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Water Level Fluctuations in the Middle and Late Holocene in the Curonian Lagoon, Southeastern Baltic: Results of the Macrofossil and Phytolith Analyses

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Abstract: This paper presents the results of a study on fluctuations in the water level of the Curonian Lagoon (in the Baltic Sea). To date, the genesis of this inland bay as part of the complex postglacial development of the southeastern Baltic is poorly understood. The data from lithological, geochronological, and phytolith analyses, as well as assessments of plant and animal macroremains from the lagoonal sediments, provide a reconstruction of local coastal biocenoses and water level dynamics in the Middle and Late Holocene time. This study reveals the fairly dynamic evolution of the coastal zone of the Curonian Lagoon over the past 7000 years, as indicated by the traced succession of plant communities from forest to near-shore, open-water biocenoses and the alternations of the drying out and inundation of the area under consideration. Thus far, a connection with two stages of the Baltic Sea water level fluctuations has been traced: the regressional stage, which took place approximately 5600 cal years BP, and the Late Subatlantic transgression, which started at approximately 1100 cal BP. This study demonstrates that phytolith (microbiomorphic) analysis is a promising method for the study of temperate-latitude lagoonal sediments, providing information not only on the local plant communities, but also on the changes in the hydrological regime of the area.

Keywords: water level fluctuations; Curonian Lagoon; southeastern Baltic; coasts; macroremains; phytoliths; Holocene

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1. Introduction

The Baltic Sea has been the subject of intensive scientific studies because of its location in the center of Europe and the important role it plays in economic and socio-cultural life. The complexity of the genesis of the Baltic Ice Lake and the subsequent Holocene development of the Baltic Sea, accompanied by periodic fluctuations in its level, is caused by the versatility of natural processes associated with the degradation of the ice sheet, eustatic fluctuations, and the glacio-isostatic leveling of the Earth's crust. The particular complexity of these processes, manifested in their multi-scale and multi-vector nature, is characteristic of the southeastern Baltic, which has undergone numerous transformations in response to isostatic uplifts, water discharge, and climatic changes [1–3]. Ancient coastal formations and their constituent deposits are key sources of information about the post-glacial development of this area [3]. However, the relative complexity of studying ancient coastal formations—some of which are currently below sea level, and some which were probably destroyed in the process of geo-morphological development of the area in the Early and Middle Holocene—leads to the existence of significant differences in ideas about the fluctuations in the level of the southeastern part of the Baltic Sea at the end of the Pleistocene and in the Holocene. In this regard, studies of coastal paleo-reservoirs, the genesis and development of which reflect the natural dynamics of the coastal part of the sea, are of particular relevance. In the southeastern Baltic, one of these water bodies is the Curonian Lagoon.

The Curonian Lagoon, an inland Baltic Sea bay, has also been the subject of numerous studies related to its biota, water regime and quality, geology of bottom sediments, and modern geography [1,4–8]. However, the Holocene evolution of the lagoon is poorly understood, and the paleogeographic description of its coastal and submarine landscapes is incomplete. General problems in the genesis of the Baltic Sea, and the Curonian Lagoon as part of it, have been studied previously [1] and in relation to the formation of the Curonian Spit [9], the Neman River delta, or the very northern part of lagoon [10]. However, the lack of detailed, targeted research has impeded the study of the emergence and evolution of the Curonian Lagoon itself. At present, there is no clear understanding of when and within what boundaries a paleo-reservoir arose at the site of the modern Curonian Lagoon, nor of what the stages of its development were. Several 2018–2020 studies, in which samples of bottom sediments were taken, were the first attempts to better understand the formation and Holocene evolution of the southern area, the largest part of Curonian Lagoon. Special attention was given to water level fluctuations of the paleo-reservoir to begin establishing their relationship with the Baltic Sea water level dynamics. The results obtained at one stage of our research, studying the evolution of Holocene coastal biocenoses in the Curonian Lagoon, are reported. Bottom sediments from the Curonian Lagoon were analyzed lithologically and geochronologically; analyses of macroremains and phytoliths were also performed. The two latter results provide a much better understanding of the local biocenoses and processes proceeding them than, for example, palynological analysis provides specific regional palaeobotanical information. Although analyses of botanical and animal macroremains have long been used in similar studies, the analysis of phytoliths in bottom sediments is just beginning to gain a place in lake and lagoon sediment research methodology [11]. Most successful studies have involved the phytolith research of lake sediments in tropical and equatorial regions [12–16]; however, studies of temperate-latitude sediments are still lacking. Therefore, one of the objectives of our study was to test the informative values and applicability of the method in regard to lagoonal sediments of the temperate zones of the northern hemisphere. In addition to phytoliths, other silica and organic microbiomorphs, such as diatoms, sponge spicules, detritus, and fungi observed on the slides under a microscope, were recorded. This approach has already been successfully applied in several previous studies, providing a broader spectrum of paleoenvironmental information [17–20].

2. Materials and Methods

2.1. Sampling and Regional Setting

The Curonian Lagoon is a shallow Baltic Sea bay. It is separated from the sea by the Curonian sand spit and is connected with the sea by a narrow strait. The lagoon is 93 km long, 17.3 km wide (average), and up to 7 m deep. The maximum depth in the sampling area was up to 4 m. The largest river flowing into the lagoon is the Neman. The lagoon is a freshwater body which freezes in winter. Modern bottom sediments in the sampling area comprise clay, sand, and silt, resting on moraines.

A core sample of bottom sediments taken in the southwestern Curonian Lagoon provided material for the paleogeographic studies (Figure 1).

The core was taken with a gravity tube at point 3P (54°57′55.6″ N, 20°32′50.00″ E). The core was 90 cm long. The gyttja strata of upper horizons (0–25 cm) were not sampled because the sediment was highly liquified.

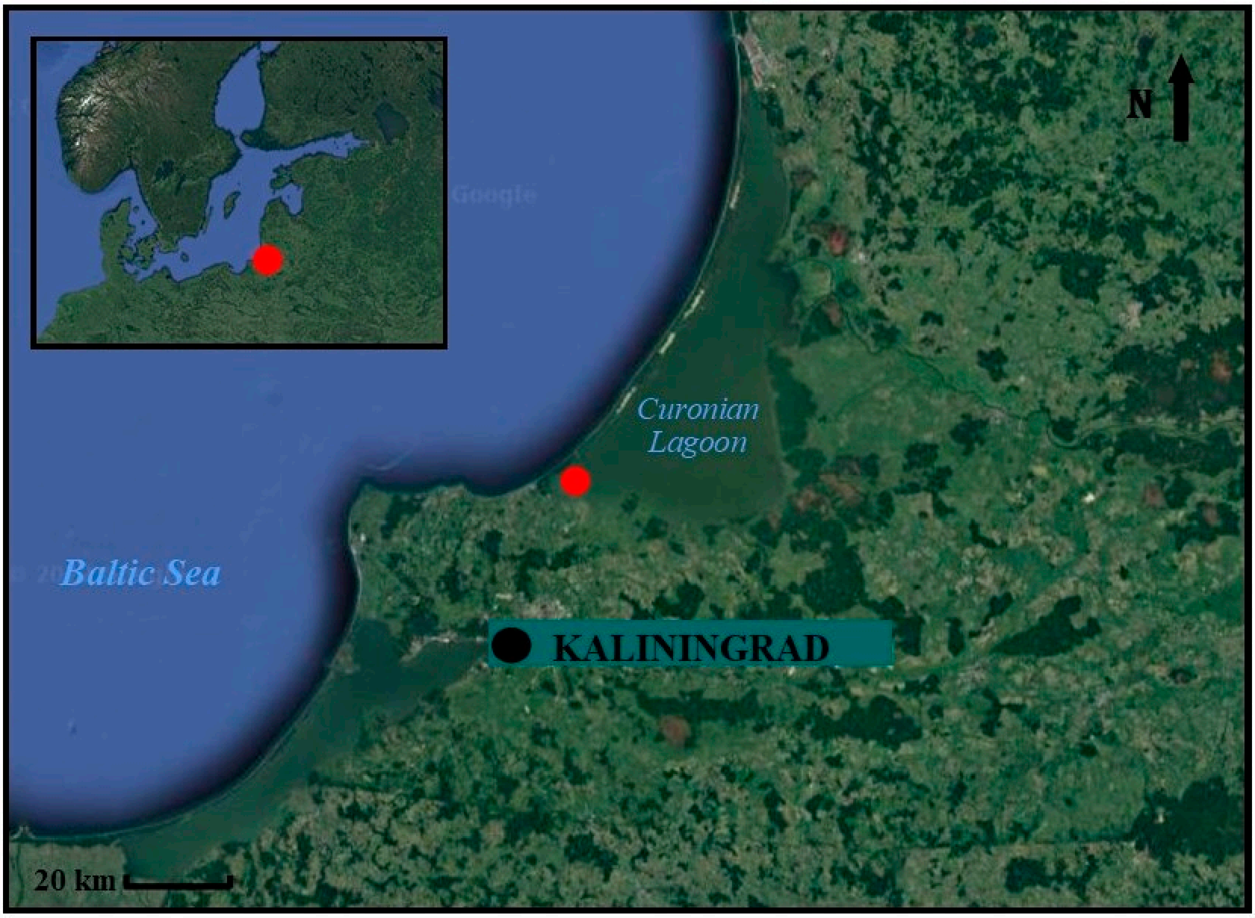

Figure 1. Location of the studied site.

2.2. Radiocarbon Dating and Lithology

Three samples of bottom sediments were subjected to radiocarbon dating using an accelerating mass spectrometry (AMS) method in the CCP Laboratory of Radiocarbon Dating and Electron Microscopy at the Institute of Geography, RAS, together with the Center for Isotopic Studies, University of Georgia, USA. One sample was dated at the Poznan Laboratory of Radiocarbon Studies, Poznan, Poland.

Lithological descriptions were based on visual and physical studies of the composition and color of bottom sediments.

2.3. Macrofossil Analysis

Analysis included a study of the degree of peat decomposition and the botanical structure of the plant remains. Peat decomposition was assessed using both microscopic and elutriation techniques [21]. In order to determine a peat type and a peat-forming plant community, botanical analysis of plant macrofossils in the peat was performed microscopically for each sample. Remains such as rootlets, fragments of rhizomes, leaves, stems, bark, epidermis, and pieces of wood were identified to species level using various identification keys [22–26]. Animal fossil records, such as cladoceran valves and ephippia eggs, ostracod and mollusk shells, fish scales, bryozoan statoblasts, etc., were also involved in consideration and calculation as associated fossils. These groups were not the subject of detailed taxonomic identification as they require a special processing technique and identification routine. Local macrofossil zones were visually identified with regard to the composition and dominance of various plant remains. A diagram of plant successions was plotted using C2 software [27]. In total, 31 samples were analyzed.

2.4. Phytoliths and Other Microbiomorphs

Approximately 5 g of matter was taken from bulk samples for analysis. The samples were prepared according to the standard protocols for phytolith analysis described elsewhere [16,28]. They were treated with hot 30% H_2O_2 solution, separated from sand and clay by sieve and gravity sedimentation techniques based on Stokes's law, and subjected to flotation in heavy liquid (cadmium iodide and potassium iodide with a specific gravity of about 2.3 g/cm^3). After 10 min centrifugation, a supernatant was placed into a tube, washed with distilled water several times, immersed in oils (silica oil or glycerine), and studied under the optical and scanning electron microscope at magnifications varying from 200 to 900 times. The quantitative content of organic and silica microbiomorphs was estimated by counting all the morphotypes found per slide. Phytolith identifications were based on standard determination, as described elsewhere [29]. The phytoliths were also divided into several biocenotic groups according to Golyeva's ecological interpretation [17,18]. In total, 15 samples were analyzed.

3. Results

The results obtained are presented in the subsequent subsections.

3.1. Radiocarbon Dating and Lithology

The lithological and geochronological description is presented in Table 1.

Table 1. Lithological and geochronological description.

Lithological Unit	Depth, cm	Sample ID	Date, cal yr BP
Peaty gyttja with peat interlayers at a depth of 85–83 and 80–78 cm	90–50	IGAN—6841 (depth 88 cm) Poz—110,588 (depth 53 cm)	6865 6044
Dark-olive silty gyttja	50–40	IGAN—8582 (depth 45 cm)	2867
Gyttja with shell interlayer	40–38	–	–
Dark-olive gyttja	38–25	IGAN—8583 (depth 35 cm)	681

3.2. Macrofossil Analysis

Eighty-five types of plant and animal macroremains of thirty-nine taxonomic groups were identified. Analysis of plant macrofossils revealed the following five zones in the sediment sequence (Figure 2).

LMAZ 1, *Alnus–Phragmites–Hypnales* (90–77 cm). There was a strong dominance of plant remains (averaging 95%). Woody plants: a high percentage of wood remains (averaging 30–35%), presumably Alnus. Herbs: *Phragmites* prevailed (40–60%); *Carex* accounted for up to 10%; the percentage of *Thelypteris* increased to 5%; *Nuphar* was present (up to 1%). Moss-like plants: Sphagna, presumably meso-eutrophic species (2–4%); the percentage of Hypnales increased to 8%, including *Brachythecium* (up to 5%). Animals: Cladocera (1–2%); chitin cover of insect and crustacean Arthropoda (1–3%), statoblasts of Bryozoa (1–3%), and Turbellaria (0.1–1%). Complete absence of coquina, almost no sand.

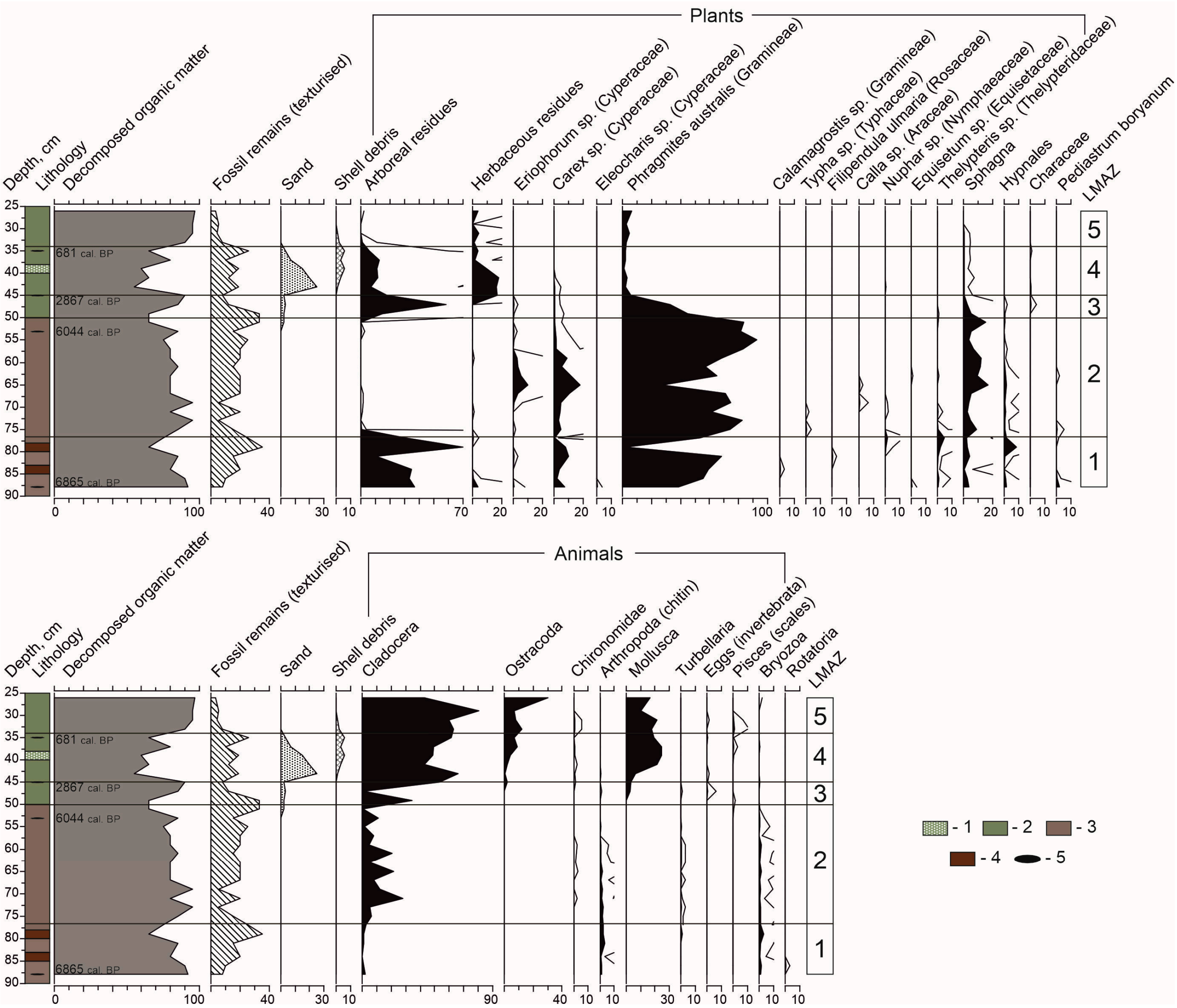

Figure 2. Results of analysis of the macroremains of bottom sediments from the Curonian Lagoon and lithological description of the column (1—mollusk shell clusters, 2—fine, silty gyttja, 3—peaty gyttja, 4—fen peat, 5—location of ^{14}C dated samples).

LMAZ 2, *Phragmites–Carex–Sphagna* (77–50 cm). Strong dominance of plant remains, averaging 88%. Woody species: practically absent (0–0.1%). Herbs: *Phragmites* prevailed (60–80%); *Carex* comprised 4–10% to 18%, and *Eriophorum* accounted for 3–10%; *Thelypteris*, *Calla*, and *Nuphar* occurred sporadically (less than 1%). Moss-like species: the percentage of meso-eutrophic species of *Sphagna* grew (3–17%); the percentage of *Hypnales* decreased to 1%. Animals: the percentage of Cladocera increased to 5–20%; the chitin coat of insect and crustacean Arthropoda increased to 2%, as did the statoblasts of Bryozoa (up to 1.5%) and Turbellaria (0.1–0.3%). Chironomidae occurred (0.1–0.2%). Complete absence of sand and coquina.

LMAZ 3, *Alnus–Cladocera* (50–45 cm). Plant remains prevailed, averaging 65%, but the percentage of animal remains increased by several orders of magnitude. Woody species: the maximum percentage of wood remaining, presumably *Alnus*, was up to 60%. Herbs: abrupt decrease in the percentage of *Phragmites* (to 5%); *Carex* and *Eriophorum* (less than 1%). Moss-like species: the percentage of *Sphagna* decreased to 5%, and that of *Hypnales* decreased to less than 1%. The occurrence of Characeae oospores was less than 1%. Animals: considerable increase in the percentage of Cladocera (up to 50%); the occurrence of Ostracoda, mollusks, and fish. Remains of the chitin cover of insects and

Bryozoa statoblasts almost disappeared. Chironomidae and Turbellaria were scarce. Sand made up 2–3%; coquina also occurred (up to 1.5%).

LMAZ 4, *Cladocera–Mollusca* (45–34 cm). Clear predominance of animal remains: 78%. Woody species: wood remains, presumably *Alnus*, contributed 6–12%. Herbs: minimum percentage of *Phragmites* (up to 3%) and *Carex* and a disappearance of *Eriophorum*. The percentage of other herbs (presumably coastal, aquatic motley grass) was up to 18%. Moss-like species: minimum abundance of *Sphagna* (less than 1%) and a complete absence of *Hypnales.* The presence of Characeae oospores was less than 1%. Animals: increase in the percentage of Cladocera up to 50–65%; mollusks up to 25% and Ostracoda up to 9%. Chironomidae and fish remains were present (less than 1%). Sand comprised 25%; increase in the percentage of coquina (up to 6%).

LMAZ 5, *Cladocera–Ostracoda* (34–25 cm). Clear predominance of animal remains: 93%. Woody species: the percentage of wood remains decreased abruptly to 1%. Herbs: *Phragmites* made up 3–6%. The total percentage of coastal, aquatic motley grass was up to 4%. A complete absence of other groups of vascular species. Moss-like species: disappearance of Sphagna; a complete absence of Hypnales and Characeae. Animals: the maximum percentage of Cladocera was 60–80%, and that of Ostracoda was up to 9%. The percentage of mollusks decreased to 10–20%. The percentage of fish remaining was approximately 1%. Chironomidae were present (less than 1%). No sand. The percentage of coquina decreased abruptly to 1%.

3.3. Phytoliths and Other Microbiomorphs

All samples contained various types of organic and siliceous microbiomorphs (Figure 3).

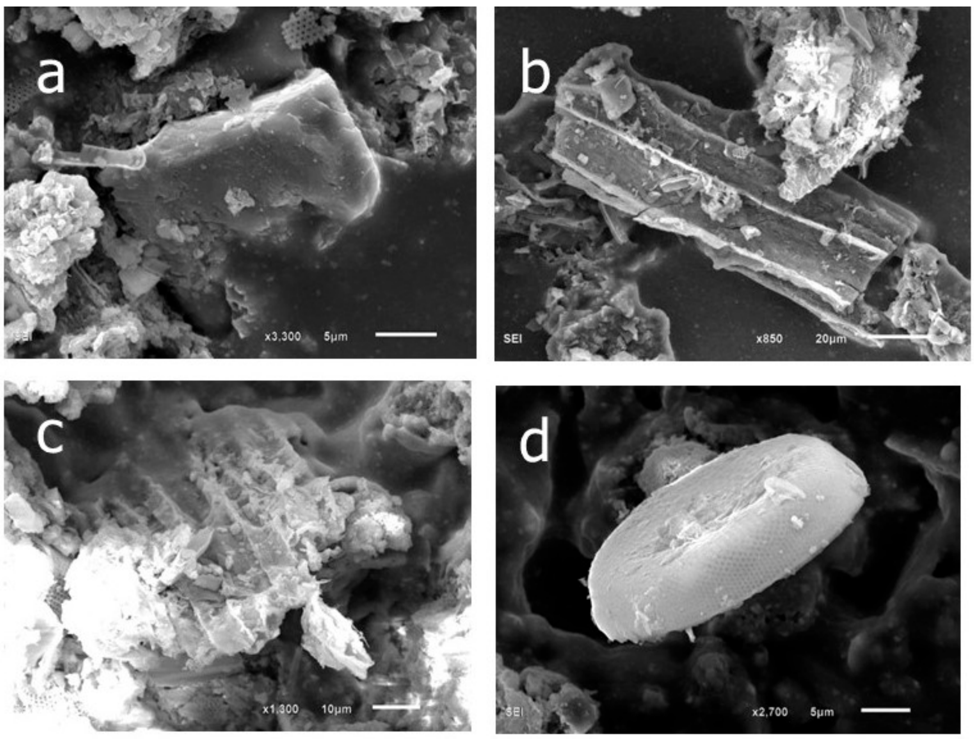

Figure 3. Organic and silica microbiomorphs revealed in the lagoonal sediments: (**a**) phytolith of coniferous trees (BLO_REC); (**b**) cuticular cast of plant cells; (**c**) planty detritus; (**d**) diatom.

The following categories of microbiomorphs were identified: (1) phytoliths (BLO_REC—coniferous trees; BIL, ELO_SIN, POL—meadow grasses; and SPH_PSI—mosses); (2) plant detritus (herbaceous and woody); (3) cuticular casts of plant cells; (4) hyphae of soil fungi; (5) coprolites of soil fauna; (6) shells of diatom algae; (7) sponge spicules; (8) amorphous organic matter; (9) and other microbiomorphs. A comparative analysis of the microbiomorph content of the samples is provided in Table 2:

Table 2. The main categories of organic and silica microbiomorphs (in units) *.

No.	Depths, cm	Phytoliths	Plant Detritus	Cuticular Casts of Plant Cells	Hyphae of Soil Fungi	Coprolites of Soil Fauna	Diatoms	Sponge Spicules	Amorphous Organic Matter	Other Bio-Morphs
1	89–87	Single	+++	–	++	++	+	Single	+	Roots, pollen
2	87–85	–	+	–	–	–	+++	–	+++	
3	85–83	+	+++	+++	–	–	–	–	+	
4	83–80	++	+++	–	–	–	+	–	Single	
5	76–74	–	+	–	–	–	Single	–	Single	
6	70–68	–	–	+++	–	–	+++	+	Single	
7	64–62	Single	++	–	–	–	–	–	Single	
8	58–56	Single	++	–	–	–	–	–	–	
9	52–50	–	+++	–	–	–	–	Single	–	
10	46–44	–	++	–	+	++	–	–	Single	Roots, pollen
11	42–40	Single	+	–	+	+	++	Single	++	Roots, pollen
12	40–38	+	++	–	++	++	Single	–	–	
13	38–36	Single	+	–	–	–	++	Single	+++	
14	34–32	–	+++	++	–	–	Single	–	Single	
15	28–25	+	+++	++	–	–	++	Single	–	

* Crosses indicate comparative microbiomorph content in units: +++ abundant (>100); ++ medium (50–100); + small (5–50); Single (<5); – absent.

4. Discussion

Our studies and the correlation of the results obtained suggest that the evolution of the coastal lagoonal biocenoses consisted of the following stages depending on the water level fluctuations.

Periodically flooded coastal forest with alder and conifers (depth 90–78 cm). A geochronological marker, AMS date of 6865 cal years BP, was obtained for the beginning of this stage in the evolution of the coastal biocenoses. At this stage, the study area seemed to have been evolving under subaerial conditions affected by periodic fluctuations in the ground water level, as indicated by the deposition of fen peat at a depth of 85–83 and 80–78 cm. The existence of coastal forest in the area, about 6800 cal years BP, was indicated by the results of phytolith and microbiomorphic analysis characteristic of wet forest litters, such as an abundance of coarse detritus containing coniferous wood, and an abundance of soil fungus hyphae indicative of soil formation, plant root remains, and pollen grains. The above evidence is also supported by the analysis of macroremains showing an abundance of arboreal taxa: 35–40% at a depth of 90–82 cm and an abrupt increase of up to 70% at a depth of 80 cm coinciding with a minimum level of *Phragmites*. The sharp decrease in arboreal taxa at a depth of 82 cm seems to be related to a rise in water level also indicated by the peak of *Phragmites*. The plant composition of the coastal forest is shown by the results of phytolith analysis and the botanical macroremains found; coniferous and dicotyledonous grass phytoliths were identified; macroremains (presumably *Alnus*) occurred. As the area was inundated, the sites occupied by *Phragmites*, *Carex*, etc., expanded. The periodical flooding of the area is indicated by the short time peaks of Rotatoria and Bryozoa (87–85 cm) coinciding with the presence of diatoms and sponge spicules in microbiomorphic samples at depths of 87–85 and 83–80 cm.

Coastal reed thicket (depth 78–50 cm). The available radiocarbon date, 6044 cal years BP, marks the end of the stage. This stage was characterized by the growth and fluctuation of Cladocera (up to 20%), the permanent presence of Turbellaria (0.1–0.3%), minimal spreading of arboreal taxa (0.1%), and maximum levels of *Phragmites* (60–80%), as indicated by considerable flooding and possibly the predominance of completely subaquatic conditions in the study area as the coastal strip of a shallow water body. This seems to have provoked the disappearance of a woody story invaded by reed thicket. The increased percentage of Cladocera indicates that flooding seems to have triggered the periodic but relatively lengthy water stagnation and the formation of water bodies over 1 m in depth. However, an abundance of fen types (*Carex*, *Eriophorum*, *Thelypteris*, *Calla*, and *Sphagna*), which do not withstand considerable inundation, may indicate a mosaic vegetation pattern on the shore in that period. It seems that fen communities evolved after the retreat of water, invading small, near-shore water bodies.

Coastal alder forest with reed thicket sites (depth 50–44 cm). Our studies show that, at a depth of 50 cm, types of deposits succeed each other (peat sapropel is succeeded by fine-silt mud), as well as showing a substantial gap in dates in this depth range; the value obtained for a depth of 45 cm showed the age 2867 cal years BP (Table 1). All this seems to indicate a hiatus in deposition between this and the preceding stage in the evolution of the study area. The depositional hiatus, which took place after approximately 6000 cal years BP, could have been provoked by a considerable decline in water level in the bay triggered, in turn, by neotectonic processes or fluctuations in Baltic Sea water level, which caused the drying out and/or erosion of deposits formed at the previous stage. Interestingly, a decline in water level in near-shore water bodies on the southern Baltic Sea coast took place, for example, about 5600 cal years BP [30].

Part of the study area dried out at this stage, as indicated by phytolith and microbiomorphic analysis at a depth of 46–44 cm: woody detritus, plant pollen and spores, grass roots, and soil fauna coprolites indicative of soil formation were found. This evidence is in good agreement with the results of the analyses of macroremains indicating the evolution of arborescent vegetation with a new maximum of up to 58% accompanied by an abrupt decrease in the percentage of Cladocera (3–4%) and the disappearance of Bryozoa in animals and a gradual decrease in the percentage of key bog species in *Phragmites*, *Carex*, and *Sphagna*.

Periodically inundated coastal herb communities with patches of arborescent vegetation (depth 44–36 cm). At the beginning of this stage, arboreal taxa decreased abruptly to a minimum of 6% with a simultaneous peak of Cladocera up to 66%, which may indicate a considerable rise in water level. These processes seem to have been followed by water regime instability, as well as the periodic flooding and drying out of the area. Subaerial conditions are indicated by soil formation at a depth of 42–38 cm, the permanent presence of arboreal taxa (up to 11%), and a slight reduction in Cladocera (to 40%). The percentage of reed communities decreased abruptly, whereas herb communities continued to spread. However, the results of the microbiomorphic analysis show an abundance of intact diatom armors and an abundant amount of amorphous organic matter, which could have been due to periodic flooding of the area. The increasing amounts of Ostracoda and Mollusca also indicate the existence of a shallow freshwater body. The increasing water level towards the end of this phase can be related to the Late Subatlantic transgression, which started at about 1100 cal BP [30].

An open water body far from the shoreline (depth 36–25 cm). This stage demonstrated another change in the evolution regime of the study area probably related to the continuing rise of the water level. This stage began about 681 cal years BP. Since then, signs of woody communities have disappeared, and the percentages of herb communities have decreased. The disappearance of the bulk of plant remains and an abrupt increase in the amount of the remains of key groups of aquatic organisms, including fish (Pisces), indicate the increasing depth of the water body and the distant shoreline.

Thus, our study has shown that phytolith and microbiomorphic analysis is a promising method for the study of temperate-latitude lagoonal sediments, especially in combination with other conventional analytical methods, e.g., the analysis of macroremains. This study has shown that several sediment horizons contained microbiomorph indicators, such as hyphae of soil fungi and soil fauna coprolites, of initial soil formation processes. This fact seems to indicate that, during certain time periods, the water level of the Curonian Lagoon was lower than the present level. When parts of the lagoon bottom were above the water level, soil formation processes could have started on the dried surface and then been followed by the spreading of coastal forest and herbaceous communities.

Taking into account the wide range of macrofossils revealed during the study, we envisage the further stages of our investigation to be followed by a separate detailed analysis of other groups of macrofossils: Cladocera, Ostracoda, Chironomidae, and Pisces (fish), as well as diatom analyses [31–33]. Each group is a significant natural proxy that can provide relevant paleoenvironmental information indicating various ecosystem parameters, substrate preferences, salinity, annual temperature, food sources, relative depth, eutrophication status, etc. Being correlated with the data obtained for the other macro- or microfossils, these studies have great potential.

Our study has also shown the fairly dynamic evolution of the coastal southeastern Baltic Sea over the past 7000 years, which is clearly indicated by the succession of plant communities and the alternation of drying out and flooding periods in the Curonian Lagoon. The revealed succession of stages could be due to climatic fluctuations, neotectonic processes, and eustatic fluctuations in the Baltic Sea water level. Active contributions of the above processes have been indicated by numerous studies [2,3,30]. The results of our study can provide a starting point in the detailed studies of fluctuations in the water level of the Curonian Lagoon in the Middle and Late Holocene and the processes which initiated these fluctuations. Further work can be performed to re-predict current and further fluctuations in the global ocean levels.

5. Conclusions

The data from lithological, geochronological, phytolith, and macrofossil analyses of the lagoonal sediments revealed at least five stages in the development of the Curonian Lagoon coastal biocenoses over the past 7000 years depending on the water level fluctuation: periodically flooded coastal forest with alder and conifers; coastal reed thicket; coastal alder forest with reed thicket sites; periodically inundated coastal herb communities with patches of arborescent vegetation; and an open water body far from the shoreline. Thus far, the connection with two stages of the Baltic Sea water level fluctuations can be traced: the regressional stage that took place at around 5600 cal years BP and the Late Subatlantic transgression, which started at about 1100 cal BP.

This study has also shown that phytolith and microbiomorphic analysis is a promising method for studies of temperate-latitude lagoonal sediments, especially in combination with other methods, e.g., analysis of macrofossils. Silica (phytoliths, shells of diatoms, and sponge spicules) and organic (herbaceous and woody detritus, hyphae of soil fungi, coprolites of soil fauna, etc.) microbiomorphs found in the samples provide information not only on the local plant communities, but also on changes in the hydrological regime of the area. This includes phytolith and microbiomorphic analysis in the palette of methods for studying the fluctuations in the water level of reservoirs and adjacent areas.

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