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Seasonal variability of phytoplankton in the river Słupia of the southern Baltic Sea

Sezonowa zmienność fitoplanktonu w ujściu rzeki Słupia w rejonie południowego Bałtyku

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Abstract: In the Baltic Sea, there can be observed seasonal variations in the structure of phytoplankton. These organisms are particularly sensitive to changes in different environmental parameters. The consequence of these changes is cyclical fluctuation of the species composition, their abundance and biomass of phytoplankton repeated every year. The spatial and temporal variability of individual phytoplankton groups is not the same in different regions of the Baltic Sea, and this is why the study was conducted in the area of the central Baltic coast, since in that particular region data on phytoplankton is not available. One of the main goals was to determine the temporal and spatial structure of the occurrence of phytoplankton, as well as to study biodiversity in the area of the Slupia river estuary in southern Baltic for the period between November 2014 and September 2016. The results of research confirm changes typical of phytoplankton in the three studied areas depending on the given season. The average values of phytoplankton abundance and biomass were typical for this kind of coastal waters and there were no significant species differences between these stations. The only research (and available studies) on phytoplankton in the central sea basin areas is currently conducted by the Institute of Meteorology and Water Management (IMWM) as part of the HELCOM Baltic Sea Monitoring at station P16, which is the closest location to the studied area. When comparing the results obtained in this study to data from the IMWM annual reports for the last decade, it can be noticed that the size and fluctuations of total biomass and phytoplankton abundance in the three studied areas are typical for the coastal region of the South Baltic.

Keywords: phytoplankton, seasonal variability, southern Baltic Sea, Ustka area

Streszczenie: W Morzu Bałtyckim obserwuje się sezonowe zmiany struktury fitoplanktonu. Organizmy te są szczególnie wrażliwe na zmiany różnych parametrów środowiska. Konsekwencją tych zmian jest cykliczna, powtarzająca się co roku, fluktuacja składu gatunkowego, liczebności oraz biomasy fitoplanktonu. Przestrzenna i czasowa zmienność poszczególnych grup fitoplanktonu nie jest taka sama w różnych rejonach Bałtyku, dlatego badania wykonano w obszarze środkowego wybrzeża południowego Bałtyku gdyż, w tamtym rejonie nie ma dostępnych danych dotyczących fitoplanktonu. Jednym z głównych celów było zbadanie struktury czasowo-przestrzennej występowania fitoplanktonu, a także określenie różnorodności biologicznej w ujściu rzeki Słupia w rejonie południowego Bałtyku w latach listopad 2014 – wrzesień 2016. Wyniki uzyskane w ramach prowadzonych badań potwierdzają typowe zmiany fitoplanktonu w trzech rejonach w zależności od pory roku. Średnie wartości liczebności i biomasy fitoplanktonu były typowe dla tego rodzaju wód przybrzeżnych i nie odnotowano znaczących różnic gatunkowych pomiędzy tymi stacjami. Jedyne badania (oraz dostępne opracowania) fitoplanktonu w tych strefach płytkowodnych środkowego wybrzeża prowadzone są przez IMGW w ramach Monitoringu Bałtyku HELCOM na stacji P16, które są położenie najbliżej badanego rejonu. Porównując otrzymane w tym opracowaniu wyniki do danych z rocznych raportów IMGW dla ostatniego dziesięciolecia, można zauważyć, że wielkości i fluktuacje całkowitej biomasy i liczebności fitoplanktonu w trzech badanych rejonach są typowe dla rejonu wód przybrzeżnych Południowego Bałtyku.

Słowa kluczowe: fitoplankton, zmienność sezonowa, południowy Bałtyk, Ustka,

INTRODUCTION

Phytoplankton are single-celled, autotrophic organisms that constitute the primary producer in marine ecosystems and are an important component in the trophic network. Periods of occurrence of particular phytoplankton groups depend strongly on environmental conditions in a given water area, such as: light, temperature, salinity, pH, carbon dioxide or availability of nutrients [15], [16], [52]. Phytoplankton is the main exponent of the trophic status of waters, as it reacts to any changes in the concentration of biogenic compounds. The consequence of these changes is the cyclical fluctuation of species composition, abundance and biomass of phytoplankton repeated every year [50].

In water basins of temperate climate, usually two distinct maxima in abundance and biomass can be observed - spring and autumn. In the spring, when there is more sunlight, which warms up the water and there are enough biogenic substances in it, the bloom of diatoms begins (Bacillariophyceae), and immediately after that (late spring) dinoflagellates bloom. After that, the water temperature is higher, but it already contains much less nutrients than in early spring [43].

After the spring blooms, the concentration of nutrients in water decreases (especially nitrogen and phosphorus), which limits the occurrence of these organisms. If the phosphates were not fully used and the water reaches high temperatures, cyanobacteria start to develop. In recent years, this group of phytoplankton [15], [50], [52] has been gaining more and more in abundance and biomass. Cryptophytes and Chlorophyta are less significant groups in the Baltic Sea both in terms of abundance and biomass. Winter inhibition of primary production (too little light and low temperature) enables full restoration of nutrients in the euphotic zone [2], [17], [18], [42], [49].

The list of phytoplankton species in the Baltic Sea contains over 2,600 items [30], [42] of which about 100 species exist in Polish waters [29]. The mechanisms of seasonal changes in the structure of phytoplankton in the Baltic waters are quite well understood [22], [51]. However, the spatial and temporal variability of individual phytoplankton groups is not the same in different regions of the Baltic Sea [45], [52] therefore the study was carried out in the area of the central coast of the southern Baltic, because in that area there is no data available on phytoplankton. Thus, the main objective of the work was to determine the temporal and spatial structure of the occurrence of phytoplankton and to study the biodiversity of the river Slupia estuary in the southern Baltic Sea region.

So far, the Ustka area in the context of phytoplankton has not been covered by comprehensive environmental research. In addition, the only research (and available studies) of phytoplankton in these shallow-water areas of the central coast is conducted by IMWM as part of the HELCOM Baltic Sea Monitoring at station P16, which is the location closest to the studied area (Figure 1) [21], [23-28], [31-33] [59-60].

STUDY AREA

The research region is the coastal zone in the vicinity of Ustka. Locally, this section of the coast is called the Ustka Bay, which covers 34 km of the shore (extends between the 218th and 252nd km of the sea shore) [40]. The bay begins in the west in close proximity to Wicko Morskie (approximately 1 km to the east of Jaroslawiec), its eastern end is a peninsula near the village of Rowy. In the central part of the Bay, there is situated maritime port of Ustka, as well as the estuary of the Slupia River. The Slupia River is a coastal river, constituting on land the axis of the Landscape Park. The river's entire drainage basin lies in the area of the Pomeranian Voivodship, and the estuary in the north-western part serves as inner waters of the port of Ustka. The coastal section of the Bay is diverse, mostly abrasive. The coast located to the east of the Slupia estuary is a dune section, very abrasive and subject to the influence of the existing hydraulic structures continuing with a cliff section further to the east,. The area in the west of Ustka has clearly visible dune embankments, whose width increases as it approaches the port channel. The depth within the Bay reaches up to 20 m. In terms of development and land use, the coastal area of the Bay plays a recreational and leisure function [3], [40], [44]. In the period of November 2014 to September 2016, research on phytoplankton and physical and chemical parameters of water was carried out in the seashore area of the central Baltic coast near the estuary of the Slupia River in the Ustka area: U1, U2, U3, in order to increase the current knowledge on phytoplankton.

METHODS

The samples were collected in the period of 2014-2016 within the Ustka area, where three measurement stations U1, U2 and U3 were located (Figure 1). Water samples for phytoplankton measurement were collected and analyzed in accordance with the HELCOM COMBINE guidelines [11] and the adopted methodology of field research of phytoplankton in transitional and coastal waters of the Polish sea regions [28].

According to this methodology, quantitative samples were collected using a bathometer from the measurement levels depending on the depth of the station (Table 2): 0.5-1 m, 2.5 m, 5 m or 1 m above the seabed. Samples for qualitative analysis of phytoplankton, i.e., seston (suspended in water) were taken using a plankton net with mesh size of 25 µm. Both quantitative and qualitative tests were poured into 250 ml containers, followed by their preservation with a Lugol iodine solution after which they were transported to the laboratory where they were stored at <10°C [29]. In total, during the research period of November 2014-September 2016, 30 quantitative and 30 qualitative samples of phytoplankton were obtained at 3 stations during 10 field trips. Laboratory analyses included qualitative analysis of phytoplankton (taxonomic composition) and quantitative analysis of phytoplankton (abundance and biomass); Qualitative analysis aimed at determining the taxonomic composition of phytoplankton organisms. It

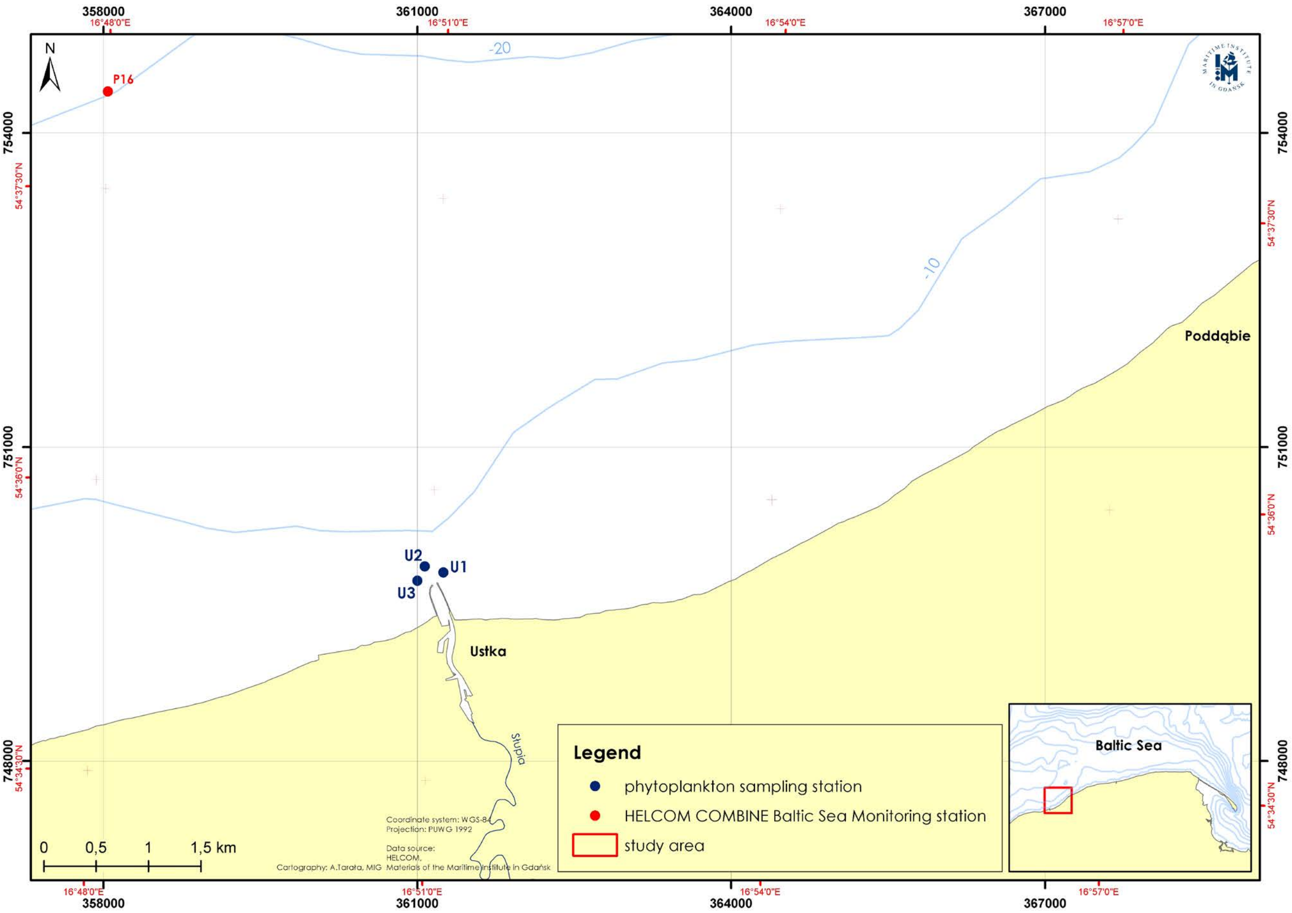

Fig1. Location of phytoplankton measurement stations in 2014-2016 in the Ustka area (estuary of the Slupia river) and IMWM station under HELCOM Baltic Sea Monitoring.

Tab. I. Measurement results of temperature, salinity and transparency of waters around measurement stations in the area of Ustka in the period from November 2014 to September 2016

PARAMETER		11. 2014	01. 2015	03. 2015	05. 2015	09. 2015	11. 2015	04. 2016	05. 2016	07. 2016	09. 2016
Water temperature [°C]	U1	11,02	3,75	4,18	9,24	15,34	7,12	5,32	9,49	18,19	18,15
	U2	11,04	3,73	4,19	9,21	15,28	7,47	5,25	9,77	18,37	18,12
	U3	11,09	3,43	3,88	9,14	15,27	7,49	5,20	9,20	18,69	18,06
Salinity [PSU]	U1	7,17	7,45	7,34	7,45	7,55	7,05	6,89	7,90	7,75	7,49
	U2	7,26	7,48	7,09	7,14	7,28	7,53	6,89	6,89	7,73	7,38
	U3	7,18	7,40	7,62	7,46	7,32	7,57	6,88	7,68	7,29	7,08
Transparency [m]	U1	6,5	3,0	1,5	2,5	4,0	2,0	4,5	3,8	4,8	5,5
	U2	6,0	3,5	1,5	3,5	5,0	2,5	4,5	3,5	5,5	5,0
	U3	6,0	4,0	2,5	3,0	5,0	2,5	4,0	4,5	4,0	4,0

was carried out using the latest available keys for taxonomic identification of phytoplankton. The names for individual taxa and groups were used in accordance with the names of phytoplankton species currently accepted by the World Registry of Marine Species, WoRMS (website 1). Quantitative analysis was performed using an inverted microscope Olympus CK40 equipped with 10x and 40x magnification lenses, a micrometer ocular lens and a Utermöhl sedimentation chamber set with appropriately matched sedimentation cylinders. The unconsolidated material was left for 8 to 18 hours in sedimentation chambers with a capacity of 10 ml or 25 ml, and then analyzed in accordance with the procedure described by Edler (1979) [4] and according to the recommendations of the Helsinki Commission - annex c6 [10]. Depending on the taxon, as a unit of measurement N, there were adopted a single cell, a cenobium (aggregations of algae cells resulting from divisions and maintaining communication via a common envelope), a colony or filaments (a set of cells arranged linearly one above the other, it is a life form of cyanobacteria in the form of a filamentous colony of cells tightly adhered to each other) with a length of

Tab. II. Periods of phytoplankton development and depth [m] in the area of Ustka based on water temperature [°C]

MONTH OF SAMPLE COLLECTION AND DEPTH	SYMBOL OF THE MEASUREMENT STATION			PERIODS OF DEVELOPMENT
	U1	U2	U3	
November 2014	11,02	11,04	11,09	Autumn 2014
January 2015	3,75	3,73	3,43	Winter 2015
March 2015	4,18	4,19	3,88	
May 2015	9,24	9,21	9,14	Spring 2015
September 2015	15,34	15,28	15,27	Late Summer 2015
November 2015	7,12	7,47	7,49	Late Autumn 2015
April 2016	5,32	5,25	5,20	Early Spring 2016
May 2016	9,49	9,77	9,20	Spring 2016
July 2016	18,19	18,37	18,69	Summer 2016
September 2016	18,15	18,12	18,06	
Depth	6,4	7,7	7,1	

100 µm [11]. The biomass of individual taxa was calculated based on the adopted size classes of phytoplankton developed and approved by HELCOM PEG (Expert Group on Phytoplankton of the Baltic Marine Environment Protection Commission) [11]. The dominance of individual taxa was calculated on the basis of both biomass and abundance, which allowed to precisely define the character of the community. The study adopted average abundance and average biomass from all measurements taken at three stations in the Ustka area. In addition, salinity and temperature measurements were made using the oceanographic probe CTD (Conductivity, Temperature, Depth) and transparency using the Secchi disk in water depth at individual measurement stations in the Ustka area, which are presented in (table I).

RESULTS

In the Ustka area, the water temperature did not exceed 18.69°C in summer of 2016, and the lowest temperature of 3.43°C was recorded in January 2015. In November 2014, the water temperature was 4°C higher than in the same month in 2015 with a value of around 11°C. In the early spring and in spring, in 2015 and 2016, temperatures were similar. Temperature differences between the stations were insignificant. In the Ustka area, the salinity in the waters during the research period fluctuated from 6.88 PSU to 7.90 PSU from November 2014 to September 2016. The highest salinity was recorded in May 2016 at the U1 station and the lowest was recorded at the U3 station in April 2016. The lowest water transparency in the analyzed period was recorded in March 2015 - 1.5 m at the U1 and U2 stations and in November 2016 - it amounted to 2 m at the U1 station and 2.5 m at the U2 and U3 stations. The greatest transparency was recorded in November 2014 - 6.5 m. In the early spring and in the spring of 2016, the transparency was higher than in the spring of 2015 (Table I).

The annual cycle of phytoplankton development takes place successively, and one of the main factors influencing the development of primary production is the water temperature. Therefore, periods (seasons) of varying durations have been identified based on the water temperature [58]. Detailed quantitative and qualitative analysis of phytoplankton samples allowed to identify taxa characterized by high volume and biomass and commonly recognized in the literature as dominants typical for a given season [53], [47]. The dominance structure of phytoplankton [58] changed due to prevailing physiochemical conditions.Of 10 phytoplankton measurements, 8 development periods were identified (table II).

In the Ustka area, 114 taxa of phytoplankton were identified from the top 10 phytoplankton groups. In addition, indeterminate flagellates and small unicellular forms (unicell) were recorded. The highest abundance of taxa occurred at the U1 station in the abundance of 96, and the lowest at the U2 station - 88 taxa. The greatest species abundance at all 3 stations in the studied area was Bacillariophyceae - 32 taxa and Cyanophyceae - 25 taxa. Among diatoms on each of the studied stations, mainly those belonging to the radial subclass (Centrales) and to the genus Chaetoceros and Cyclotella were recorded. Species such as Skeletonema marinoi, or Coscinodiscus sp were also observed.

The samples also included diatoms that belong to different subclasses represented by, among others: Nitzschia sp., Navicula sp., Diatoma tenue or Entomoneis paludosa. The smallest quality variation in diatoms was recorded at the U2 station. Among the cyanobacteria in the Ustka area, nanoplankton species predominated and belonged mainly to the genus Aphanocapsa, Aphanothece, Cyanodictyon, and Merismopedia. The species of filamentous cyanobacteria: Aphanozomenon flosaceae, Aphanizomenon gracile and species of the genus Anabaenopsis or Planktolyngbya were also determined. The qualitative structure of Chlorophyta was represented by a much smaller number of taxa - 21 to be precise. The most noted species occurred in the form of a cenobium, such as Desmodesmus armatus var. armatus, Pseudopediastrum boryanum and Scenedesmus sp. Among the samples from all stations, 4 species of green algae of the genus Monoraphidium were found.

Tab. III. Taxonomic composition of phytoplankton in the area of Ustka from November 2014 to September 2016.

TAXON / STATION SYMBOL	U1	U2	U3
CHLOROPHYTA			
Actinastrum hantzschii			+
Acutodesmus acuminatus	+	+	+
Chlorococcales (rotational ellipsoid)			+
Coelastrum microporum	+		
Crucigenia quadrata			+
Crucigenia tetrapedia	+		
Desmodesmus sp.	+	+	+
Desmodesmus armatus var. armatus	+	+	+
Desmodesmus communis	+	+	+
Dictyosphaerium pulchellum	+		+
Monoraphidium arcuatum	+	+	+
Monoraphidium contortum	+	+	+
Monoraphidium griffithii	+	+	+
Monoraphidium minutum		+	+
Oocystis sp.	+	+	+
Pseudopediastrum boryanum	+	+	+
Planctonema lauterbornii	+	+	+
Pyramimonas	+	+	+
Scenedesmus sp.	+	+	+
Scenedesmus ellipticus	+	+	+
Tetrastrum sp.	+	+	+
CHRYSOPHYTA			
Dinobryon sp.	+	+	
Pseudopedinella sp.	+	+	+
CILIOPHORA			
Mesodinium rubrum	+	+	+
CRYPTOPHYTA			
Hemiselmis sp.	+	+	+
Katablepharis sp.	+	+	+
Leucocryptos marina	+	+	+
Plagioselmis prolonga	+	+	+
Teleaulax acuta	+	+	+
CYANOPHYCEAE			
Anabaena sp.	+		
Anabaenopsis elenkinii	+	+	
Aphanizomenon flos-aquae	+	+	+
Aphanizomenon gracile	+	+	+
Aphanocapsa sp.	+	+	+
Aphanocapsa delicatissima	+	+	+
Aphanothece sp.	+	+	+
Aphanothece paralleliformis	+	+	+
Chroococcus sp.	+		
Coelosphaerium minutissimum			+
Cyanodictyon sp.	+	+	+
Cyanodictyon planctonicum	+	+	

Tab. III. cd. Taxonomic composition of phytoplankton in the area of Ustka from November 2014 to September 2016.

TAXON / STATION SYMBOL	U1	U2	U3
Dolichospermum flos-aquae	+	+	+
Lemmermanniella sp.	+		
Limnothrix sp.	+	+	+
Merismopedia sp.	+	+	+
Merismopedia warmingiana	+	+	
Oscillatoriales	+	+	+
Planctolyngbya contorta	+	+	+
Planktolyngbya sp.		+	+
Planktolyngbya limnetica		+	
Pseudanabaena limnetica	+	+	+
Snowella sp.	+		+
Snowella septentrionalis		+	+
Woronichinia sp.	+	+	+
BACILLARIOPHYCEAE			
Actinocyclus sp.	+	+	
Amphora sp.		+	+
Asterionella formosa	+	+	+
Attheya decora	+		+
Centrales	+		+
Ceratoneis closterium	+	+	+
Chaetoceros sp.	+	+	+
Chaetoceros constrictus	+		
Chaetoceros danicus	+	+	+
Chaetoceros decipiens	+	+	+
Chaetoceros simplex	+	+	+
Chaetoceros wighamii	+	+	
Coscinodiscus sp.	+	+	+
Coscinodiscus granii	+	+	+
Cyclotella sp.	+	+	+
Cyclotella choctawhatcheeana	+	+	+
Cyclotella meneghiniana	+	+	+
Diatoma tenue	+	+	+
Diploneis elliptica	+	+	+
Entomoneis paludosa	+	+	+
Grammatophora marina	+		+
Gyrosigma			+
Leptocylindrus minimus	+	+	+
Melosira sp.	+		
Navicula sp.	+		
Nitzschia sp.	+	+	+
Nitzschia acicularis f. acicularis	+	+	+
Pennales		+	+
Skeletonema marinoi	+	+	+
Synedra acus var. acus	+		+
Synedra ulna var. ulna	+	+	+
Thalassiosira baltica	+	+	+

Tab. III. cd. Taxonomic composition of phytoplankton in the area of Ustka from November 2014 to September 2016.

TAXON / STATION SYMBOL	U1	U2	U3
DINOPHYCEAE			
Amphidinium crassum	+	+	+
Amphidinium sphenoides		+	+
Amylax triacantha	+		
Cladopyxis setifera	+	+	+
Dinophysis acuminata	+	+	+
Dissodinium pseudolunula		+	+
Gymnodiniales			+
Gymnodiniales (rotational ellipsoid)	+		
Gymnodiniales (sphere-10%)		+	
Gymnodinium sp.	+	+	+
Gymnodinium simplex	+	+	+
Gyrodinium sp.	+	+	
Heterocapsa rotundata	+	+	+
Heterocapsa triquetra	+	+	+
Katodinium glaucum	+	+	+
Oblea rotunda	+	+	+
Peridiniales	+		
Peridiniella catenata	+		
Prorocentrum minimum	+	+	+
Protoperidinium bipes		+	+
Protoperidinium brevipes	+	+	+
EUGLENOPHYTA			
Eutreptiella sp.	+	+	+
DISCOMITOCHONDRIA			
Flagellates	+	+	+
HAPTOPHYTA			
Chrysochromulina sp.	+	+	+
OTHERS			
Unicell	+	+	+
ZOOMASTIGOPHORA			
Calliacantha longicaudata	+	+	+
Calliacantha simplex	+	+	+
Ebria tripartita	+	+	+

The most species of dinoflagellates belonged to the genus Gymnodinium. There also occurred Oblea rutunda, Prorocentrum minimum, Protoperidinium brevipes, Dinophysis acuminata, Disssodium pseudolunula, and Amphidium crassum. The lowest variation was found among: Cryptophyta and these were mainly taxa: Hemiselmis sp., Plagioselmis prolonga and Teleauax acuta, and among Haptophyta, namely Chrysochromulina sp.. Among Euglenophyta the species Eutreptiella sp. was identified, while among ciliates there was the species of Mesodinium rubrum. In the area of Ustka there were three species of Zoomastigophora: Ebria trupartita, Calliacantha longicaudata and Calliacantha simplex. The samples also included Chrysophyta represented by the species Pseudopediniella sp. and Dinobryon sp. The qualitative structure of phytoplankton was similar at all three test stations in this area (table III).

The average abundance of phytoplankton from three stations in the Ustka area amounted to 2,083,478 units dm-3. The total abundance of phytoplankton ranged from 195,718 at the U3 station to 228,688 at the U1 station. The abundance of phytoplankton was the highest at U1 - the station closest to the coast and gradually decreased further into the sea. Stations in this region were located in a similar depth range, between 6 and 8 m (Table IV).

The largest percentage of phytoplankton in the Ustka area was

Tab. IV. The average number of phytoplankton in [N · dm-3] in the area of Ustka from November 2014 till September 2016

GROUP	STATION		
	U1	U2	U3
Chlorophyta (green algae)	22319	17368	21015
Chrysophyta (golden algae)	2422	1714	1952
Ciliophora (ciliates)	3110	3073	3323
Cryptophyta (cryptophytes)	21480	20666	29300
Cyanophyceae (cyanobacteria)	22994	24955	25827
Bacillariophyceae (diatoms)	105931	91509	63862
Dinophyceae (dinoflagellates)	8238	5346	6753
Euglenophyta (euglenids)	1977	5926	2828
Flagellates (flagellates)	12199	8843	15016
Haptophyta (haptophytes)	12421	5731	8813
Zoomastigophora	14332	14881	15422
Unicell (others)	1266	625	1607
Suma	228688	200637	195718

Tab. V. The average number of phytoplankton in [N · dm-3] in the area of Ustka from November 2014 till September 2016

GROUP	STATION		
	U1	U2	U3
Chlorophyta (green algae)	10,18	16,37	14,02
Chrysophyta (golden algae)	0,42	0,25	0,54
Ciliophora (ciliates)	41,87	40,34	49,25
Cryptophyta (cryptophytes)	2,37	1,98	2,89
Cyanophyceae (cyanobacteria)	3,23	3,64	4,16
Bacillariophyceae (diatoms)	435,89	479,39	404,86
Dinophyceae (dinoflagellates)	39,71	23,93	22,20
Euglenophyta (euglenids)	1,13	4,62	1,23
Flagellates (flagellates)	1,04	0,67	2,06
Haptophyta (haptophytes)	1,09	0,50	0,80
Zoomastigophora	4,03	0,61	0,44
Unicell (others)	3,48	1,30	2,99
Suma	544,44	573,58	505,45

represented by diatoms, constituting nearly 40% of the total abundance. Cyanobacteria also played an important role in the phytoplankton volume, accounting for about 12% of the total abundance while cryptophytes amounted to 11%. The distribution of other phytoplankton groups had a less significant share and was spread quite evenly.

The average biomass of phytoplankton in the Ustka area amounted to 541.16 mm3 · m-3. The biomass of all phytoplankton groups was similar at all three measurement stations. The highest biomass was recorded at the U2 station, and the lowest at the U3 station (Table V).

Diatoms played the most important role in the phytoplankton biomass in the Ustka area, as the average percentage of diatoms amounted to 80% of the total phytoplankton biomass. Such a high percentage of biomass indicates numerous blooms of large diatoms. Other groups ub which biomass reached much lower values were Ciliophora - 8%, Mesodinium rubrum species.

The studies of phytoplankton seasonality in the southern Baltic coastal waters in the area of Ustka made in the years 2014-2016 have shown that the dominant structure of individual taxa has changed over the entire study period. The diatoms had a significant effect on abundance, and in particular on the biomass of phytoplankton at all three measurement stations during the seasonal cycle (Figures 2-4). However, the high biomass of a given phytoplankton group in a given area was not always reflected in the abundance of phytoplankton, which is related to the construction and size of individual taxa. Based on the abundance or biomass of phytoplankton, typical dominating species during seasonal succession in the Ustka area were distinguished. This allowed to fully characterize the structure of particular phytoplankton groups in a

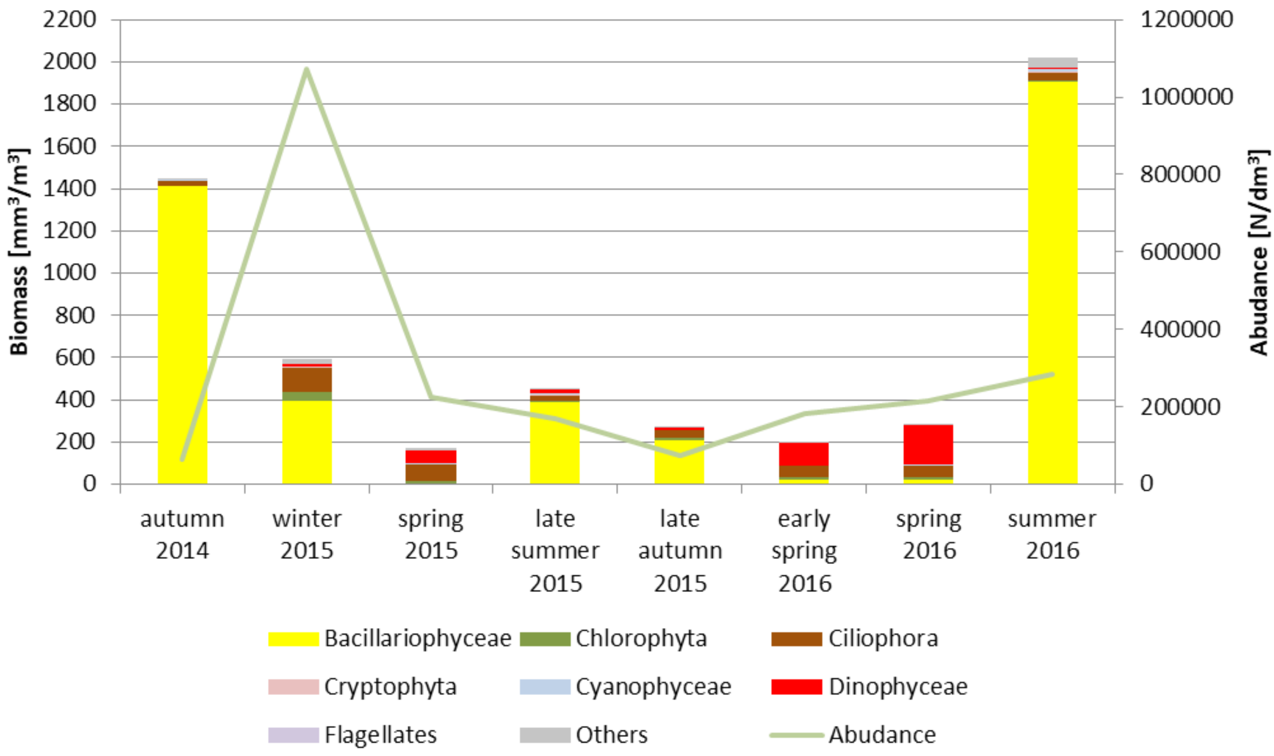

Fig 2. Share of biomass and abundance of major phytoplankton groups in the U1 region in selected seasons in 2014-2016.

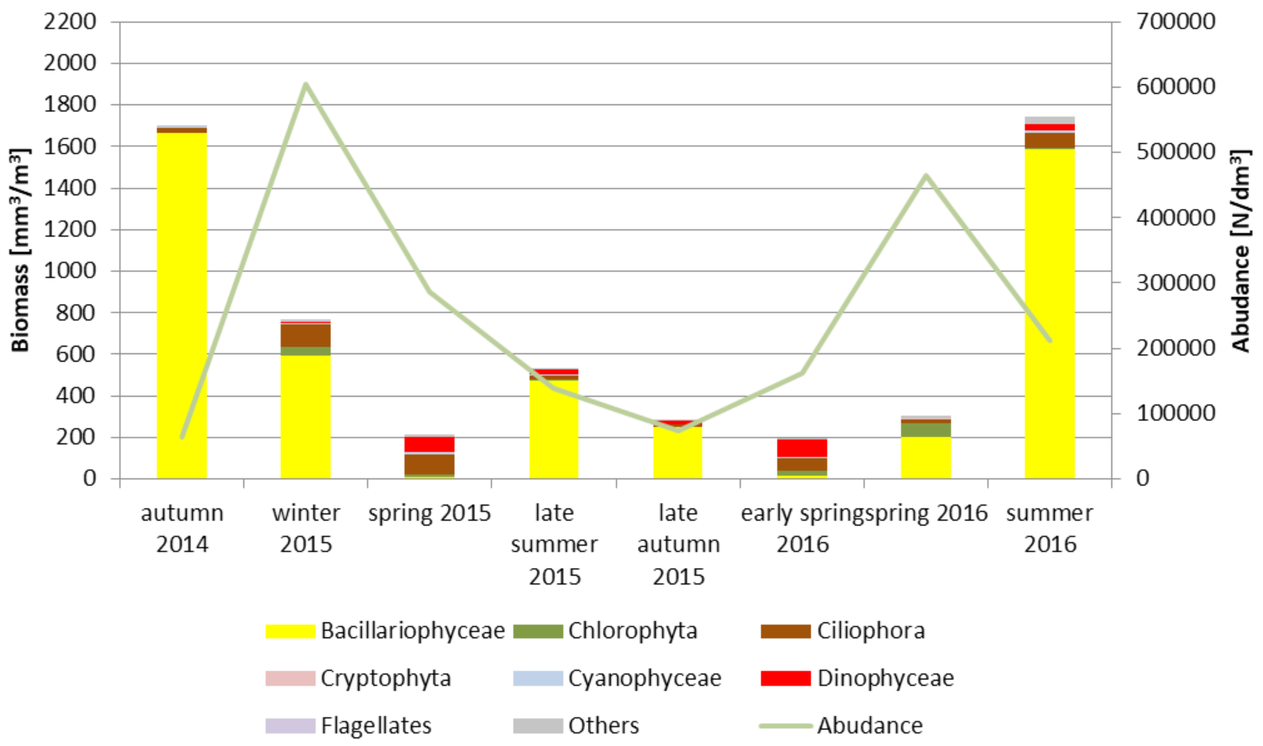

Fig 3. Share of biomass and abundance of major phytoplankton groups in the U2 region in selected seasons in 2014-2016.

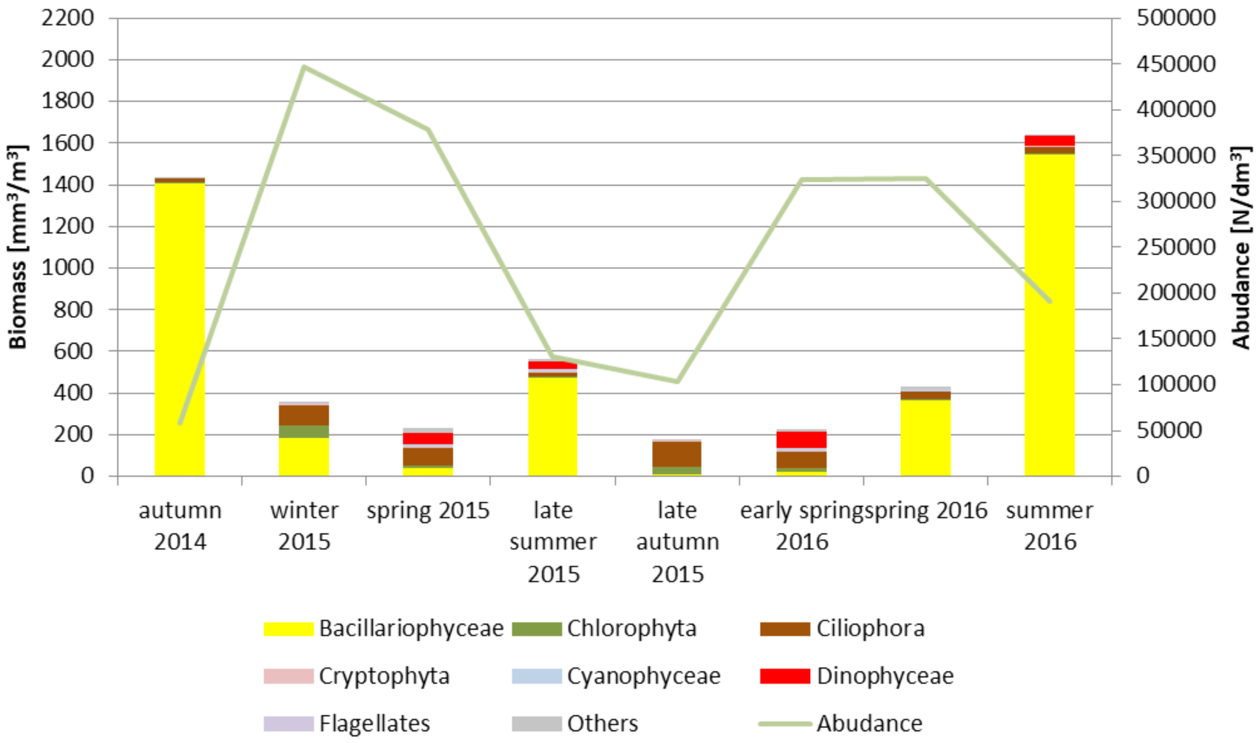

Fig 4. Share of biomass and abundance of major phytoplankton groups in the U3 region in selected seasons in 2014-2016.

given season. In the periods (seasons) determined based of the water temperature, the share of biomass and abundance of the main phytoplankton groups on three phytoplankton measurement stations was presented, depending on the seasons for the Ustka area (Figures 2-4). High abundance from January 2015 to July 2016 was mainly caused by the blooms of diatoms, cyanobacteria, and cryptophytes. The highest abundance was recorded at the U3 station. In November 2014, there was also a large abundance in samples at all stations, which was caused by blooming of diatoms from the Coscinodiscus genus and cryptophytes from the Plagioselmis prolonga and Teleaulax acuta species. In autumn 2014, winter 2015, summer 2015 and spring and summer 2016, diatoms were predominant in the water, especially in biomass. In the spring of 2016, there was an increase in the abundance of diatoms from the Skeletonema marinoi species. In late spring 2015, early spring 2016 and summer 2016, cyanobacteria could be clearly observed in the total abundance of cyanobacteria. Due to the small size of the nanoplankton species, except for September in 2015, they did not reach significant biomass during the analyzed period, which is visible in the graphs (Figures 2, 3, 4). During the entire period of research in all areas, the abundance of cryptophytes had a significant influence on the abundance, accounting for 50% of the total abundance of phytoplankton. The dominant taxa in this group originated from the Teleaulax acuta and Plagioselmis prolonga species.

In the Ustka area, the highest biomass was recorded in autumn 2014 and in summer 2016. The highest biomass value in autumn 2014 amounted to 1700 [mm3 · m-3] at the U1 station and was caused by the presence of large diatoms of the Coscinodiscus genus. In January, diatoms from the Coscinodiscus genus were still blooming at each station, however, the primary production in water was smaller, which is visible in the diagrams. In spring 2015 and in April-May 2016, a large part of the biomass was made by dinoflagellates, which had a significant impact on the biomass of phytoplankton in those months. In addition, a ciliate Mesodinium rubruma, in this case classified as phytoplakotn, constituted large proportion of phytoplankton biomass in this period at all stations. The highest biomass was achieved in spring months (in May 2015 and in April-May 2016). In September 2015, diatoms dominated the biomass, and the abundance was relatively low there. In the summer of 2016, diatoms dominated once more, which can be seen in the charts. Other taxonomic groups that had a significant impact on biomass in the studied areas in warm months were Chlorophyta and Dinophyceaea.

DISCUSSION

The research on species composition, distribution of abundance and biomass of phytoplankton structures made based on the samples taken from the Ustka area in the years 2014-2016 confirmed changes typical of phytoplankton depending on the season of the year. Division and taxa recorded in the area of Ustka were typical for the coastal waters of the southern Baltic [7], [9], [42]. The enrichment of the Baltic Sea with nitrates and phosphates, which may come with river waters to the Baltic Sea, causes a general increase of phytoplankton biomass, including some species of cyanobacteria, diatoms or dinoflagellates, and thus, an increase of water turbidity, reduction of oxygen and changes in the taxonomic composition of phytoplankton [8], [46], [54].

The structure of the abundance of individual phytoplankton taxa in the course of seasonal succession is extremely difficult to interpret because it is influenced by a range of factors. Examining the whole annual cycle, it can be noticed that fluctuations in the abundance values in most phytoplankton groups do not coincide with biomass values. The maximum number of a given phytoplankton group in an annual cycle is often recorded in a different month or time of the year than their maximum biomass. This is related to the size of studied phytoplankton species in a given season. Despite often observed high abundance, small-sized phytoplankton (length less than 10 µm) had a small share in the total phytoplankton biomass. On the other hand, the presence of large phytoplankton species (e.g., 50 - 130 µm in diameter, or up to 300 µm in length), in a smaller amount, means that the total biomass in a given research period can be significant. Therefore, the maximum abundance and biomass can be observed at different times during the entire annual cycle of phytoplankton development, which is more accurately described earlier in article in subsection: results (Figures 2-4).

The qualitative structure of phytoplankton in the analyzed period was also changing depending on the season of the year. This was due to fluctuating environmental conditions (especially temperature and insolation, as well as the availability of biogenic compounds in water) and life preferences of particular groups of organisms, which is widely described in the literature [5], [48], [51], [42], [57]. In temperate water basins, such as the Baltic Sea, two distinct abundance and biomass maxima are usually observed – in spring and autumn [5], [22], [50]. In a temperate climate, seasonal succession in coastal waters usually starts with winter-spring diatoms, followed by a summer bloom of dinoflagellates. In the Baltic Sea, there is a general trend of domination of diatoms during spring but with a simultaneous bloom of dinoflagellates. The diatoms and dinoflagellates have comparable environmental requirements [16]. The situation is similar in the studied area. During the research, clear maxima for biomass were observed - in autumn 2014 and late summer 2015, where diatoms predominated in the entire water basin, mainly from the Coscinodiscus granii species. A clear maximum in abundance was also noted in winter 2015, while in March, the number of cryophilic diatoms dominated in the abundance, including Skeletonema marinoi, Diatoma tenue and Chaetoceros sp. [15-17]. The species diversity of diatoms during blooms is usually higher than that of dinoflagellates, which was also confirmed during these studies (16). During the diatoms blooms, they quickly reach high biomass, because they intensively absorb nutrients needed for growth. Due to their sedimentation properties, their quantity in the water rapidly decreases, and they become food for benthic organisms at the bottom [12]. Dinoflagellates grow slower than diatoms and due to their ability to migrate vertically in water, they can use nutrients from its lower layers. Recent reports indicate that the ratio of the number of diatoms to dinoflagellates reflects the state of the ecosystem and the quality of the phytoplankton biomass as food for other members of the food chain [22], [53]. During the entire study period, the significant contribution to biomass was the autotrophic species of ciliates Mesodinium rubrum. Its presence in the winter-spring and autumn periods is commonly recorded in the waters of the Gulf of Gdansk (especially during the spring blooms of dinoflagellates). According to the latest research, the abundance and biomass of this organism is increasing and is becoming an important element of plankton [1], [10], [20], [55]. Studies of abundance and biomass of the ciliate Mesodinium rubrum in the coastal waters of the South Baltic conducted in the years 2006-2008 near the Ustka area [45] show that the highest abundance of ciliates was recorded in April--June. High average biomass of ciliates was recorded for more eutrophic regions of the Baltic Sea, e.g., for the Gdansk Basin or Arkoński Basin [45]. The significant contribution in biomass and abundance of spring and autumn phytoplankton diatoms from the species Coscinodiscus, Chaetoceros and the ciliate Mesodinium rubrum is consistent with the observed general increasing trend in the share of these organisms in the Baltic waters, as reported [53], [15], [45], [22]. In the late spring of 2015 and early spring of 2016, blooms were mainly caused by dinoflagellates from the genus of Gymnodinium and Heterocapsa. In autumn and winter, small cryptophytes (Plagioselmis prolonga, Teleaulax acuta) predominated the entire water depth in terms of abundance in phytoplankton, accounting for approximately 50% of total phytoplankton abundance.

If phosphorus in water is not used during the spring blooms of diatoms and dinoflagellates, this - in combination with a long period of warm sunny weather and a large amount of nutrients in the water - results in blooms of cyanobacteria. They are visible on the surface of the blooms assimilating atmospheric nitrogen, which is a natural phenomenon. However, this causes eutrophication in many areas of the Baltic Sea, which is becoming more and more intense and appearing with greater frequency, especially since the late 1980s. One of the main components of these blooms is the toxic species of Nodularia spumigena [35-38]. The intensity of blooms is determined mainly by the amount of nutrients accumulated during winter and the temperature of water [16-18], [52-54]. In addition, the structure of phytoplankton is determined by the ability of individual species to adapt to both physical and chemical factors such as temperature, concentration of nutrients in water, pH, water dynamics, and insolation. [19]. The Baltic Sea contains species of cyanobacteria that belong to the order of Nostocales, f.ex. Nodularia spumigena, Aphanizomenon flos-aquae and Dolichospermum sp., as well as single-cell cyanobacteria mainly belonging to the Synechococcus genus (Chroococcales order) [38, 39]. In the area of Ustka there was an increase in the number of cyanobacteria in spring and summer - mainly small, colony species from the genus Merismopedia. Aphanocapsa and Anathece. Owing to these nanoplankton species, the abundance of cyanobacteria in the summer months was high. Aphanizomenon flos-aquae dominated in the biomass,

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which according to literature, is a natural phenomenon [36]. The toxic species of Nodularia spumigena was not observed during the research period, which may be due to the average water temperature of 18°C in 2016. According to the literature [Mazur-Marzec], the optimum salinity for the bloom of cyanobacteria Nodularia spumigena lies within the range of 5-13 PSU, while the average salinity at the station was around 7. It is also possible that the bloom of this species didn't occur during measurements. According to [36], the blooms of toxic cyanobacteria species in brackish waters are less common than in fresh waters. The dominance of cyanobacteria in plankton in the summer confirms reports that these organisms prefer higher water temperature and higher insolation [47-48].

The results obtained as part of the conducted studies and presented in this paper confirm typical changes of phytoplankton in the examined three areas depending on the season of the year. There were no significant species differences between the stations. The significant share in biomass and abundance of spring and autumn phytoplankton diatoms of genus Coscinodiscus, Chaetoceros and ciliates Mesodinium rubrum is consistent with the observed general trend of the growth of these organisms in Baltic waters [1], [10], [13], [15], [52], [55], [61]. Comparing the results obtained in this study to data from the IMWM annual reports for the last decade, it can be noticed that the values and fluctuations of total biomass and phytoplankton abundance in the three studied areas are typical for the South Baltic coastal region [21], [23-28], [31-34]. However, all changes in the quality structure and phytoplankton and seasonal succession are related to various factors, such as climate change, human activity, and introduction of alien species [41]. This is confirmed by the annual research conducted as part of the IMWM monitoring, which shows similarity among particular phytoplankton species that dominate in the coastal zone in the previous years 2016 and 2017. Diatoms were also predominant at the P16 station in these years , , especially in November - a large biomass of Coscinodiscus granii and spring (April). In summer, Nodularia spumigena and Aphanizomemnon flos-aqua were recorded at this station. The qualitative and quantitative distribution of phytoplankton at the P16 station in 2016 and 2017 was similar to the distribution in the area of Ustka [47-49].

Due to the variable nature of this parameter and the possibility of missing the bloom in a given season, the fluctuations of both abundance and biomass may be different in subsequent years of the research depending on the place and time of sampling, as noted in the literature [56] [61]. In each of the three measurement stations, the same dominants in abundance and biomass can be observed. The overall high abundance and biomass of diatoms in this area may be caused by the inflow of river waters - the Slupia River. The literature confirms that the number of diatoms increases along with proximity to the freshwaters of the river [49].

In seas with low salinity, such as the Baltic Sea, beside saltwater species, there are saltwater algae, and in the coastal zone, especially at the estuaries of rivers and streams, diatoms or freshwater cyanobacteria can be found. The only research (and available studies) of phytoplankton of the shallow central coastal zone is carried out by IMWM as part of the HELCOM Baltic Sea Monitoring at station P16, which is the closest to the studied area, being also in the range of 0-10m layer. The waters of the studied areas were characterized by moderate salinity stability (6.88 - 7.9 PSU), and the recorded fluctuations were negligible and had no limiting impact for the commonly occurring species.

CONCLUSIONS

Based on the obtained results, typical changes in seasonality and temporal and spatial structure of the occurrence of phytoplankton in the region of the Slupia river estuary in November 2014 - September 2016 were found. The biological diversity that was characteristic for the coastal waters of the southern Baltic in given development seasons of phytoplankton was also determined. Phytoplankton seasonality analyses show that an increase in the cyanobacteria, diatoms and dinoflagellates abundance and biomass may contribute to the eutrophication of the water basin, which can lead to far-reaching changes in the ecosystem in the Baltic Sea. During the blooms, they quickly reach high abundance and biomass. Recent reports indicate that the ratio of the number of diatoms to dinoflagellates reflects the state of the ecosystem and the quality of the phytoplankton biomass as food for other members of the food chain [22], [53] which proves the validity and necessity to study seasonality, as well as the temporal and spatial structure of phytoplankton occurrence, with special emphasis put on the biodiversity of phytoplankton composition in the Baltic Sea.

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