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Mid- to late Holocene Bond events reflected in the pollen-inferred vegetation history of the southeastern Baltic Sea region: a case study of the Curonian Lagoon[1]

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Abstract

This paper presents the results of a study on climate fluctuations (Bond events) and related vegetation changes in the southeastern Baltic area. To date, regional and local palaeoenvironmental responses and their climate association with Bond events remains poorly understood. New data from lithological, geochronological, and palynological analyses of the Curonian Lagoon sediment sequence provide a reconstruction of regional vegetation changes considered on the background of short-term climate fluctuations. This study reveals that palynological data do not reflect climate events evenly. Thus, climate changes that occurred approximately 5900 and 2800 cal yr BP are most clearly reflected in palynological record. At the same time, the events of 1400 cal yr BP and the Little Ice Age are weaker expressed in the pollen curves. Whereas, the 5900 and 2800 cal yr BP cold events are marked by significant reduction of Quercetum mixtum (QM) pollen and, in particular, oak and elm, the onset of the

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Little Ice Age is characterised by a short-term decrease of anthropogenic indicators. The study also showed that besides climate, changes in local hydrological conditions and anthropogenic factor could have a significant impact on the vegetation cover of the study area. The influence of the anthropogenic factor has been increasing over the last 3000 years, making it difficult to fully disentangle natural and human-induced changes in ecosystems of the southeastern Baltic.

Keywords: Bond events, climate fluctuations, vegetation, southeastern Baltic

1. Introduction

As an interglacial period, the Holocene appears to be an interval of relatively warm and stable climate. However, more detailed time scales have shown that during the Holocene, numerous short-term climate fluctuations existed against a general trend, when precipitation and/or temperature fell sharply (Borisova, 2014).

In the last two decades, the term ‘rapid climate change (RCC) event’ has become widely used. Mayewski et al. (2004) examined ~50 globally distributed paleoclimate records and revealed several periods of significant rapid climate change during the time periods 9000–8000, 6000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 cal yr BP. Most of these climate change events are traced globally and expressed by polar cooling, tropical aridity, and major atmospheric circulation changes. Verification of the age boundaries for these RCC events is based on GISP2 chemistry series and glacier fluctuation record (Mayewski et al., 2004).

Bond et al. (1997) documented eight cold events based on ice debris records in deep-sea sediments of the North Atlantic that date back to 11100, 10300, 9400, 8200, 5900, 4200, 2800, and 1400 cal yr BP, respectively. The establishment of “Bond events” (BE) was based on quartz and hematite stained grains recovered from subpolar North Atlantic marine cores documenting nine large-scale and multi-centennial North-Atlantic cooling phases. These BE were subsequently supplemented by two additional short-term climate fluctuations: at 7200 cal yr BP and the Little Ice Age started at around 700-600 cal yr BP (Zielhofer et al., 2019). The BE mostly lasted decades or centuries with ~1500 year intervals. In general, BE have been accompanied by cooling in the high and drying in the low latitudes of the northern hemisphere.

Despite of a globally distributed signature of major climate events, the differences in climate fluctuation and differences in the sensitivity of the proxies from record to record exist on a more detailed regional scale (Mayewski et al., 2004; Wanner et al., 2008). These regional and local palaeoenvironmental responses and their climate association with RCC/BE remains poorly understood despite having extensive studies on climate change reconstruction all over the world and in the Baltic region (Šeirienė et al., 2006; Stančikaitė et al., 2015; Wachnik, 2009; Apolinarska et al., 2012; Kołaczek et al., 2013; Borzenkova et al. 2015; Druzhinina et al. 2020). Meanwhile, they are important in identifying the reasons and driving mechanism of the Holocene climate events, which are of major theoretical and practical significance due to the social, econimical and ecological impacts of ongoing climate change and possible climate fluctuations in the future.

There is an ogoing discussion on the driving mechanism and the scale of climate impact of the BE (Mayewski et al., 2004; Wanner et al., 2011, 2014). The evidence for consistent hydro-climate connections between the subpolar North Atlantic and distant regions is also not clear (Wanner and Bütikofer, 2008). The paper attempts to trace a response to the BE in a new regional-scale palaeoenvironmental record in the southeastern Baltic Sea region, which environment is directly influenced by its connection to the North Atlantic basin. The study is based on palaeovegetation reconstructions inferred from palynological data obtained from a coring sequence in the Curonian Lagoon (the southeastern part of the Baltic Sea) in 2018 and 2021. Vegetation being one of the key components of terrestrial ecosystems is also one of the most sensitive to climate fluctuations. In term, several studies reveal that vegetation itself influences the local climate conditions by the exchanges of matter and energy between the land and atmosphere via the effects of albedo, roughness, canopy conductivity, leaf area, etc. (Li et al., 2023). Thus, understanding of interrelation 'climate – vegetation' on the levels from global to local is important. Numerous studies showed also that the visibility of short-term Holocene climate fluctuations in pollen data are disputable and differently pronounced in northern, central and eastern Europe (Tinner and Lotter, 2001; Seppä et al., 2007; Giesecke et al., 2011; Feurdean et al., 2014). Over the last few decades, numerous researches have been carried out in the Baltic region concerning vegetation dynamics and its relation to climate change in general (Šeirienė et al. 2006; Stančikaitė et al., 2015; Wachnik 2009; Apolinarska et al. 2012; Pochocka-Szwarc 2013; Druzhinina et al., 2015, 2020; Napreenko et al., 2021). However, works examining the manifestation of BE in palaeobotanical records are lacking. In the present paper, new results from palynological analys are considered to provide a picture of the regional vegetation dynamics and its response to BE during the Middle and Late Holocene.

2. Methods and material

2.1. Sampling

A core sample of bottom sediments (3P) was taken in the southwestern part of Curonian Lagoon (54°57'55.6" N, 20°32'50.00" E) with a gravity tube (Fig. 1). The core was 90 cm long.

As upper horizons of gyttja (0–25 cm) were highly liquified they were not sampled during the study.

2.2. Radiocarbon Dating and Lithology

Six samples of bottom sediments were subjected to radiocarbon dating using an accelerating mass spectrometry (AMS) method (Table 1). Dating was completed in the CCP Laboratory of Radiocarbon Dating and Electron Microscopy at the Institute of Geography RAS, Moscow (IGAN), together with the Centre for Applied Isotopic Studies, University of Georgia, USA, at the AMS Centre of the Novosibirsk State University and the Institute of Nuclear Physics, Novosibirsk (GV), and at the Laboratory of Radiocarbon Studies, Poznan, Poland (Poz). Calibration of radiocarbon dates was performed in the CALIB programme, version 8.2.0, using the IntCal20 calibration curve (Stuiver et al., 2020).

The age-depth models were generated by interpolation between the calibrated radiocarbon ages using OxCal software, version 4.4.4 (Bronk Ramsey, 2017).

Lithological description was based on visual and physical studies of the composition and color of bottom sediments.

2.3. Palynological analysis

Pollen analysis was conducted on 31 peat and gyttja samples which were taken from the sediment monoliths in every 2 cm and processed according to Faegri-Iversen technique (1989) for preparation of pollen specimens. Specimens were microscopically examined under 400-x magnification or larger magnification (1000-x) for problematic objects. No less than 400 arboreal pollen grains had been counted in each sample. To calculate pollen concentration in 1 cm^3 of sediment, *Lycopodium clavatum* tablets were added to the samples prior to the maceration (Stockmarr, 1971). The percentage of taxa was calculated relative to the total terrestrial pollen sum, including arboreal and non-arboreal pollen (AP+NAP). To avoid local effects, pollen from aquatic plants, spores and algal coenobia (*Pediastrum* spp.) were excluded from the total pollen sum, and their frequency values were calculated in relation to the sum AP + NAP. The pollen diagram (Fig. 3) was plotted using C2 software (Juggins, 2014). Local pollen assemblage zones (LPAZ) were visually defined as intervals where the pollen of a species reaches peak content in a horizon and where some species appear / decline (Boitsova, 1977). *Tilia, Quercus, Ulmus, Fraxinus* and *Corylus* are included in “Quercetum mixtum” in the discussion of results.

3. Results

3.1. Geochronology and Lithology

Geochronological results and lithological description are presented in the Table 1.

The obtained results show that at a depth of 48–47 cm type of deposits changes: peaty gyttja is succeeded by silty gyttja. There is also a substantial gap in dates in this depth range. All this seems to indicate a hiatus in deposition that started after approximately 5600 cal yr BP and lasted till shortly before 3300 cal yr BP. Taking this into account, the two age-depth models were generated for both part of the sequence (Fig. 2).

Palinological analysis 3.2

The palynological analysis, depicted in the pollen diagram (Figure 3), allowed us to distinguish three palynological zones and several subzones in the section under consideration (Table 2, Figure 3).

4. Discussion

The lower part of the section (Figure 3, depth of 90–53 cm) is represented by pollen from vegetation typical of the Holocene climate optimum in this part of the Baltic area and on many territories in Europe (Steffen, 1931; Kołaczek et al., 2013; Birks and Tinner, 2016; Napreenko and Napreenko-Dorokhova, 2020). Temperate deciduous forests (Quercetum mixtum) prevailed. Oak (*Quercus*) with significant participation of elm (*Ulmus*) and hazel (*Corylus*), and to a lesser extent lime (*Tilia*) were the main elements. The total share of nemoral elements in the pollen spectrum in this period reaches 40-45%. Moist black alder forests (30-35%) were quite widespread in lowland areas too. Hornbeam (*Carpinus*) and beech (*Fagus*) had already started to penetrate, but their share was still insignificant. Small quantitative values of pine (*Pinus*), spruce (*Picea*) and birch (*Betula*) were recorded. Probably, participation of these species in the vegetation composition was limited. Pine may have grown together with oak on sandy habitats as is the case now on river terraces in surroundings: oak patches are located on more fertile soils while pine is dominant on poorer sandy soils (Napreenko and Napreenko-Dorokhova, 2020).

The '5900 event'. This cooling marks the end of the Holocene climate optimum (Borzenkova et al., 2015). On the global scale, warming was replaced by cooling, which was the most clearly manifested in the middle and high latitudes of the Earth, causing changes in the composition and distribution of plant communities and activation of mountain glaciation. Palaeobotanical data testify that the northern boundary of the forest in Eurasia was retreating southwards, with a decreasing role of thermophilic species in the plant communities (Borisova, 2014). These global climate processes are clearly reflected in the studied geological section (Figure 3, LPAZ 1). Time period of 6000–5500 cal yr BP is characterised by a significant reduction of Quercetum mixtum pollen and, in particular, oak and elm. Probably, the cooling suppressed *Corylus* having a negative fluctuation on the pollen record. At the same time, the share of pine and birch pollen increases. The decrease of *Alnus* may indicate some ground water lowering, although the proportion of bog mosses (*Sphagnum*, Polypodiaceae) does not fluctuate significantly. As it seems, a remarkable decrease of green coccal algae (*Pediastrum* sp.) reflects decreasing productivity triggered by lowering of water temperature and nutrient availability.

A period of hiatus. The depositional hiatus and erosion of sediments, which took place after approximately 5500 cal yr BP (Figure 3), could have been caused by a considerable decline in water level triggered by neotectonic or other processes. Water level drop occurred in some near-shore water bodies on the southern and eastern Baltic coast too (Lampe and Janke, 2014). The depositional hiatus in the Curonial Lagoon sequence lasted untill about 3300 cal yr BP. The rise of water that began afterwards is marked by the deposition of fine-silt gyttja and can be explained by the onset of the Post-Litorina Sea transgression, which occurred in the region during the period 3700–2400 cal yr BP (Lampe and Janke, 2014; Druzhinina et al., 2023). The similar patterns of water level fluctuations are also recorded in the Koz’ye Bog area, situated 60 km from the study site, on the northeastern coast of the Curonian Lagoon, where the time interval 3500–2700 cal yr BP is marked by the inundation of the territory and a widespread distribution of the alder carrs (Napreenko et al., 2021).

The ‘2800 event’. The advance of mountain glaciers in Europe and the lowering of the upper limit of forests in the mountains of Scandinavia and in the Khibiny marked the cooling of 3500–2500 cal yr BP, expressed as the 2800 BE (Borisova, 2014). In the studied section, this period corresponds to the change of bottom sediments, when silty gyttja accumulation begins (Figure 3, LPAZ 2a). On the palynological diagram, the change in the sediments is marked by the maximum value of *Alnus* (up to 50%) testifying the expansion of alder carrs, presumably due to the rise of water level and inundation of the area (Druzhinina et al., 2023). Further on, an increasing presence of conifers (*Pinus, Picea*) may indicate that the climate fluctuation around 2800 cal yr BP probably reflects a cooling along with increasing precipitation. *Picea*, a tree most competitive in moist conditions, reaches its peak throughout the sequence. During this period, arboreal taxa and QM declined significantly, in particular *Ulmus*, *Quercus*, *Tilia*. Simultaneously, the maximum of *Pinus* pollen is recorded throughout the studied sequence. The value of Ericaceae pollen grows pointing at more openness in woods. Discussing the latter, a certain contribution of the anthropogenic factor should be taken into account. On the palynological diagram, the period under consideration clearly correlates with the appearance and increasing percentage of cereal pollen grains, *Secale* and *Triticum*. The significant number of archaeological sites in the southeastern Baltic coastal area during this and subsequent historical periods (Suvorov, 1985) along with continuous curves of Cerealia enables us to consider this factor as one of the most important shaping the vegetation cover. In this regard, part of the pine forests could also have a secondary origin reflecting human-induced deforestation. On the palynological diagram, a peak of *Fagus* is remarkable. According to Tinner and Lotter (2006), short-term cold climate fluctuations played a positive role in pulses of *Fagus* expansion. In addition to climatic change, human impact is considered as another the most plausible reason of spreading of beech in Europe during the Holocene (Tinner and Lotter, 2006; Bradshaw et al., 2010). A sharp and short-lasting decline of *Alnus* at 2870 cal yr BP could be triggered by a change of local hydrological conditions discussed above. Probably, shortly after the '2800 cooling' the amelioration of climate took place, as QM recover on the pollen diagram, while *Pinus*, *Salix* and Ericaceae decline.

The '1400 event'. The cooling of 1400 cal yr BP is not as clearly traceable as previous cold spells, thought its traces are found globally (Borisova, 2014; Borzenkova et al., 2015). During this period, the Icelandic minimum and the Siberian maximum weakened and the atmospheric circulation in the northern hemisphere decreased correspondingly. The identification of '1400 climate event' in the sedimentary strata of the Curonian Lagoon is difficult. The chronological mark related to the event is based on the modelled age for the upper part of the sequence (gyttja, depths of 48–25 cm). According to the modelling, the '1400 event' corresponds to the shell interlayer at a depth of 39-38 cm (Figure 3). However, the deposition of the interlayer indicates that sedimentation conditions may have been very dynamic, with alternating rises and falls in the lagoon water level (Druzhinina et al., 2023). This, in turn, does not allow us to consider with certainty the continuity of sedimentation in this part of the studied section. On the pollen diagram, this period is marked, first of all, by small peaks of QM and *Pinus* prior to the 1400 event interval with simultaneous decrease of *Betula*, and a gradual decline of all broadleaf taxa (including *Carpinus*) after the event. A notable increase in plants – indicators of soil erosion and grazing (*Artemisia, Plantago lanceolata, Rumex*) – starts during this interval (Figure 3, LPAZ 2b-2c).

The Little Ice Age (LIA). Despite the global imprint of the LIA in the palaeogeographic data (Borisova, 2014) and effect on medieval society in most parts of Europe (Wanner and Bütikofer, 2008), the reflection of the cooling in the Curonian Lagoon record is not so obvious.

It resambles the ‘2800 event’ by a peak of *Pinus* and a negative fluctuation of *Betula* and *Alnus,* but unlike the latter, pollen curves are more gentle in this case. The most clear and remarkable sign of this climate fluctuation on the diagram is a short-term decrease of pollen of all indicators of agricultural activity (*Plantago lanceolata, Rumex, Secale, Triticum*) centered at 680 cal yr BP (Figure 3, LPAZ 3), thought they recover fast and continue with some fluctuations till the top of the sequence. In the 13-14th centuries, the population of the southeastern Baltic had to face the Teutonic Order's conquest of the area, which as well caused essential changes in the pattern of human activities (Suvorov, 1985). Thus, vegetation dynamics observed during the period under consideration was perhaps brought on by the combined effects of human and climate.

5. Conclusion

This study allows us to draw several conclusions about the relationship between local and regional vegetation cover and cold climate events.

Firstly, the study showed that palynological data do not reflect climate events evenly. Thus, climate changes that occurred approximately 5900 and 2800 cal yr BP are most clearly reflected in palynological record. At the same time, the events of 1400 cal yr BP and the Little Ice Age are weaker expressed in the pollen curves. The reasons for this may be both the magnitude of the climate fluctuations and the significance of other factors shaping vegetation cover. Another reason could be the resolution of the sequence study, which does not allow tracking short-term changes in natural parameters. Whereas, the ‘5900’ and ‘2800’ cold events are marked by significant reduction of Quercetum mixtum pollen and, in particular, oak and elm, the onset of the Little Ice Age is characterised by a short-term decrease of anthropogenic indicators.

The study also showed that besides climate, changes in local hydrological conditions and anthropogenic factor could have a significant impact on the vegetation cover of the study area. The influence of the anthropogenic factor has been increasing over the last 3000 years, making it difficult to fully disentangle natural and human-induced changes in ecosystems. Fluctuations in the water level of lagoon and groundwater have further complicated the picture of local vegetation evolution, causing considerable change of natural plant communities and having an indirect effect on vegetation through changes in local anthropogenic activities.

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Tables

Table 1. Geochronological results and lithological description of the Curonian Lagoon sediment sequence

Lithological unit	**Depth, cm**	**Sample ID**	**Age ^{14}C, BP**	**Calibrated age interval, cal yr BP 95.4 (2 sigma)**	**Median probability, cal yr BP**
Dark-olive gyttja	38 – 25	IGAN – 8583 (depth 35 cm)	765±20	670 - 723	686
Gyttja with shell interlayer	40 – 38	–	–	–	–
Dark-olive silty gyttja	48 – 40	IGAN – 8582 (depth 45cm)	2780±20	2789 - 2825 2844 - 2952	2875
Peaty gyttja with peat interlayers at a depth of 85 – 83 and 80 –78 cm	90 – 48	GV04053 (depth 49 cm)	4839±43	5473 – 5607 5623 – 5654	5556
		Poz – 110588 (depth 53 cm)	5340±40	5998 - 6210 6240 - 6272	6122
		GV04052 (depth 71 cm)	5821±44	6499 – 6523 6527 – 6735	6628
		IGAN – 6841 (depth 88 cm)	6015±20	6790 - 6936	6854

Table 2. Results of the palynological analysis of the Curonian Lagoon sediment sequence

Pollen zone	**Depth, cm**	**Description**
1. ***Quercetum mixtum***	88–48	Arboreal taxa prevail in the spectrum (pollen up to 95%). Quercetum mixtum (*Quercus, Ulmus, Tilia*) up to 20%, *Corylus* (up to 20%), *Alnus* (up to 35%). *Pinus* and *Betula* – up to 10% for each species. *Picea* – up to 1%. *Carpinus* – up to 1% (except subzone b). *Fagus* appears episodically (single pollen grain). Non-arboreal taxa: negligible abundance. Two short periods with a sharp rise in the share of coastal hygrophytes are distinguished: *Phragmites* (probably, *in situ*), *Thelypteris* (probably, *in situ*), Cyperceae, *Menyanthes*, *Typha*, Umbelliferae. **Subzone a: *Quercus*** (89–53 cm). Maximum value of *Quercus*: 12–18%. **Subzone b*: Carpinus – Ericaceae*** (53–48 cm). *Carpinus* (3-4%) and Ericaceae (5-6%) increase.
Hiatus		
2. ***Carpinus – Fagus – Picea***	48–35	Arboreal taxa prevail in the spectrum (pollen up to 90%). Increasing value of *Carpinus* (3-4%), *Fagus* (1-2%) and *Picea* (5-7%). Increasing value of *Pinus* and *Betula* – approximately 25% for each species. Significant decline in broad-leaved species: Quercetum mixtum (*Quercus, Ulmus, Tilia*) – 5-10%, *Corylus* (up to 5%). *Alnus* – average 30% (except subzone a). Non-arboreal taxa: share increases up to 10%. The most exposed are Ericaceae, Gramineae and Cerealia (*Secale* + *Triticum*). **Subzone a: *Alnus – Pinus*** (48–45 cm). Max value of *Alnus* (up to 50%), *Pinus* (up to 30%) and *Picea* (7%). Substantial share of Ericaceae (up to 4%). **Subzone b*: Quercus – Corylus*** (45–38 cm). Value of *Quercus* (up to 9%) and *Corylus* (up to 7%) grow. **Subzone c: *Salix – NAP*** (38–35 cm). Value of herbs increases (up to 12%), *Cakile* and *Salix* are remarkable (probably as coastal psammophytes).
		Arboreal taxa: total percentage of 82%. Value of *Pinus* and *Betula* grows and compiles together 50%.

3. ***Pinus* – *NAP***	35–26	Minimum of broad-leaved trees: Quercetum mixtum (less than 5%), *Corylus* (up to 2%), *Carpinus* (1-2%), *Fagus* (less than 1%). *Alnus* – 20%. *Picea* – 3-4%. Non-arboreal taxa: share increases up to 20%. Cereals are the most remarkable: Gramineae (up to 7-8%) and Cerealia (*Secale* + *Triticum*, 4-5%). Value of synanthropic plants increases up to 6% (Cichorioideae, Chenopodiaceae, *Centaurea cyanus*, *Artemisia*, *Plantago lanceolata*, *Rumex*).

Figures

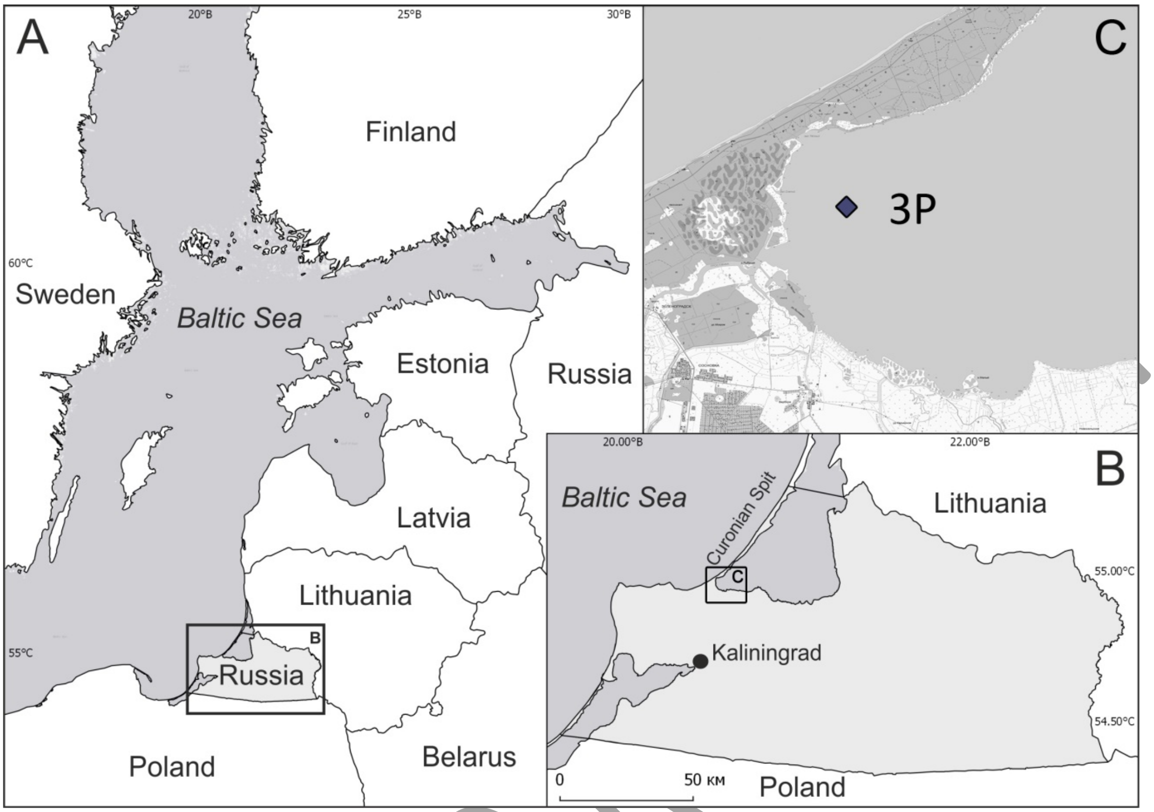
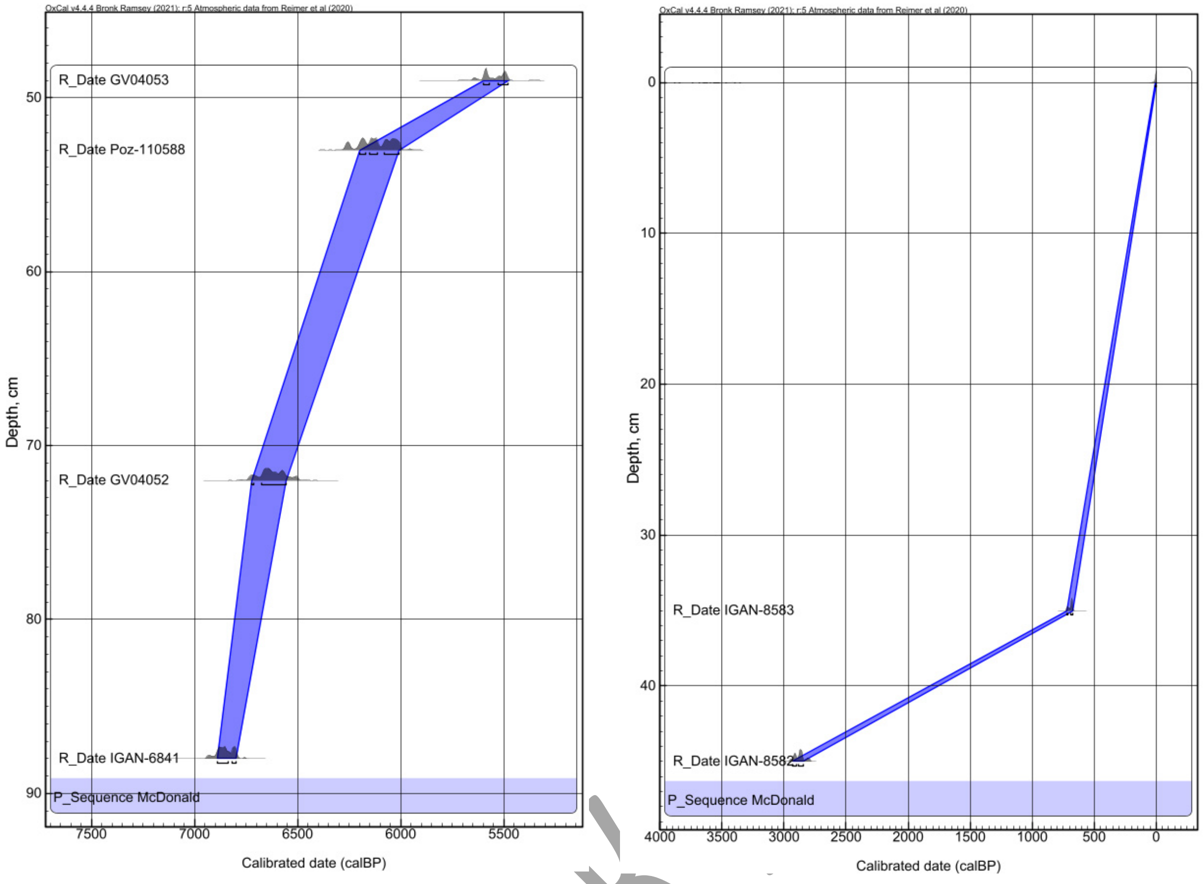


Fig. 1. Location of the study site: Kaliningrad Oblast (a), the Curonian Lagoon of the Baltic Sea (b), sampling point of the sediment core 3P (c) (Map source: https://www.geoguessr.com).



(a) **(b)**

Fig. 2. Age-depth models for the sediment core 3P in the Curonian Lagoon: lower part of peaty deposits, 90–48 cm (a), upper part of gyttja sediments, 48–25 cm (b).

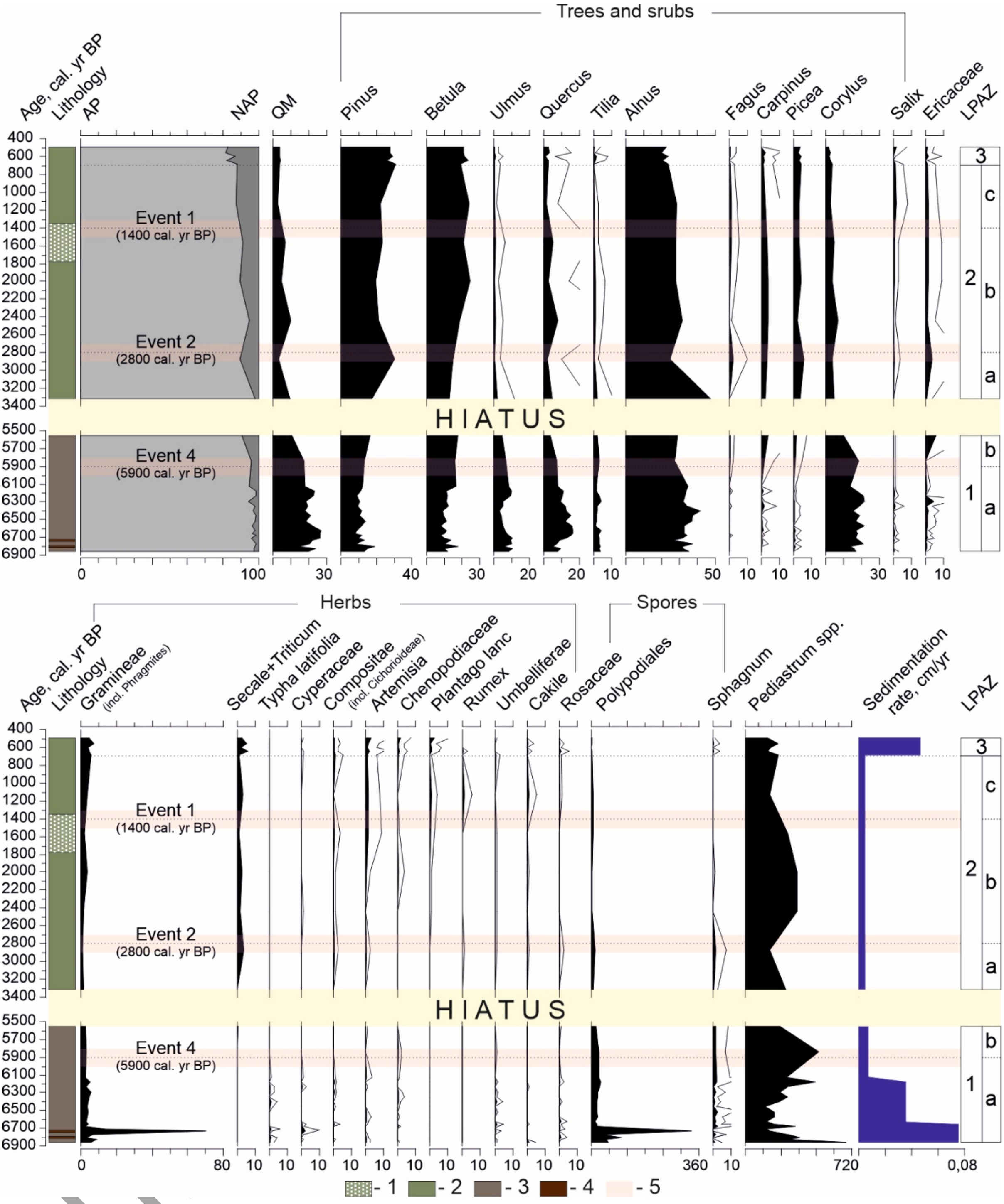


Fig. 3. Results of the pollen analysis for the Curonian Lagoon sediment core combined with the AMS-based modelled age scale and lithological description: 1—mollusk shell layer, 2—fine, silty gyttja, 3—peaty gyttja, 4—fen peat, 5—BE.

События Бонда в среднем и позднем голоцене и их отражение в динамике растительности юго-восточной Прибалтики: результаты палинологического исследования донных отложений Куршского залива[2]

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Аннотация

Представлены результаты исследования изменения растительности юго-восточной Прибалтики в ответ на климатические колебания (события Бонда) в среднем и позднем голоцене. На сегодняшний день реакция региональных и локальных природных систем на события Бонда остается плохо изученной. Представленные в статье новые данные литологического, геохронологического и палинологического анализов колонки донных отложений Куршского залива (Калининградская область) позволяют реконструировать региональные изменения растительности, рассматриваемые на фоне кратковременных колебаний климата. Установлено, что климатические события по-разному отражены в палинологической летописи. Причинами этого могут быть величина климатических колебаний; преобладающая значимость других факторов, формирующих растительный покров; а также разрешение исследования, не позволяющее в полной мере отслеживать краткосрочные изменения

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[2] Исследование выполнено при поддержке Российского научного фонда, проект 22-17-00170, https://rscf.en/project/22-17-00170.

природных параметров. Так, например, похолодания 5900 и 2800 кал.л.н. более четко фиксируются по изменению растительности, чем последующие. Они характеризуются, прежде всего, значительным сокращением пыльцы Quercetum mixtum (QM) и, в частности, дуба и вяза. Похолодание 2800 кал.л.н. сопровождалось также ростом кривой бука, распространению которого могли способствовать не только климатические условия, но и антропогенная деятельность. В то же время, начало малого ледникового периода (680 кал.л.н.) отмечено кратковременным снижением антропогенных показателей. Исследование также показало, что помимо климата существенное влияние на растительный покров исследуемой территории оказывали изменения локальных гидрологических условий и антропогенный фактор. Влияние человека на растительность в юго-восточной Прибалтике усиливалось на протяжении последних 3000 лет, что затрудняет разграничение естественных и антропогенных изменений в растительных сообществах позднего голоцена.

Ключевые слова: события Бонда, колебания климата, растительность, юго-восточная Прибалтика.