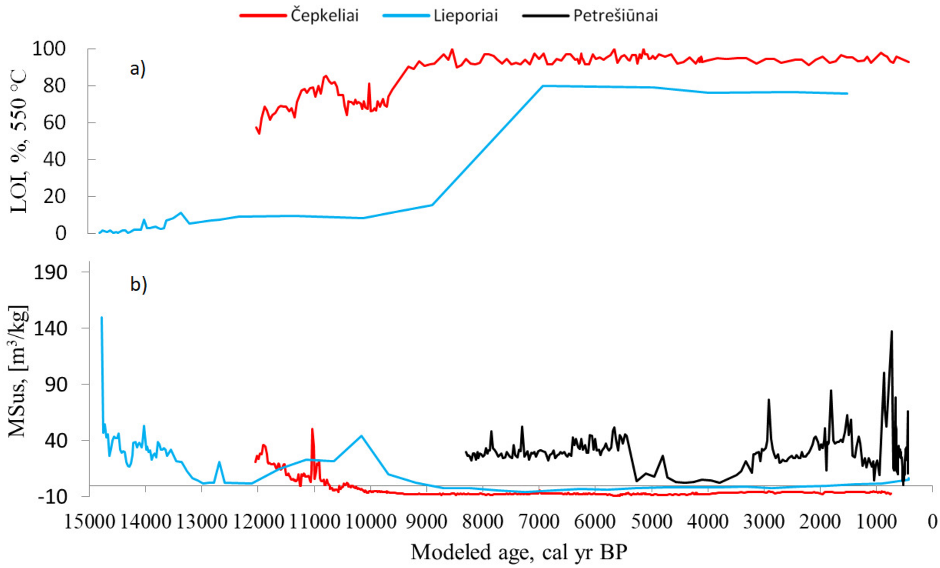

Figure 3. LOI (a) and MSus (b) data versus modeled age.

3.3. Distribution of geochemical data

Despite the increasing number of LG and Holocene palaeoenvironmental investigations conducted in the E Baltic, not so much is known how regional and global factors, including the palaeoclimatic regime, have influenced the abiotic environment. The analysis of long-term changes in lake sediment geochemistry gives additional information about abiotic environmental variations during the LG and Holocene allowing detection of small-scale variations previously not fixed in surrounding regions. For this reason, the geochemical survey was one of the main analytical methods applied. It also allows tracing human impact on the landscape in the last few millennia.

The results of a geochemical analysis are discussed and presented in **Papers II** and **IV** in detail. Based on the results of CONISS analysis, geochemical records have been sub-divided into local ChEAZ, which are described in Table 5. The variations of the selected elements (Fig. 4) and element ratios (Fig. 5) are shown on the age scale. The Čepkeliai geochemical stratigraphies are split into ten significant intervals (**Paper II**), and five are indicated in Lieporiai (**Paper IV**) (Table 5). During the LG, Lieporiai sediments contain a high amount of silicaclasts (i.e. Si, K, Ti, Rb) and increased Fe and S values up to about 13 700 cal yr BP. In the interval between 13 400 and 12 600 cal yr BP, the sediments which contain an increased clay-sized particle concentration are enriched with Ca and Sr, carbonates, and also contain higher Ca/Mg and Mn/Fe ratios. During GS-1 and the beginning of the Early Holocene, between 12 600 and 10 200 cal yr BP, sediments are enriched with Si, Al, Ti, K, Mg, Rb, Zn, Cu, and P, also with Fe, As, and S. During the Middle Holocene from about 6 200 cal yr BP, decreased values of terigenic elements and increased values of Mn, Fe, and S are fixed. During the last stages, higher values of terigenic elements and increased Cu and Mn values are fixed. In Čepkeliai, during the final stages of GS-1 and initial stages of the Early Holocene, the highest concentrations of Mn and Fe are observed. Higher concentrations of elements related to clay minerals and siliciclastic rocks predominate and last until about 9 700 cal yr BP. The following stages reveal a continuous decrease of the latter elements until about 8 200 cal yr BP, when the values of Si, Al, K, Ti, Rb, Ca, S, and Zn show a more differentiated pattern with elemental fluctuations. The concentration of S drastically decreases at about 6 200 cal yr BP, but the content of terigenic elements, i.e. K, Rb, Mg, Zr, Ti, and Al starts to rise simultaneously. At the last stages of the Middle Holocene and during the Late Holocene, terigenic element values are relatively low, but between about 5 600 and 4 500 cal yr BP and at about 1 900 and 800 cal yr BP the values exhibit some fluctuations. Nevertheless, Mn/Fe values do continuously decline and Ca/Mg do increase upwards the end of the Late Holocene.

Table 5. Local chemical element assemblage zones.

ChEAZ	Depth, cm	BCE/ CE	Cal yr BP	Description of the zones
Čepkeliai				
$Č_{CH-1}$	1200–1150	10 070–9 700	12 000–11 650	High but decreasing values of Ca, Sr, Si are noted in the lower part of the zone. Meanwhile, the concentration of Al, K, Ti, also P, S increases upwards. Mn/Fe ratio has the highest value, but high Mn and Fe contents exhibit a remarkable drop upwards.
$Č_{CH-2}$	1150–1005	9 700–8 600	11 650–10 550	Variation of Al, K, Ti, Rb, Mg, Si, Zr, also As, Fe, P, Mn is great and their average values remain high. The representation of Mn and Fe increases at about 11 300–11 100 cal yr BP. A high Mn/Fe ratio is noted throughout the zone. Instability of some element content is characteristic of the zone where peaks of S, P, Fe, As, Mn, also Ti, Al, K are observed between about 11 700 and 11 000 cal yr BP. Increasing sediment enrichment with Ti, Mg, K, Zr, also Sr is from about 11 000 cal yr BP.
$Č_{CH-3}$	1005–930	8 600–8 250	10 550–10 200	Increasing sediment enrichment with Zr within the zone, and with Ti, Mg, K, also Sr, Mg/Sr up to 10 600 cal yr BP, but after sediment depletion with these elements is noted. High but decreasing contents of As, S, Mn/Fe ratios within the zone are noted. After 10 500 cal yr BP Ca concentration gradually increases onward.
$Č_{CH-4}$	930–815	8 250–7 500	10 200–9 450	Sediment enrichment with Ti, Zr, Mg, Al, K, Rb, also Sr gradually decreases upwards the zone. Si, also As, S and Si/Ti ratio increases and culminates at about 9 400 cal yr BP.
$Č_{CH-5}$	815–750	7 500–6 550	9 450–8 500	Average concentrations of most elements decrease remarkably in comparison with $Č_{CH-4}$ while only S average content shows a less expressed reduction. From about 9 400 cal yr BP Fe/Ti,

ChEAZ	Depth, cm	BCE/ CE	Cal yr BP	Description of the zones
				Ca/Ti and Mg/Sr ratios start to increase.
Č$_{CH-6}$	750–670	6 550– 5 500	8 500– 7 450	A high concentration of S experiences a sudden drop at about 8 100 cal yr BP. Instability is noted in most curves, i.e. S, Ca, Mg, Al, K, Si, Zr, also Si/Ti, Fe/Ti, Ca/Ti, covering 8 200–7 900 cal yr BP time interval.
Č$_{CH-7}$	670–530	5 500– 4 050	7 450– 6 000	A high concentration of S suddenly drops at about 6 900 cal yr BP and drastically decreases at about 6 200 cal yr BP. At about 7 100 cal yr BP Cu, Zn experiences some fluctuation and later starts gradually to decrease. At that time, K, Rb, Mg, Ti, Al, Zr start to increase.
Č$_{CH-8}$	530–400	4 050– 3 100	6 000– 5 050	An average of Ca/Mg ratio reaches its maximum within the zone. At about 5 600 and 5 100 cal yr BP concentration of Rb, Al, K, Ti, Si, Zr insignificantly increases. Some instability is noted between 5 400 and 5 300cal yr BP when the content of Fe, S, P, Mn, As, Cu, Zn fluctuates.
Č$_{CH-9}$	400–300	3 100– 2 250	5 050– 4 500	An average of Mg, Sr, also Mg/Sr and Ca/Ti ratio increases, but at the end of the zone, it decreases. An average S concentration is the lowest.
Č$_{CH-10}$	300–200	2 250–50	4 500– 2 000	Mg/Sr and Ca/Ti ratios about 4 500 cal yr BP slightly drop and rise again, but after this instability, from about 4 200 cal yr BP start gradually to decrease. At the same time, the concentration of S and Ca/Mg ratio significantly increases onward. Ca value begins to decrease from about 3 000 cal yr BP. At about 800 cal yr BP concentration of Al, K, Ti, Rb, Mg, Si, Zr, Ca, also Mn, S, Fe insignificantly increases.
Lieporiai				
1a	200–165	Before 12 050	Before 14 000	Si clearly predominates, meantime Ti, Al, K, Rb exhibits some fluctuations but remain within constant lower values. The highest Si/Ti, Rb/Ti, high Mg/Ti, and lowest Rb/Si ratios evaluated. Sediments are enriched with P and As.
1b	165–160			Sediment is significantly enriched with K, Mg, Ti, Al, Rb, also P, Fe and depleted with Ca, Sr, also As, Mn, Cl in comparison with the previous zone.
2a	160–125	Before 12 050– 11 850	Before 14 000– 13 800	Concentrations of Ti, Mg, Al, K also Zn reach the highest levels observed in the core, while some imperceptible decrease occurs approaching the upper part of the zone.
2b	125–118	11 850– 11 750	13 800– 13 700	Sediment enrichment with Ti, Al, K, Mg, Rb, also with Ca, Sr, and Mn, Fe, Zn, Cu has a decreasing trend. The values of Rb/Ti and Rb/Si ratios decrease accordingly. Mg/Ca, Si/Ti ratios have an increasing trend in this zone.
2c	118–106	11 750– 11 400	13 700– 13 400	Sediment enrichment with Ti, Al, K, Mg, Rb, Si, also Mn, Fe, Zn, as well as Si/Ti, Mg/Ca ratios shows a decreasing trend in the zone. At the same time representation of Ca, Sr, S, and Rb/Si ratio increases approaching the upper part of the zone.
3	106–90	11 400– 10 650	13 400– 12 600	The zone is characterized by the highest levels of Ca and Sr observed in the core and the lowest values of all other elements. The most abundant elements reach peak values at about 13 000 cal yr BP and start gradually to decrease afterward. A strong signal of higher Rb/Si, Rb/Ti, Mg/Ti ratios and an abrupt increase in Mn/Fe ratio is observed.
4a	90–80	10 650– 8 250	12 600– 10 200	Ca, Sr and Mn abruptly decrease. The increased Si, Al, Ti, K, Mg, Rb, Zn, Cu, P, also Fe, As, and S in the upper interval at about 10 650 cal yr BP characterize an interval. Alongside, Si/Ti, Mg/Ca ratios show an increasing signal.
4b	80–67	8 250– 6 050 and later	10 200– 8 000 and later	At the beginning of the zone Ca and Sr increase and become the most abundant elements. After about 8 700 cal yr BP, concentrations exhibit a remarkable drop. Mn/Fe ratio experiences a similar increase with subsequent decrease. In

ChEAZ	Depth, cm	BCE/ CE	Cal yr BP	Description of the zones
				parallel, average Al, K, Ti, Rb, Si values decrease. Slightly higher values of Fe, S, As, P, Cu are established towards the topmost limit of the zone.
5a	67–55			Low contents of Al, K, Ti, Rb, Mg, Si and the highest concentration of Cu and S and high of P, are typical for the zone.
5b	55–42	Later than 6 050	Later than 8 000	The highest concentration of Mn and the highest Mn/Fe ratio are observed in the lower part of the zone with some decreasing trends upwards. Rb/Si ratio in the lower part of the zone is among the highest and, after a subsequent decrease in the middle of the zone, has a slightly increasing trend toward the top of the zone. Zn curve has an increasing trend towards the top of the zone.

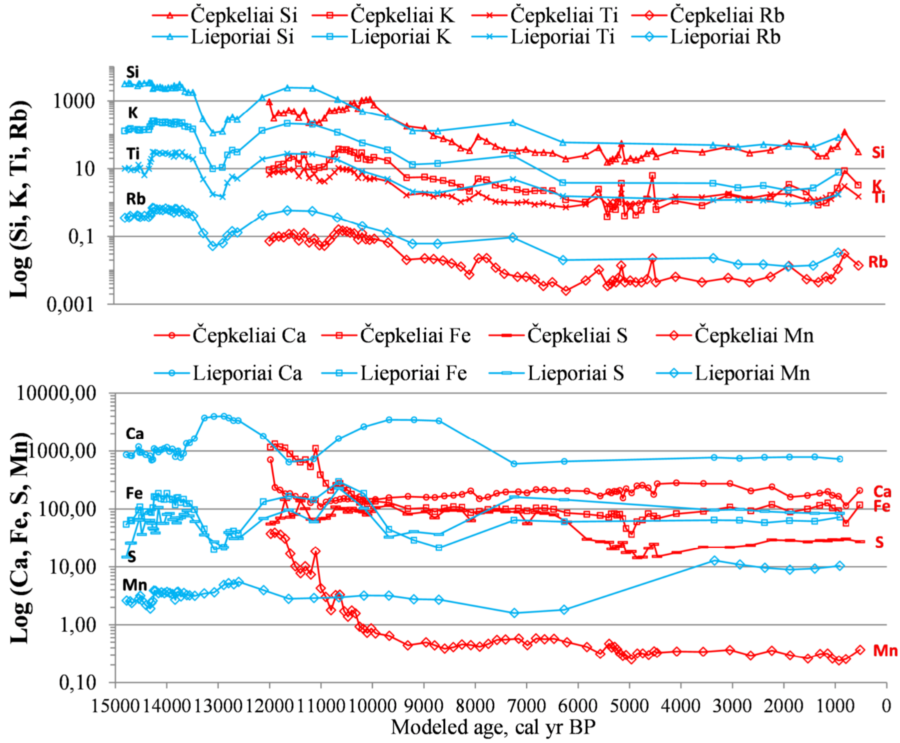

Figure 4. Content of the selected chemical elements (logarithmic scale).

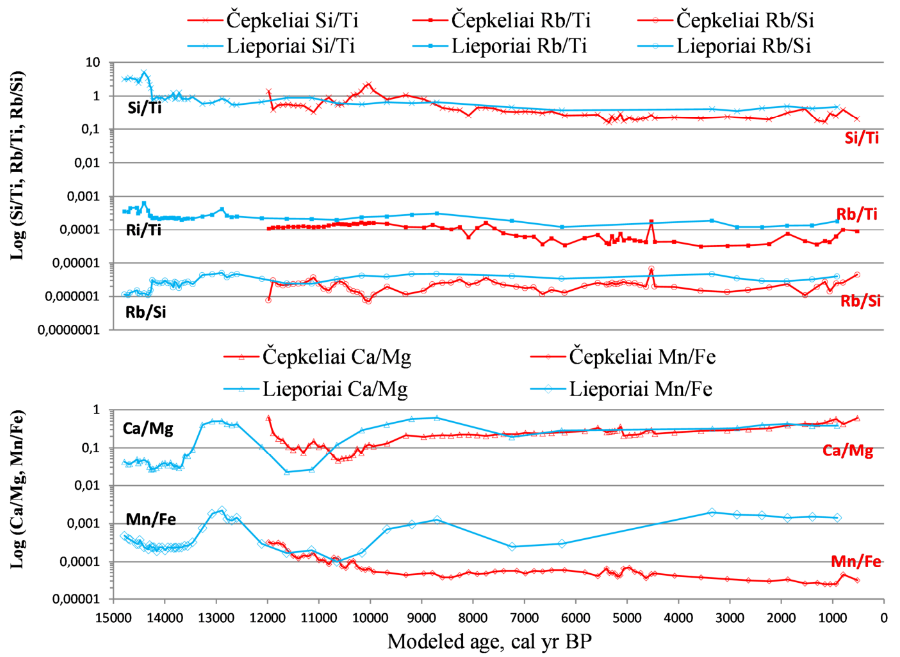

Figure 5. Log-ratios of the selected chemical elements.

3.4. Vegetation dynamics

The palaeobotanical survey is one more method playing a major role in this investigation. The vegetation history was discussed in all papers published (**Papers I–V).** Together with pollen analysis, the results of plant macrofossil analysis were involved (**Papers I** and **II)**. A comparison of the main vegetation taxa (Fig. 6) represents local and regional vegetation development and migration during the LG and Holocene.

Pollen record representing the Lieporiai core covers the sedimentation interval from GI-1e, or the so-called Bölling warming, to the Early Holocene (**Paper IV**), while the investigated part of the Čepkeliai core covers LG/Holocene transition, Early, Middle and Late Holocene, i.e. 12 000 cal yr BP (**Papers I** and **II**). Petrešiūnai sediments cover Middle and Late Holocene, i.e. 8 000 cal yr BP (**Paper III**).

Prior to 13 700 cal yr BP, Poaceae–*Salix*–*Betula* predominating vegetation flourished in the area; between 13 700 and 13 300 cal yr BP, *Pinus*–*Betula* forest gained more ground; in period 13 300–12 600 cal yr BP, *Pinus* forest was formed; at about 12 600–10 200 cal yr BP, NAP and *Betula*–Poaceae were predominating in the local vegetation structure; after 11 300 and until about 10 450 cal yr BP, *Betula*–Poaceae–*Ulmus* predominated in the vegetation structure; and until about 8 600 cal yr BP, the increasing representation of *Ulmus, Corylus,* and *Alnus* was noted. For the first part of the Middle Holocene until about 6 200 cal yr BP, the flourishing of dense deciduous woods with *QM* and high participation of *Picea* in the NE part of the area was noted. Between 6 200–5 400 cal yr BP, the flourishing of *Pinus*–NAP is noted, while after, between 5 400–4 500 cal yr BP, *Pinus,* human-induced vegetation, including appearance of cultivars, is recorded. At about 4 050–3 450 cal yr BP, participation of *Picea* increases and the same is for *Betula* in NE Lithuania, while after, until 1 800 cal yr BP, a decline of *Picea* is noted, and *Betula* together with *Artemisia* recovered here. The increasing representation of apophytes and anthropohores, i.e. *Triticum*, Cerealia, is noted during the last millennial, i.e. after 950 cal yr BP.

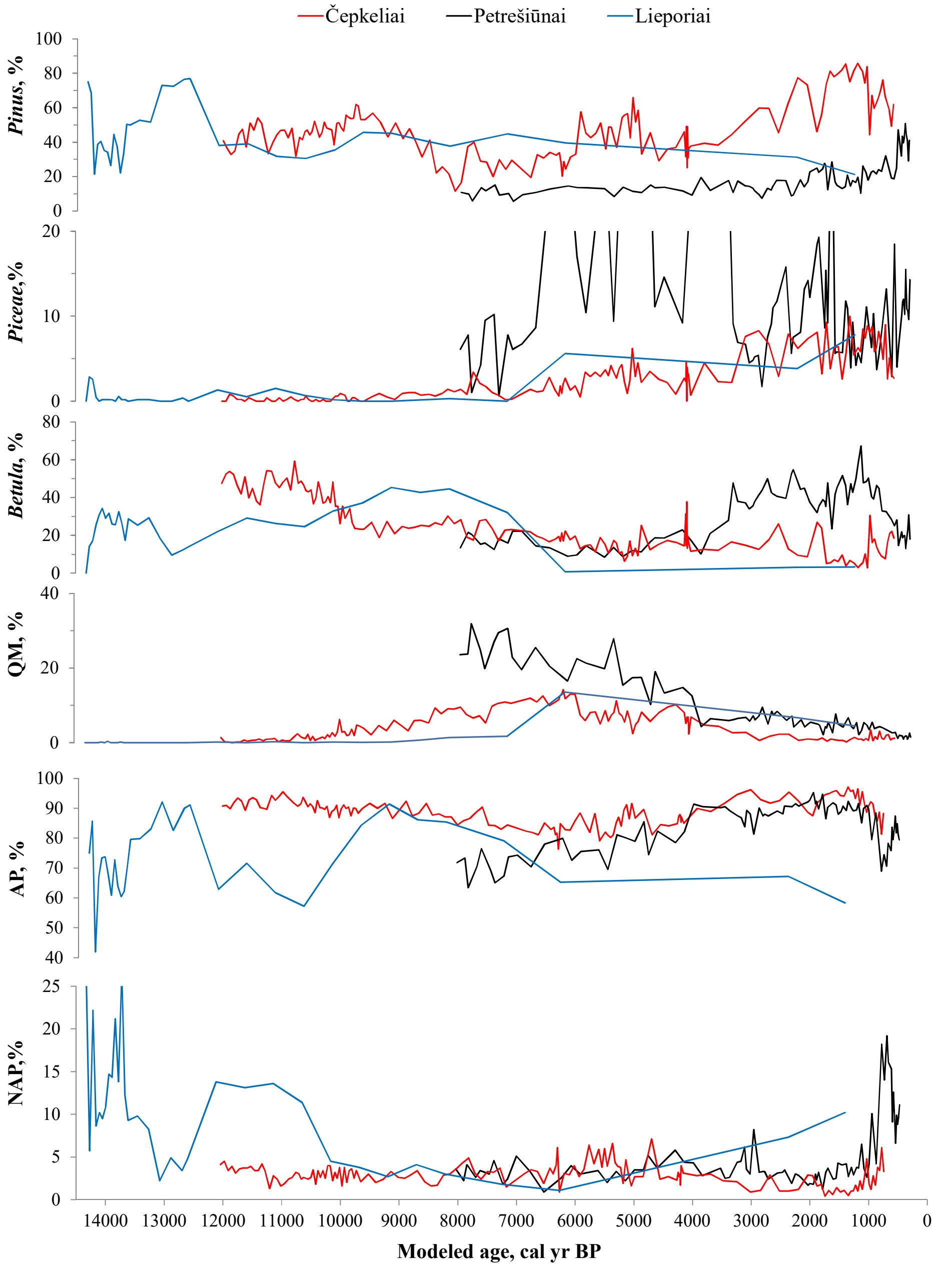

Figure 6. Selected pollen taxa.

4. DISCUSSION

4.1. History of vegetation successions – local structures and regional pattern

The results from the palaeobotanical approach enabled a detailed reconstruction of terrestrial and aquatic vegetation over the sedimentation period. A comparison of pollen data represents differences between local vegetation successions and reflects regional similarities. In most cases, biostratigraphical boundaries correspond well to the chronostratigraphical ones, therefore, the history discussed in the context of natural (astronomical, global, regional and local) (**Papers I-IV**), as well as anthropogenic factors (**Papers I** and **III**), gave an opportunity to analyze vegetation patterns also through the multilevel physical forcing perspective. Compared to other regions in Europe, reconstructed vegetation patterns were discussed in view of understanding average temperatures, water level changes, precipitation, erosion, and other processes during the LG (**Paper IV**) and the Holocene (**Papers I-IV**). Holocene vegetation patterns were also tested for the presence of long-term and short-term solar activities or other astronomical forcings that could have affected the composition of plant community (**Paper V**).

Lateglacial

After the retreat of the ice sheet at about 13.1 ± 0.3 ^{10}Be ka (Rinterknecht et al., 2006) from the N Lithuania, tundra was the most extensive biome here. Vegetation contained higher production of herbs and grasses which was accompanied by sporadic appearance of shrubs such as *Hippophae*, *Juniperus*, *Salix*, and *Betula.* Regional pollen-based temperature reconstructions show that by GI-1e summer air temperatures in ice-free S regions reached +13–+15°C (Borzenkova et al., 2015) as it was also indicated by the occurrence of *Hippophae rhamnoides* and *Typha latifolia*. Situated in the S of the same geographical region, Kamyshovoje Lake sediment studies reveal a general reconstructed July temperature trend reaching 19.8°C for 14 370 cal yr BP (Druzhinina et al., 2015), while S Sweden still suffered deglaciation and July temperature reached 12°C only (Berglund et al., 2008).

It should be pointed out that although the first reliable ^{14}C data from the Lieporiai site (**Paper IV**) shows 13 975 cal yr BP of the investigated layer, recorded pollen spectra with sporadic Caryophyllaceae, *Artemisia*, and scattered *Pinus*, *Picea, Betula* suggests earlier climate improvement in the region. *Betula* pollen curve exceeding 25% (Huntley, Birks, 1983) and fruits of *Betula nana* L. recorded in the area (Stančikaitė et al., 2015) indicate local presence of the birch in the surroundings. However, some early thermophilous plants i.e. *Corylus*, *Alnus*, *Tilia,* and *Ulmus,* as well as corroded and degraded *Pinus* and *Betula* pollen grains were most probably re-deposited from the older interglacial deposits (**Paper IV**; Stančikaitė et al., 2015). As suggested by Veski et al. (2012) these should not be taken into account while discussing Early LG vegetation history.

Later, until about 13 400 cal yr BP (GI-1d-c), due to rapid ice retreat from the Eastern Baltic area, quickly rising temperature lead to vegetation change and the formation of moderate forest cover with plots of pine and birch and with very high floristic diversity playing a leading role in both regional and local vegetation successions all along the region (Stančikaitė et al., 2002; Kabailienė, 2006). Meantime, the gradual appearance of aquatic plants suggests upcoming favorable conditions for lacustrine sedimentation with the existence of deep, temperate, oligotrophic water body. During this stage, at about 13 800 cal yr BP, the temporal cooling caused some instability in vegetation as plains were mostly vegetated by grassland species with dwarf shrubs and bushes in moister regions. Nevertheless, an episode of regionally well-known GI-1d or „Older Dryas" cooling event (Stančikaitė et al., 2008a, 2015; Veski et al., 2012) caused a drop in *Pinus* population.

Between 13 400 and 12 600 cal yr BP (GI-1c-a) the climatic conditions have improved a lot. Environmental stage, quite typical to other parts of C and N Europe i.e. Estonia (Saarse et al., 2009), NE Poland (Ralska-Jasiewiczowa et al., 2004), Sweden (Berglund et al., 2008, 1993), E Latvia (Veski et al., 2012) and Lithuania (Stančikaitė et al., 2008a) basically stands out form other LG periods by flourishing of *Pinus*-predominating vegetation (**Paper IV**) and decreasing number of unstable soil tolerant species. Expansion of woodland obviously resulted in a reduction of floristic diversity while increasing production of organic matter has positively influenced soil formation. In addition, due to lush formed vegetation erosion of banks was reduced.

Vegetation changes recorded between 12 600 and 11 400 cal yr BP suggest the destabilization of the forest cover that could be correlated with the GS-1 cooling event that remarkably affected the increasing opening of the vegetation structure in all Northern Hemisphere. According to pollen-based temperature reconstructions, the mean annual temperatures evidently dropped. The coldest period in E Latvia (Stivrins et al., 2015) and Baltic-Belarus region at that time was approximately 6±1°C lower (Veski et al., 2015) than the present mean annual temperature. In N Lithuania *Pinus* remarkably decreased and *Picea* (**Paper IV**) entered the area characterizing increased humidity noted on the regional scale (Heikkilä et al., 2009;

Stančikaitė et al., 2008a, 2009a). Meantime in S Lithuania during the GS-1 event changing conditions negatively affected *Pinus*, which was replaced by open tundra vegetation (**Paper II**).

Early Holocene

Early Holocene palaeobotanical records reflect rather modest vegetation reaction to an increasing temperature and humidity during the initial stages (Kupryjanowicz, 2007; Karpińska-Kołaczek et al., 2014; Gałka et al., 2014). In the E Baltic, NE Russia and partly NE Poland (Stančikaitė et al., 2009, 2015; Wohlfarth et al., 2007; Zernitskaya et al., 2015; Kołaczek et al., 2015) an interval until about 11 400 cal yr PB was described as suggesting delayed environmental reaction to Pleistocene/Holocene warming i.e. humid and cool climate regime still predominated here at that time. However, obtained results point to some instability of the vegetation which are rather synchronous to various centennial-scale environmental and climatic fluctuations fixed in NW and N Europe (Alley et al., 2003; Björck et al., 1997) and discussed as triggered by various astronomical, particularly the solar activity changes (**Paper V**, Magny, 2004; Seppä, Poska, 2004; Wanner et al., 2011) during the later part of the Early Holocene.

According to Borzenkova et al. (2015) over a greater part of Sweden, Estonia, Lithuania, and Latvia (Stivrins et al., 2015) summer temperatures increased more than 7–10 °C above these attained during GS–1 and that was the main trigger for establishment of open boreal woodland. Decreasing participation of herbs and grasses and the expansion of early boreal forest is recorded since 11 400 cal yr BP onwards (**Papers II** and **IV**).

Since about 10 600–10 300 cal yr BP, noted instability in terrestrial and aquatic vegetation points to re-organization of the vegetation structure. Immigration of thermophilous deciduous taxa i.e. *Corylus*, *Ulmus*, *Tilia* and closing of the forest cover suggests the general warming. However, changes noted in the palaeobotanical records suggest that some environmental anomalies were superimposed upon the general warming and dated back to 11 200–11 000 cal yr BP, 10 600–10 300 cal yr BP, and 8 200–7 800 cal yr BP. Recorded sudden drop of *Alnus* and *Corylus* curves and an increase of *Pinus*, *Picea* and light-demanding, cold-tolerant open vegetation, were noted regionally as *"Preboreal"* and *"10.2 Ka"* oscillations or *"8.2 Ka"* event (Björck et al., 1997; Björck et al., 2001; Hammer et al., 1986; Veski et al., 2004, 2015; Seppä, Poska, 2004; Gałka et al., 2014) (**Papers II, III** and **V**).

Middle Holocene

Despite the fact that the highest solar radiation occurred between about 11 000–5 000 cal yr BP due to the combination of tones of Milankovitch cycles (**Paper V**; Pestiaux et al., 1988) HTM experienced 2 000–3 000 years delay in Europe (Renssen et al., 2012). According to our data (**Papers II** and **III**) flourishing of thermophilous deciduous forest, noted between 8 600–6 500/6 200 cal yr BP, generally coincides with the above mentioned chronological interval while some differences most probably have occurred due to the local conditions. An expansion of thermophilous tree forest and pollen-based temperature reconstructions (Heikkilä, Seppä, 2010) characterize this climatic interval as dry and warm, with reduced groundwater and lake levels (Hammarlund et al., 2003). The ongoing lowering of the water table has provoked the bogging processes dated back to 7 300–7 200 and 6 600–6 700 cal yr BP in Čepkeliai. These shifts are in a positive correlation with the simultaneous changes of the (a)biotic proxies noted on the regional scale suggesting regional coherence of climate dynamics (Seppä et al., 2005; Edvardsson et al., 2012).

The general re-organization of the forest structure that started at about 6 000 cal yr BP was expressed first of all by the increased representation of *Picea* in the local vegetation (**Papers II** and **III**). Simultaneously, representation of thermophilous taxa has lowered and the area of open habitats increased supporting the climatic deterioration. Climate became more humid and cooler and changes were noted in the different biotic and abiotic proxies from all around the Europe (Laumets et al., 2014; Heikkilä, Seppä, 2003; Feurdean et al., 2008; Grindean et al., 2015). Mentioned variations might have been determined by a climatic event of a global scale centered to 5 900 cal yr BP (Bond et al., 2001) and noted as the end of the HTM (Laumets et al., 2014).

Alongside the natural factors of the different scale that have been driving the vegetation changes during the Middle Holocene, some recorded variations could be interpreted as indicating anthropogenic forcing. A small scale vegetation stress suggesting decay of the forest cover, increasing representation of charred particles and ruderals prove an episodic human activity during the final stages of the interval suggesting episodic Neolithic Age human activity (**Paper III**).

Late Holocene

The onset of the Late Holocene i.e. 4 200 cal yr BP is marked by continuous decline of the broad-leaved taxa and re-establishment of the *Pinus-Betula* or even *Picea* predominated forest, suggesting ongoing climatic cooling. Due to climatic reversal, formation of the forest cover was predominantly controlled by natural factors i.e. temperature, hydrology, soil cover. Generally reorganized vegetation felt stronger anthropogenic impact only at about 3 250–2 950 cal yr BP and at about 950–650 cal yr BP, when a slight increase in animal husbandry and agriculture was recorded in the surroundings of Petrešiūnai. Nevertheless, charred particles preserved in sediments (**Paper III**) distinguish low magnitude fire activity driven by both (i) global (depending on natural factors i.e. dry season and fuel relationship) and (ii) local scale (human-induced fires) regimes with fire occurrence due to forest burning (Dietze et al., 2018). However, the Petrešiūnai area was still heavily forested, mostly by *Betula* trees, up to 1 550 cal yr BP. Furthermore, human activity intensifies i.e. open cultivated areas with the introduction of new winter crops is observed at 950–650 cal yr BP (**Paper III**). Further vegetation records reveal a slight decline of human interruption to the environment at about mid-14th century in the Petrešiūnai area. Čepkeliai palaeobotanical records highlights hydroclimatic changes predominated in SE Lithuania over the last two millennia suggesting moister periods at about 1 650–1 450 and 1 000–100 cal yr BP, recorded regionally (Edvardsson et al., 2016) and in S/SE Baltic countries (Gałka et al., 2013; Lamentowicz et al., 2015). Warm and drier periods during which lake levels were low are established at about 1 850, 1 350, 1 200 cal yr BP and since mid-19th century (**Paper I**). These changes could identify terrestrial and aquatic vegetation periods related to ones that were recorded before in the region i.e. Roman Warm Period (Heikkilä, Seppä, 2010), the Medieval Warm Period (Lamentowicz et al., 2008), the Little Ice Age (Wanner et al., 2011) and the Industrial Era (**Paper I**). However, some inference must be treated carefully taking into account that some previous studies in N Baltics did not register significant changes in temperatures (Heikkilä, Seppä, 2010) also water level oscillations registered in particular Baltic peatlands do not always agree with regionally fixed ones (Gałka et al., 2017). For this reason, registered in the proxies environmental changes rather point to local than regional and/or climatic induced dynamics during the last millennia. Recorded variations in the vegetation structure reflect changes of the water level and are most probably related to geographical position of the sites. It reminds us that Baltic region is located at sensitive transitional margin between temperate and boreo-nemoral vegetation zones and is strongly altered by the continental climate of Eurasian mainland and oceanic climate of W Europe (**Paper I**, BACC II Team, 2015).

4.2. Post-glacial dynamics of abiotic environment – the site-related changes and general trends

The abiotic properties of sediments accumulated in all three sedimentary basins reflect environmental transformations and lakes' evolution during the last 14 600 years.

Generalized abiotic environment evolution indicates the following transformations: (i) landscape formation with strong water currents predominating and quick non-lacustrine sedimentation in the early LG; (ii) early lake stage evolution with low amount of organic matter and high participation of fine-grained allochthonic matter during the subsequent intervals of the LG Interstadial; (iii) the lake stage of highly eutrophic conditions with increased bioproduction and gradual lowering of the water level due to climatic amelioration recorded at the onset of Holocene; (iv) highly oxygenized low trophic condition stage followed by increased allochthonic matter precipitation due to highly changeable water level during Early Holocene; (v) the stage of the gradually rising trophic conditions with decreased inflow of allochthonic matter until it reaches HTM; (vi) the stage of the decreasing trophic conditions with more intensive mineralization of the organic matter during HTM reversal; (vii) minor eutrophication and/or enrichment with allochthonic elements due human impact, deforestation and land-use changes during the last millennia.

Summarized trends of Holocene abiotic data reveal environmental intervals that are highly consistent with the standardized global temperature stack trend (**Paper V**; Marcott et al., 2013): cool, but with increasing temperature Early Holocene (up to about 8 200 cal yr BP), light temperature decrease in the interval between 8 200–7 800 cal yr BP, increasing temperature during HTM (from 7 800 cal yr BP to 4 200 cal yr BP) and gradual cooling during Late Holocene period (**Papers II, V**). According to several Holocene period climate reconstructions and modeling (Seppä, Poska, 2004), some periodic patterns of our planet's climate interact with multilevel physical forcings including astronomical ones such as solar activity or precession, etc. (**Paper V**). Consequently, this observation could be used to explain forcings that had a major impact on the development of the (a)biotic palaeoenvironment during Holocene in the region.

Lateglacial

According to chronologically constrained combined results (**Paper IV**), after the retreat of the last Scandinavian Ice Sheet, the sedimentary environment of the Lieporiai region was affected by very unstable environmental conditions. Mineral matter predominating bottom sediments enriched with unsorted very coarse sand and gravel indicate severe hydrological regime common during the earliest stages of the LG (Pawłowski et al., 2016; Gałka et al., 2014; Mirosław-Grabowska et al., 2015). Intensive mechanical denudation most probably caused by rapid water flow, which is reflected in sediment geochemical composition, confirms intensive re-organization of the surface. Erosional material transported and subsequently re-deposited included Devonian carbonates, which are close to the present surface in the area (Narbutas, 2004). Recorded geochemical composition of the strata, as well as other proxies found in the sediments (**Paper IV**), are in a good agreement with the regional records (Kylander et al., 2013b; Apolinarska et al., 2012; Heikkilä, Seppä, 2010; Veski et al., 2012; Amon et al., 2014; Borzenkova et al., 2015; Druzhinina et al., 2015). Apart from the fact, small scale differences in regional deglaciation pattern firstly due to geographical distribution are recorded here. According to NGRIP $\delta^{18}O$ variations (Rasmussen et al., 2006), the peak of GI-1 warming observed in Greenland ice core has started at about 14 600 cal BP. However, palaeotemperature reconstruction in the E Baltic suggests the delayed start of GI-1 (Veski et al., 2015, 2012) recovering differences depending not only on geographical ice retreat pattern but also on local features: i.e. landscape, melting rate of buried dead ice blocks and other geological-geomorphological peculiarities.

During later intervals of the LG Interstadial, the sediment composition of investigated sequences reflects the rapid amelioration of the environmental situation. Reduced input of siliciclastic matter and significantly increased participation of clay mineral-related elements i.e. K, Al, Mg, Rb prove changing transportation intensity and stabilization of sedimentation environment (**Paper IV**). The contents of the latter chemical elements, Mg/Ca, Rb/Si and K/Na ratios, and also MSus values gradually decreased, suggesting less intensive sediment enrichment with the allochthonic matter. Such circumstances were favorable for the formation of transparent water basins which enabled the early appearance of bioproductivity in the basin. Similar alterations of environmental regime affecting both biotic and abiotic proxies were noted at the beginning of the LG Interstadial all around the region (Stančikaitė et al., 2015; Borzenkova et al., 2015; Druzhinina et al., 2015).

In the meantime, reflected in multi-proxy records the repeated variations in grain-size, MSus, mineral matter and geochemical composition of the strata noted during the period, dated up to about 13 600 cal yr BP, represent small-scale disturbances of the environmental regime (**Paper IV**). Stratigraphically constrained such variations in the sediment sequence can help to establish the timing and the size of an effect of short-lasting processes. The variability of Si, Al, K, Mg, Ca and Fe noted approximately at 13 800 cal yr BP, chronologically synchronizes with GI-1d cold event dated back to 14 075–13 954 cal yr BP in Greenland ice core (Lowe et al., 2008; Rasmussen et al., 2006), noted between about 14 000–13 650 cal yr BP in the C Europe (Pawłowski et al., 2016), between 14 200 and 13 500 cal yr BP in the NE Baltic (Veski et al., 2012) and observed locally (Stančikaitė et al., 2015; 2008a) according to palaeobotanical markers and other signals i.e. volcanic ash. Most probably, ongoing climatic processes played a major role in the mentioned changes while geographical position including latitudinal differences, and elevation above sea level, also stability of the soil layer, the local hydrological network might have influenced the pattern of the local processes as well as the sedimentation.

Between 13 400 and 12 600 cal yr BP (during GI-1c-a interval), the highest concentration of carbonates was noted in the sediments (**Paper IV**). Simultaneously, the representation of silicaclastic elements (i.e. Si, Al, Ti, K, Mg, etc.) lowered in the strata suggesting the stabilization of the sedimentation regime. The recorded change synchronizes well with the interval of the LGM recorded between 13 600–12 800 cal yr BP in the NE Baltic (Veski et al., 2015). At that time improved thermal conditions lead to the factors i.e. drier soils, decreased water level, etc. that might have affected the geochemical pattern of the sediments. The other hypothesis, which was previously discussed while trying to find the mechanisms initiating carbonate precipitation in the lake located in N Poland region (Apolinarska et al., 2012), state that carbonates probably reached aquatic system due to enhanced carbonate weathering and mobility initiated by decreased soil pH due to changed vegetation composition (Dean, Schwalb, 2000; Loizeau et al., 2001; Anderson et al., 2008) i.e. flourishing of conifer-predominating forest (**Paper IV**). Nevertheless, increasing biodiversity could be suggested as one more local factor supporting high carbonate participation. This fact was supported by the appearance of mollusks and enrichment of the sediments by *Chironomus plumosus* type and *Tanytarsus mendax* type chironomidae taxa (Gastevičienė personal communication) thriving in warm (Nazarova et al., 2017), nutrient-enriched and oxic water (Koinig et al., 2003) (that are also characterized by significantly raised Mn/Fe ratio). Despite the processes initiated, such intense carbonate precipitation could have affected the degree of sediment dilution by carbonates and the sedimentation rate (Pawłowski et al., 2016, Dypvik, Harris, 2001). Conditions, which prevailed throughout the uppermost part of GI-1 interval, reported earlier in closest surroundings (Stančikaitė et al., 2015) and in Poland (Apolinarska et al., 2012, Goslar et al., 1999).

Rapidly participated silty deposits enriched with lower amount of organic gyttja and shells chronologically correspond to so-called GS-1 cooling event, the best-documented climatic interval of the LG that started in Lieporiai at about 12 600 cal yr BP. Timing of environmental destabilization fits well with the C Europe GS-1 scenario (Apolinarska et al., 2012; Kupryjanowicz, 2007; Goslar et al., 1999, Stančikaitė et al., 2002, 2008a, 2015, Veski et al., 2015). Increased participation of terigenic elements (i.e. Ti, Al, Si, K, Rb, Mg, etc.), higher MSus (**Papers II and IV**) and decreased values of carbonates verifies destabilization suggested by an increasing opening of the vegetation cover and states that common landscape forming processes, such as soil erosion, were intensified (Goslar et al., 1999; Pawłowski et al., 2016). Sediments enriched with high Mn, Fe, and P values point to highly oxygenated conditions of aquatic system during LG, which at the end of the event changes. Clear separation between LG and early Holocene intervals from about 11 600–11 300 cal yr BP is seen in PCA results (**Paper II**).

Early Holocene

According to the dating results, the onset of the stabilization of the sedimentation regime in the region has started about 11 500 cal yr BP (**Paper IV**). In N Lithuania it was marked by rapid changes in the geochemical composition and other proxies of the sediments i.e. gradually increasing participation of $CaCO_3$, and clay-sized particles, higher Ca, Sr values as well as Rb/Si ratio, the drop of MSus and LOI curves. The described changes suggest an increased groundwater level. In addition, further enrichment with the organic matter and very low accumulation rate, as well as increased Mn values together with the high Mn/Fe ratio indicate the oxic regime of the basin until about 10 000 cal yr BP. Such change of the aquatic environment together with low sedimentation rate is typical of shallow lakes with increased bioproduction.

Despite the fact, that from about 12 000 cal yr BP an input of allochthonic matter drastically decreased, highly variable lithological and geochemical data (Table 5) suggests ongoing intensive mechanical denudation and increasing accumulation processes until about 10 500 cal yr BP: (i) between 11 600–11 300 cal yr BP, sediments have the highest values of Al, K, Mg, Si, Zr, Ti, also low Fe, Mn; (ii) at about 11 300 cal yr BP, recorded drop in most terigenic elements confirms progressive thinning of the material as well as the change of hydrological condition; (iii) around 11 000 cal yr BP, distinct peaks of Fe, Mn values and increased MSus infer some processes, which could be related to strongly reduced conditions in the lake; (iv) from about 11 000 cal yr BP, increasing representation of weathering elements is recorded. Captured fluctuations in abiotic proxy records allowed detecting previously unrecorded intervals of environmental instability because geochemical proxies responded to climatic shifts more sensitively in comparison with the biotic proxies at the beginning of the early Holocene.

Though some amelioration of environmental situation was recorded after 11 800 cal BP in the S region (Stančikaitė et al., 2015) the environmental changes chronologically synchronous with climatic warming fixed in NW and N Europe and dated back to 11 600 cal yr BP (Wanner et al., 2008) started with some delay in E and NE Europe (Wohlfarth et al., 2007; Stančikaitė et al., 2008a, 2015; Lauterbach et al., 2011). No traces of lithostratigraphical disturbances or biostratigraphical limits have been recorded in (a)biotic proxies at about 11 700 cal yr BP, suggesting predominance of a stable depositional environment. Obviously, local conditions, including the climatic regime typical for the E and NE Europe, had played the leading role in the territory of present Lithuania. The recorded intervals of Early Holocene environmental instability, that were synchronous with so-called *"Preboreal Oscillations"* (Björck et al., 1997), most probably have been triggered by both global processes i.e. short-lasting solar activity changes (Magny, 2004; Wanner et al., 2011) and centennial-scale climatic variations (Alley et al., 2003) with participation of regional factors and local conditions as well (**Paper II**). For example, the increased representation of mineral matter, including the highest Al, K, Zr, Mg, Ti values and increasing MSus, refers to higher inflow of allochthonic matter (**Paper II**) between 10 500 and 10 200 cal yr BP. At the same time, rising accumulation rates evidence higher intensity of the erosional processes that could be related to some opening of the vegetation cover. Besides everything else the PCA results agree with environment change modeling scenarios, pointing that general abiotic proxies and vegetation depend on the same environmental components.

The further changes (**Paper II**) in sediment composition (i.e. gradual increase of organic matter and decrease of terigenic elements) reflect ongoing bogging processes. Due to the changing hydrological situation the open water basin was surrounded by wetland vegetation preventing additional nutrition income from about 10 200–10 000 cal yr BP onwards. Decreasing Mn/Fe values confirm that less of dissolved oxygen has reached the lake indicating stronger anoxic conditions and probably lowering of water pH level at the site (**Paper II**). At about 9 400 cal yr BP peak of Si and Zr also high Si/Ti ratio could suggest ongoing erosional processes, which resulted in higher participation of sand fraction in the sediments. The high concentration of organic matter, low MSus and low values of most terigenic elements represent the final stabilization of the surface from about 9 400 cal yr BP onwards.

Further stages of the basin history confirm a progressively warming climate that has transformed Čepkeliai into the oligotrophic, low–

oxygenated, lentic aquatic system. Despite gradually increasing Ca/Ti and Fe/Ti ratios, which show a constant transition from cool to warm period, variations in the content of terigenic elements i.e. Ca, Mg, Sr, Al, K, Si, Zr, S, P and K/Na, Rb/Ti ratios reveal short-scale environmental disruptions. One prominent variation i.e. abrupt decrease and then quick rise of most of the terigenic elements (Fig. 5) is recorded in Čepkeliai between 8 200 and 7 800 cal yr BP, signaling negative temperature excursions. So-called *"8.2 Ka"* climatic event (Hammer et al., 1986), previously recorded in the E Baltic (Seppä, Poska, 2004, Veski et al., 2004) had strongly affected the hydroclimate system, causing the water table drop which also affected vegetation pattern (**Paper II**). Subsequently, thinner soil cover was more sensitive to water level fluctuations, wind and other destructive processes, causing increasing intensity of the erosion processes recorded in abiotic proxies as well.

Middle Holocene

Organic matter predominates in the sediments deposited during 8 000–4 000 cal yr BP indicating a rather stable depositional environment. Up to about 6 000 cal yr BP low but steady content of silicaclasts was recorded with an increasing Ca and Ca/Ti, Fe/Ti ratios suggesting higher biogenic productivity. High values of S and As could indicate ongoing secondary processes in the basin. Due to intensive organic matter mineralization or humification of the peat (proved by low accumulation rate) in anoxic environment (proved by low Mn/Fe ratio), pyrite production from the sulfate-rich water (López-Buendía et al., 2007; Eusterhues et al., 2005) might have taken part in aquatic system. Despite the fact that recorded shift provoked bogging processes and organic matter predominated in the sediments, low-scale variations in the geochemical parameters were determined in the second part of the interval. Higher values of Al, K, Si, Zr, P and lower of Ca, Mg and Ca/Ti, Fe/Ti ratios determined in the sediments at about 5 600, 5 100, 4 400 cal yr BP indicate drier climatic intervals, which were caused by small climatic deterioration provoking increased erosional processes, in between the long-lasting humid periods. Such climatic fluctuations most probably were caused by decadal to millennial lasting events including astronomically forced high summer insolation (**Paper II**). The most prominent variations of abiotic proxy record (i.e. Ca/Ti ratio) occurred at about 4 500 cal yr BP, i.e. at the end of the HTM (Seppä, Poska, 2004). At that time the highest accumulation rate was recorded, indicating high humidity and favorable conditions for bioproduction, most probably, associated with climatic conditions.

Late Holocene

Between 4 500–4 000 cal yr BP clay mineral-related elements i.e. Sr, Al, also P, S increased insignificantly and Ca, Mg has the highest peaks in the case of Čepkeliai (**Paper II)**. In N Poland similar variations of recorded abiotic proxies, including low accumulation rate, were fixed in different peatlands responding to lowered water table (Lamentowicz et al., 2019) dated back to 4 200 cal yr BP and noted as *"4.2 Ka"* dryness event in the Northern Hemisphere (Arz et al., 2006; Staubwasser et al., 2003; DeMenocal, 2001). While organic matter still predominated in the material analyzed, nevertheless the visible decline was fixed in accumulation rate until about 1 500 cal yr BP suggesting cooler climatic reversal which most likely has activated mineralization processes in the investigated basin (**Paper II**). In addition, erosional processes of different origins were activated as have been confirmed by increased values of MSus record (**Paper III**) and higher deposition of some terigenic elements and/or heavy metals (**Paper IV**). Together with that, the increase in charcoal patterns clearly demonstrated more intensive use of fire for introduction of agriculture, signalling human-induced changes due to increased land erosion. By all counts, there is no wonder that site-specific factors played an increasingly important role in the developments of abiotic environment during the late Holocene.

CONCLUSIONS

1. The highest diversity of the abiotic record, particularly in the geochemical signal fixed in the sediments deposited before 13 400 cal yr BP, i.e. during the earliest LG interstadial oscillations (GI-1e-d), was contemporaneous with the flourishing of the mineral-soil pioneer vegetation, including scattered stands of *Pinus* and *Betula*. Intensive participation of the natural factors of local character, superimposed upon the general climatic amelioration of the Hemispherical scale, played the leading role in the history of environmental development.
2. During further stages of LG interstadial oscillations (GI-1c-a), between 13 400 and 12 600 cal yr BP, the formation of the moderate pine-birch forest was replaced by the pine-predominating vegetation, which was coincident with the stabilization of the sedimentation regime accompanied by increasing bioproductivity in the oxygenated and carbonate-enriched basin. A multi-proxy abiotic approach exhibits a decreasing importance of the local-scale natural factors while those of regional or global scale, climatic amelioration for example, took over.
3. Since about 12 600 cal yr BP (GS-1), the obvious destabilization of the environmental regime was proved by all (a)biotic parameters obtained, i.e. opening of the vegetation pattern with scattered tree patches, including those of *Picea* in the northern part of the country, have been accompanied by the increased erosion of surface and lower precipitation of carbonates proving the decay of organic constituent in the environment. Though recorded changes have been driven by global factors such as climatic deterioration of the Hemispherical scale, the importance of site-related environmental forming processes increased in area.
4. Both abiotic and biotic data confirm a delayed environmental reaction to the Holocene climatic warming pointing to the regional significance of this phenomenon and, accordingly, the importance of regional factors, while the environmental anomalies of the Greenlandian Stage that have been recorded for the first time in the area and date back to 11 200–11 000 cal yr BP, 10 600–10 300 cal yr BP, and 8 200–7 800 cal yr BP are contemporaneous with the pronounced climatic shifts (i.e. dry and cool intervals) known on the continental scale, i.e. *"Preboreal"* and *"10.2 Ka"* oscillations and *"8.2 Ka"* event, and can be putatively linked to the astronomical scale events, i.e. periodicities of solar cycles.
5. A heavily forested landscape with broad-leaved deciduous trees dominating the taxa existed in the area between about 7 800 and 4 500 cal

yr BP, while expansion of spruce suggests environmental instability that started prior to the general decline of the HTM and could be interpreted as a reaction to the local-scale climatic reversal dating back to about 6 100–5 900 cal yr BP. The natural factors of different scale played a leading role in the development of the (a)biotic environment, while site-specific and anthropogenic ones remained negligible during the Northgrippian Stage.

6. The Meghalayan Stage represents the increasing importance of anthropogenic factors for the development of the palaeoenvironment. The recorded reorganization of the (a)biotic proxies, including the formation of diverse vegetation with increasing participation of *Picea* after 4 200 cal yr BP and responses of the sediment geochemistry, i.e. a more intensive mineralization of organic matter, increasing participation of Ca in strata, etc., was determined by cold and wet climatic reversals on a global scale, while some changes in vegetation and short-scale lithological and sedimentological fluctuations noted at about 3 250–2 950 and 950–650 cal yr BP are interpreted as induced by anthropogenic factors.
7. Alongside with the increasing intensity of human activity, the site-specific factors of anthropogenic origin became evidently important in the area during the last three thousand years. In most cases, the recorded fluctuations of (a)biotic palaeoenvironmental proxies are in a positive correlation with the dynamics of the subsistence economy of the local population, i.e. introduction of animal husbandry and agriculture at about 3 250–2 950 cal yr BP, spread of agriculture from about 1 550–950 cal yr BP, and establishment of regular cultivation practices at about 6th-7th c. AD.

SANTRAUKA

MOKSLINĖ PROBLEMATIKA

Pasaulyje paleoaplinkos tyrimams skiriama vis daugiau dėmesio. Gamtinės aplinkos kaitos charakterizavimas yra ypač aktualus siekiant chronologinėje perspektyvoje suprasti šiuolaikinius klimato kaitos procesų fone vykstančius svyravimus ir pagal kaitos modelius prognozuoti galimus gamtinės aplinkos pokyčių scenarijus, taip užtikrinant saugią ateinančių žmonijos kartų aplinką.

Atliekant praeityje vykusių gamtinės aplinkos pokyčių tyrimus, t. y. įvertinant globalių ir lokalių veiksnių, tokių kaip klimato kaita, įtaką abiotinės ir biotinės aplinkos komponentams, ženkliausi pokyčiai paprastai išryškėja pereinamojo (arba tarpinio) tipo klimato, sedimentacinių aplinkų, augalijos sudėties ir panašiose zonose. Kompleksiškai tiriant sedimentacinių baseinų nuosėdas, įvertinami (a)biotinių veiksnių svyravimai laike ir erdvėje. Tokių tyrimų metu neretai identifikuojami ir charakterizuojami anksčiau neaprašyti pasikeitimai, kuriuos lėmė vietinės sąlygos. Panašių, anksčiau nefiksuotų paleoaplinkos sąlygas charakterizuojančių pokyčių teritorinis ir chronologinis apibrėžimas globalių ir vietinių juos lėmusių veiksnių kontekste, pasitelkiant originalius tyrimų metodus, ir buvo esminis atliktų tyrimų uždavinys. Sprendiniai, nagrinėjantys skirtingus šios problemos aspektus, autorės kartu su kolegomis buvo pateikti penkiose pagrindinėse (**I–V**) ir keturiose papildomose (**VI–IX**) publikacijose.

Disertacijoje analizuojamas laiko intervalas, apimantis vėlyvojo ledynmečio ir holoceno laikotarpius. Paskutiniam kontinentiniam Skandinavijos ledynui ištirpus (Ehlers ir kt., 2004), įvairiuose ledyninės ir prieledyninės kilmės duburiuose susiformavo sedimentaciniai baseinai, kuriuose iš pradžių kaupėsi beveik išimtinai neorganinės, o vėliau, vyraujant palankioms klimatinėms sąlygoms bei teritorijoje įsitvirtinus įvairioms gyvosios gamtos formoms, pradėjo kauptis ir organinės kilmės nuosėdos. Su regioniniu ir/ar globaliu mastu nustatytais klimato pokyčiais sinchronizuoti šių nuogulų kompleksinių tyrimų rezultatai leidžia įvertinti aplinkos sąlygas: temperatūrinį ir drėgmės režimą, vandens lygį, deguonies kiekį jame ir kt.

Moksliniame darbe, remiantis kompleksinių tyrimų, kurių pagrindą sudarė palinologiniai ir geocheminiai ežerinių bei pelkinių nuosėdų tyrimai, rezultatais nagrinėjama paleoekologinių sąlygų raida vietinių ir globalių veiksnių poveikio kontekste. Saulės aktyvumo kaita yra vienas iš daugelio natūralių gobaliai fiksuojamų procesų (**V publikacija**), lemiančių kai kuriuos šimtmečių bei tūkstantmečių klimato kaitos ciklus ir kartu gamtinės (a)biotinės aplinkos pokyčius.

Autorė vėlyvojo ledynmečio ir holoceno paleoaplinkos sąlygoms bei jų pokyčiams nagrinėti naudojo ir abiotinius parametrus (**II** ir **IV publikacijos**). Remiantis gauta informacija, buvo nustatyti chronostratigrafiškai apibrėžti fizinių ir geocheminių parametrų pokyčiai, kurių įvertinimas leido apibūdinti gamtinės abiotinės aplinkos atsaką į išorinius veiksnius.

Holoceno gamtinės aplinkos raida pastaraisiais dešimtmečiais regione tirta gana intensyviai (Stivrins ir kt., 2014; Veski ir kt., 2004, 2012, 2015; Heikkilä, Seppä, 2010; Šeirienė ir kt., 2009; Gaidamavičius ir kt., 2011; Gryguc ir kt., 2013; Kabailienė ir kt., 2015), tačiau abiotinės aplinkos raidos tyrimai gana negausūs, todėl jie aprašyti autorės darbuose (**II** ir **III, IV publikacijos**).

Tiriant holoceno paleoaplinkos sąlygų kaitą ir identifikuotų svyravimų santykį su globaliais bei vietiniais veiksniais, ypač svarbu įvertinti galimą žmogaus veiklos įtaką ekosistemai. Ypač ženklus šio poveikio šuolis sietinas su žemdirbystės bei gyvulininkystės plėtra regione (Maldre, Luik, 2009; Simniškytė, 2013; Daugnora, Girininkas,1998; Girininkas 2002; Poska, Saarse, 2006). Atlikti biotinės aplinkos parametrų tyrimai, įvertinant tyrimų regione fiksuojamą žmogaus veiklą, bei gautos informacijos analizė globalių ir vietinių veiksnių kontekste, pateikti dviejuose autorės darbuose (**I** ir **III publikacijos**).

DARBO TIKSLAS IR UŽDAVINIAI

Darbo tikslas – remiantis nuogulų kompleksinių tyrimų duomenimis, rekonstruoti biotinės ir abiotinės aplinkos raidą paskutinio kontinentinio Skandinavijos ledyno pietrytiniame pakraštyje vėlyvojo ledynmečio ir holoceno laikotarpiu ir nustatyti aplinkos kaitos priežastis lėmusius gamtinius (astronominius, globalius, regioninius, vietinius) bei antropogeninius veiksnius.

Tikslui įgyvendinti iškelti tokie uždaviniai:

1. Naudojantis radioaktyviosios anglies analizės metodu (C^{14}) gautais duomenimis, sudaryti chronologines tirtų baseinų nuosėdų kolonėlių skales.
2. Atkurti chronologiškai apibrėžtą vėlyvojo ledynmečio ir holoceno augalijos kaitos raidą, vykusią gamtinių ir antropogeninių veiksnių kontekste.

3. Atkurti chronologiškai apibrėžtą abiotinių komponentų kaitą, akcentuojant cheminių elementų pokyčius bei įvertinant skirtingų veiksnių įtaką fiksuojamiems svyravimams.
4. Charakterizuoti biotinių ir abiotinių aplinkos komponentų pokyčių tarpusavio priklausomybę.
5. Įvertinti fiksuotus (a)biotinės paleoaplinkos sąlygų pasikeitimus skirtingo masto gamtinių (astronominių, globalių, regioninių, vietinių) ir antropogeninių veiksnių atžvilgiu.

DARBO AKTUALUMAS IR NAUJUMAS

Gauti tirtų nuogulų geocheminių ir kitų abiotinę aplinką charakterizuojančių tyrimų rezultatai pirmą kartą buvo panaudoti, siekiant apibūdinti aplinkos dinamiką poledynmečiu ir įvertinti fiksuojamų svyravimų prigimtį skirtingo masto išorinių veiksnių poveikio kontekste.

Kompleksiniai biotinės aplinkos tyrimai ir gautų rezultatų interpretacija leido nustatyti anksčiau regione nefiksuotus sausumos bei vandens augalijos raidos etapus, įvertinant jų kaitos dinamiką gamtinių (astronominių, globalių, regioninių, vietinių) ir antropogeninių procesų kontekste.

Gauti tyrimų rezultatai, sinchronizuoti ir sukoreliuoti pagal NGRIP chronologinę skalę bei naują holoceno chronostratigrafinį suskirstymą (Lowe ir kt., 2008; Walker ir kt., 2009), buvo analizuoti skirtingu mastu (astronominiu, globaliu, regioniniu, vietiniu) išryškėjančių veiksnių kontekste.

REZULTATAI IR APTARIMAS

Disertacijoje, remiantis kompleksinių tyrimų duomenimis, atkurta vėlyvojo ledynmečio ir holoceno augalijos kaita, įvertinta abiotinės aplinkos pokyčių dinamika. Pasirinkta tyrimų teritorija apima pietrytinį paskutinio kontinentinio Skandinavijos ledyno maksimalaus išplitimo pakraštį. Detalūs tarpdisiplininiai tyrimai atlikti trijuose objektuose: Čepkelių aukštapelkėje (pietryčių Lietuva) (**I, II** ir **V publikacijos**), Petrešiūnuose (šiaurės rytų Lietuva) (**III publikacija**) ir Lieporiuose (šiaurės Lietuva) (**IV publikacija**). Darbe daugiausia remtasi žiedadulkių ir geocheminių tyrimų rezultatais, o nustatytų (a)biotinių aplinkos rodiklių tarpusavio sąsajos vertintos taikant įvairius statistinius metodus. Sudarius chronologiškai apibrėžtą nuosėdų amžiaus skalę, (a)biotiniuose parametruose fiksuoti pokyčiai sinchronizuoti ir sukoreliuoti su fiksuotais regione bei pasaulyje. Tai leido identifikuoti ir charakterizuoti anksčiau regione neaprašytus svyravimus, kuriuos lėmė vietiniai veiksniai.

Remiantis tyrimų rezultatais (**IV publikacija**), vėlyvojo ledynmečio pradžioje (iki 13 400 kal. m. PD (kalibruoti metai prieš dabartį) regionui buvo būdinga tundros tipo žolinė augalija. Klimatui šylant, pamažu plito pušų–beržų retmiškiai. Ežerinėse nuosėdose vyrauja įvairaus rupumo smėlis ir žvyras, o nustatyti dideli Si, Ti, Al, Rb kiekiai rodo, jog sąlygos buvo nepalankios susiformuoti dirvožemiui ir tai turėjo įtakos erozinių procesų intensyvumui. Cheminių elementų koncentracijos didėjimas vėlyvojo ledynmečio viduryje ir nuosėdų dalelių dydžio mažėjimas rodo, jog geodinaminiai procesai darė vis mažesnę įtaką aplinkos formavimuisi. Ties 13 800 kal. m. PD riba fiksuojamas trumpas (a)biotinės aplinkos nestabilumas, regione gerai žinomas kaip GI-1d atšalimas (Lowes ir kt., 2008; Stančikaitė ir kt., 2008, 2015; Veski ir kt., 2012), sutapo ir su ženkliais augalijos sudėties pasikeitimais – pušynus pakeitė žolinė augalija. Tokie pokyčiai leidžia manyti, jog vėlyvojo ledynmečio klimatas buvo kaitus ir gerokai vėsesnis nei dabar, panašus į šiandieninės tundros klimatą šiaurinėje Norvegijos dalyje.

Vėlyvojo ledynmečio antroje pusėje (13 400–12 600 kal. m. PD) regione vyravo pušynai (**IV publikacija**), sedimentacinės sąlygos ženkliai pakito. Pakitusi cheminė ir granuliometrinė nuosėdų sudėtis (padidėjo karbonatų, Rb, organikos kiekis, molio dalelių koncentracija, didelės Mn/Fe santykio reikšmės) rodo sulėtėjusią sedimentaciją ir oksidacines sąlygas, palankesnes bioprodukcijai formuotis.

Vėlyvojo ledynmečio pabaigoje (12 600–11 400 kal. m. PD) regione įsivyravo skurdi žolinė augalija, nyko pušų–beržų retmiškiai. Labai ryškus ežerinių nuosėdų sudėties (nustatytas silikaklastinių Si, Ti, Al, Rb elementų kiekio padidėjimas; Ca, Mn/Fe santykio ir organinės medžiagos sumažėjimas) pasikeitimas susijęs su intensyvesne krantų erozija. Augalijos ir nuosėdų litologinės sudėties pokyčiai byloja apie bioprodukcijai formuotis nepalankias aplinkos sąlygas, šaltą ir gana sausą klimatą laikotarpio viduryje, pakilusį vandens lygį vėlesniais jo etapais. Šis intervalas atitinka globaliai fiksuojamą GS-1 atšalimą (**II, IV publikacijos**).

Tyrimų metu gauti duomenys ir jų palyginamasis įvertinimas leidžia teigti, jog vėlyvojo ledynmečio gamtinės aplinkos, augalijos, nuosėdinės dangos ir ežerinių nuosėdų sudėčiai didelę reikšmę turėjo tiriamos teritorijos fizinės ir geografinės sąlygos bei temperatūrų svyravimai, kuriems įtakos turėjo globalūs ilgalaikiai veiksniai.

Ankstyvajame holocene fiksuoti trumpalaikiai augalijos ir nuosėdų litologijos pasikeitimai byloja apie kaičias gamtines sąlygas, kurių metu regione buvo drėgna ir gana šilta. Aplinkos pokyčiai buvo trumpalaikiai, vis dar jautėsi GS-1 atšalimo padariniai. Periodo pradžioje (iki 10 000 kal. m.

PD) regione augo reti borealiniai miškai, kuriuose vyravo pušys, atsirado pirmieji plačialapiai. Fiksuojamas didesnis litogeninės medžiagos prinešimas (pietryčių Lietuvoje ežerinėse nuosėdose daugėja Si, K, o šiaurės Lietuvoje – Ca) byloja apie vyraujančius mechaninės denudacijos procesus, menką dirvožemio sluoksnį (**II, IV publikacijos)**. Mažėjančios Mn/Fe santykio reikšmės susijusios su redukcinėmis sąlygomis. Nuosėdose nustatytas anksčiau teritorijoje nefiksuotas labai kaitus cheminių elementų kiekis rodo globalius trumpalaikius klimato pokyčius, įvardijamus kaip osciliacijos, kurių poveikis biotinei ir abiotinei aplinkai priklausė nuo fizinės ir geografinės objekto padėties.

Nuo 10 000 kal. m. PD gamtinės aplinkos sąlygos pamažu stabilizavosi, miškuose padaugėjo plačialapių medžių, prasidėjo intensyvus ežerų pakrančių pelkėjimas, terigeninių nuosėdų prinešimas į baseinus menko. Terigeninės medžiagos kiekis, tiesiogiai priklausantis nuo oksidacinių sąlygų ir atvirkščiai proporcingas augalinės masės prieaugiui, rodo, jog pelkėjimo procesai šiuo laikotarpiu darė vis didesnę įtaką aplinkos formavimuisi.

Vidutiniškai ties 8 100 kal. m. PD riba (a)biotiniuose komponentuose nustatyta trumpalaikė fliuktuacija: staigiai nukritęs ir paskui padidėjęs mineralinės medžiagos kiekis bei trumpalaikiai augmenijos pokyčiai rodo klimato atšalimą, kuris koreliuojamas su šiauriniame pusrutulyje fiksuojamu *„8.2 Ka“* įvykiu (Lowe ir kt., 2008) (**II publikacija**).

Viduriniojo holoceno (nuo 8 200 iki 4 200 kal. m. PD) metu teritorijoje paplito tankūs šilumamėgiai miškai, o eglių gausa byloja apie didelį drėgmės kiekį aplinkoje. Nuosėdų cheminės sudėties pokyčiai (nežymiai didėjantis Ca kiekis, Mn/Fe reikšmės) rodo, jog prasidėjo intensyvūs pelkėjimo procesai. Viduriniojo holoceno pabaigoje fiksuojamos didelės cheminių elementų kiekių fluktuacijos. Labai varijuoja molio mineralų ir silikaklastų sudėtyje esančių Rb, Si, Ti, Al, K koncentracijos, fiksuojami trumpalaikiai gausesnės terigeninės medžiagos prinešimo etapai. Manoma, jog tokie pokyčiai susiję su vietinės ar regioninės reikšmės aplinkos sąlygų svyravimais (**I, II** ir **III publikacijos**), gruntinio vandens lygio kitimu. Sąlygos atitinka holoceno klimatinį optimumą: fiksuoti pokyčiai ir pelkėjimo procesai yra vienalaikiai su procesais, fiksuojamais gretimose šalyse (Feurdean ir kt., 2008; Grindean ir kt., 2015; Langdon ir kt., 2003) ir sietini su regionine klimato kaita (Hammarlund ir kt., 2003; Seppä ir kt., 2005).

Vėlyvojo holoceno metu (nuo 4 200 kal. m. PD) ženkliai pakito augalijos sudėtis – tankius plačialapių miškus pamažu pakeitė pušynai, atskirose teritorijose – eglynai. Pakitusi augalija, nuosėdose fiksuojamas padidėjęs mineralinės medžiagos kiekis, didėjantis Mn/Fe santykis rodo šiek tiek intensyvesnį organinės medžiagos skaidymąsi, o fiksuojamas Ca/Ti santykio mažėjimas sietinas su aukštapelkės formavimusi (**II publikacija**). Antroje intervalo pusėje (nuo 1 000 kal. m. PD) fiksuojamas žolinės augalijos plitimas, išryškėja nedidelės nuosėdų sudėties variacijos (padidėję Ca, Sr, Ti, Fe, Zn, K, Rb kiekiai, stambesnė frakcija, žemesni MSus rodikliai, sumažėjusi organikos koncentracija) ir nustatyta litogeninių elementų padidėjimo tendencija gali būti susijusi su padidėjusia paviršinių nuosėdų mineralizacija, nukritusiu vandens lygiu. Šie pokyčiai yra vienalaikiai su globaliai fiksuojama holoceno maksimalaus temperatūrinio piko pabaiga ir galimai susiję su intensyvėjančia žmogaus ūkine veikla, t. y. jiems įtakos turėjo tiek vietiniai, tiek ir didesnio masto veiksniai (**I, II** ir **III publikacijos**).

Paskutiniojo tūkstantmečio paleobotaniniai duomenys regione fiksuoja drėgnesnius (1 650–1 450 ir 1 000–100 kal. m. PD), šiltesnius ir sausesnius (1 850, 1 350, 1 200 kal. m. PD) laikotarpius (**I** ir **III publikacijos**), kurie koreliuojami su Romėniškuoju (Heikkilä, Seppä, 2010; Büntgen ir kt., 2011) ir Viduramžių (Bertland ir kt., 2002; Tiljander ir kt., 2003; Van der Linden ir Van Geel, 2006; Lamentowicz ir kt., 2008) šiltmečiais, o kiti – su Mažuoju ledynmečiu (Wanner ir kt., 2011). Tiesa, minėti svyravimai išryškėja toli gražu ne visuose regione tirtuose pjūviuose, todėl panašios prielaidos turi būti atidžiai vertinamos suvokiant vietinių ir regioninių bei globalių veiksnių įtaką.

IŠVADOS

1. Pirmoje vėlyvojo ledynmečio interstadialo pusėje, prieš 13 400 kal. m. PD (GI-1e-d), susikaupusiose nuosėdose nustatyta didžiausia abiotinių komponentų, ypač geocheminio signalo, įvairovė yra vienalaikė su mineralinio dirvožemio pionierinės augalijos, įskaitant pušų–beržų retmiškius, paplitimu. Pagrindinę įtaką aplinkos raidai darė intensyvūs vietinio pobūdžio gamtiniai veiksniai, išryškėję bendro klimato pašiltėjimo, fiksuojamo visame šiauriniame pusrutulyje, kontekste.
2. Vėlesnių vėlyvojo ledynmečio interstadialo stadijų, apimančių intervalą nuo 13 400 iki 12 600 kal. m. PD (GI-1c-a), metu pušų–beržų retmiškius pakeitė pušynai, sedimentacijos režimas stabilizavosi, deguonies ir karbonatų prisotintame baseine padidėjo bioproduktyvumas. Kompleksinių tyrimų rezultatai rodo mažėjančią vietinio masto bei didėjančią regioninio ar globalaus masto gamtinių veiksnių, pavyzdžiui, klimato pokyčių, svarbą.
3. Nuo maždaug 12 600 kal. m. PD (GS-1) visi (a)biotiniai parametrai liudija akivaizdų aplinkos režimo destabilizavimą. Pušis pakeitė atviro kraštovaizdžio tundros su pavieniais medžiais, tarp kurių, ypač šiaurinėje regiono dalyje, plito eglės. Pokyčius augalijoje lydėjo suintensyvėjusi paviršiaus erozija ir mažesnis karbonatų nusėdimas, bylojantis apie organinės medžiagos aplinkoje nykimą. Nors užfiksuotus pokyčius lėmė globalūs veiksniai, tokie kaip klimato atšalimas visame šiauriniame Žemės pusrutulyje, teritorijoje didesnės įtakos turėjo vietiniai aplinkos formavimo procesai.
4. Abiotinių ir biotinių duomenų pobūdis patvirtina vėluojančią aplinkos reakciją į holoceno klimato atšilimą, t. y. regioninio pobūdžio veiksnių įtaką paleoaplinkos dinamikai. Regione pirmą kartą užfiksuotos „Greenlandian“ stadijos metu išryškėjusios paleoaplinkos sąlygų anomalijos, datuojamos 11 200–11 000 kal. m. PD, 10 600–10 300 kal. m. PD ir 8 200–7 800 kal. m. PD, yra susijusios su ryškiais klimato pokyčiais (t. y. sausais ir vėsiais intervalais), kurie kontinentiniame lygmenyje žinomi kaip *„Preborealio“*, *„10.2 Ka“* svyravimai ir *„8.2* Ka*”* įvykis ir kuriuos galima numanomai susieti su astronominio masto įvykiais, pavyzdžiui, saulės ciklų periodiškumu.
5. Tankius lapuočių miškus, regione klestėjusius 7 800–4 500 kal. m. PD, pamažu keitė eglynai, kurių plitimą prieš maždaug 6 100–5 900 kal. m. PD lėmė klimatinių sąlygų pokytis, pasireiškęs dar prieš holoceno klimatinio optimumo nuosmukį ir, manome, buvęs gana lokalaus pobūdžio. „Northgrippian“ etapo metu skirtingo masto

gamtiniai veiksniai išliko lemiantys formuojantis (a)biotinei aplinkai, o antropogeninės kilmės veiksnių įtaka buvo labai menka ir lokali.

6. Tyrimų metu išryškėjusią (a)biotinių parametrų kaitą, t. y. akivaizdžiai pakitusią augalijos sudėtį, pasireiškusią eglynų paplitimu, ir pakitusią nuosėdų cheminę sudėtį, kuri atspindi intensyvesnę organinių medžiagų mineralizaciją bei padidėjusią Ca koncentraciją ir pan., didžia dalimi lėmė po 4 200 kal. m. PD globaliai fiksuojamas klimato atšalimas ir aplinkoje padidėjęs drėgmės kiekis, tačiau atskiri trumpalaikiai augalijos bei litologinių ir sedimentologinių sąlygų svyravimai, išryškėję maždaug 3 250–2 950 ir 950–650 kal. m. PD yra vertintini kaip sukelti antropogeninių veiksnių. Akivaizdu, jog „Meghalayan“ stadijos metu žmogaus įtaka paleoaplinkos dinamikai ženkliai išaugo.

7. Didėjant žmogaus ūkinės veiklos intensyvumui, lokalaus masto antropogeninės kilmės veiksnių įtaka paleoaplinkos dinamikai per pastaruosius tris tūkstančius metų taip pat ženkliai išaugo. Fiksuojami (a)biotinių paleoaplinkos rodiklių svyravimai išryškėjo harmoningai su žmogaus gamybinio ūkio formų pokyčiais, t. y. ankstyvaisiais gyvulininkystės ir žemdirbystės etapais, datuojamais 3 250–2 950 kal. m. PD, žemdirbystės plitimu prieš 1 550–950 kal. m. PD bei šios ūkio formos suklestėjimu mūsų eros VI–VII amžiais.

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PAPER I

Late-Holocene vegetation dynamics in response to a changing climate and anthropogenic influences–Insights from stratigraphic records and subfossil trees from southeast Lithuania

Edvardsson, J., Stančikaitė, M., Miras, Y., Corona, C., Gryguc, G., **Gedminienė, L.,** Mažeika, J., Stoffel, M.

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PAPER II

Holocene vegetation and hydroclimatic dynamics in SE Lithuania–Implications from a multi-proxy study of the Čepkeliai bog

Stančikaitė, M., **Gedminienė, L.,** Edvardsson, J., Stoffel, M., Corona, C., Gryguc, G., Uogintas, D., Zinkutė, R., Skuratovoč, Ž., Taraškevičius, R.

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PAPER III

Reconstruction of the Mid- to Late- Holocene history of vegetation and land-use in Petrešiūnai, north-east Lithuania: implications from palaeobotanical and archaeological data

Stančikaite, M., Simniškytė, A., Skuratovič, Ž., **Gedminienė, L.,** Kazakauskas, V., Uogintas, D.

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PAPER IV

The Lateglacial-Early Holocene dynamics of the sedimentation environment based on the multi-proxy abiotic study of Lieporiai palaeolake, Northern Lithuania

Gedminienė, L., Šiliauskas, L., Skuratovič, Ž., Taraškevičius, R., Zinkutė, R., Kazbaris, M., Ežerinskis, Ž., Šapolaitė, J., Gastevičienė, N., Šeirienė, V., Stančikaitė M.

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PAPER V

Holocene vegetation patterns in southern Lithuania indicate astronomical forcing on the millennial and centennial time scales.

Spiridonov, A., Balakauskas, L., Stankevič, R., Kluczynska, G., **Gedminienė, L.**, Stančikaitė, M.

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