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The spatial and temporal structure of phytoplankton in 2014-2016 in the Poddabie area of the southern Baltic Sea

Struktura przestrzenno-czasowa fitoplanktonu w latach 2014 - 2016 w rejonie Poddąbie w obszarze południowego Bałtyku

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Abstract: The Baltic Sea demonstrates seasonal changes in the structure of phytoplankton during which the species composition, abundance, and phytoplankton biomass change. However, the spatial and temporal variability of individual phytoplankton groups is not the same in all regions of the Baltic. The only research (and available studies) of phytoplankton in these shallow central sea basin zones has been conducted by the Institute of Meteorology and Water Management (IMWM) as part of the HELCOM Baltic Sea Monitoring at station P16, which is located closest to the studied area. In the years 2014-2016, phytoplankton seasonality studies were carried out, which allowed to supplement data in the area of the central coast of the south Baltic [61]. Based on the above literature, the aim of this study was to determine the temporal and spatial structure and to examine the species composition of phytoplankton occurrence and biodiversity in the Poddabie region from November 2014 till September 2016. The following article presents the results obtained at three measuring stations (P1, P2, and P3) in the area of Poddabie. These results confirm typical changes of phytoplankton in three measurement stations depending on the season of the year. The data collected for this article constitute the second part, from three other publications in the area of the central coast of the southern Baltic. It shows the exact results of species composition and seasonal changes of phytoplankton in the Poddabie region. The average values of phytoplankton abundance and biomass were typical for this sort of coastal waters and there were no significant species differences between these stations. Comparing the results obtained in this study with data from the IMWM annual reports for the last decade, it can be observed that the volumes and fluctuations of total biomass and phytoplankton abundance in the three analyzed areas are in line with trends typical for the South Baltic coastal area.

Keywords: seasonal variability, species composition, abundance and biomass of phytoplankton, southern Baltic Sea, Poddabie area

Streszczenie: W W Morzu Bałtyckim obserwuje się sezonowe zmiany struktury fitoplanktonu podczas której następuje zmiana składu gatunkowego, liczebności oraz biomasy fitoplanktonu. Jednakże przestrzenna i czasowa zmienność poszczególnych grup fitoplanktonu nie jest taka sama w różnych rejonach Bałtyku. 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. W tym celu w latach 2014-2016 wykonano badania sezonowości fitoplanktonu, co pozwoliło na uzupełnienie danych w obszarze środkowego wybrzeża południowego Bałtyku [61]. W oparciu o powyższą literaturę celem niniejszej pracy było określenie struktury czasowo-przestrzennej i zbadanie składu gatunkowego występowania fitoplanktonu oraz różnorodności biologicznej w rejonie Poddąbia w okresie listopad 2014 – wrzesień 2016. Poniższy artykuł przedstawia wyniki uzyskane na 3 stacjach pomiarowych (P1, P2 oraz P3) w rejonie Poddąbia. Wyniki te potwierdzają typowe zmiany fitoplanktonu na 3 stacjach pomiarowych 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. 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 zgodne z trendami typowymi dla rejonu wód przybrzeżnych Południowego Bałtyku.

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Słowa kluczowe: zmienność sezonowa, skład gatunkowy, liczebność i biomasa fitoplanktonu, południowy Bałtyk, Poddąbie

INTRODUCTION

The periods of occurrence and development of individual groups: Bacillariophyceae, Dinophyceae, Cyanophyceae, Cryptophyta, and Chlorophyta depend strongly on environmental conditions in a given area such as: light, temperature, salinity, pH, carbon dioxide, and the availability of nutrients [15], [16], [52]. Phytoplankton reacts to any changes in the concentration of biogenic compounds, which is why it is the main indicator of the trophic state of waters. The consequence of these changes is cyclical, repeated every year, fluctuation of the species composition, abundance, and biomass of phytoplankton [50]. In temperate water basins, two distinct maxima in abundance and biomass are usually observed - spring and autumn. In the spring, when the availability of sunlight increases and the water warms up offering enough biogenic substances, blooms of diatom begin (spring), and are immediately (late spring), followed by the blossom of dinoflagellates. The water temperature is then higher, but it already contains much less nutrients than in early spring [43]. After spring blooms, the concentration of nutrients in the water decreases. Incomplete use of the phosphate pool and high temperatures of water induce the development of cyanobacteria. In recent years, this group of phytoplankton [15], [50], [52] has been gaining more and more abundance and biomass. Cryptophytes and green algae are less significant groups in the Baltic Sea both in terms of abundance and biomass. In winter there is low 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 the Polish waters [29]. The mechanisms of seasonal changes in the structure of phytoplankton in Baltic waters are quite well understood [22], [51], however, the spatial and temporal variability of individual phytoplankton groups is not the same in different areas of the Baltic [46], [52]. The central coastal region is characterized by exceptional natural values in comparison with other fragments of the Polish Baltic coast. Due to the distance from industrial centers, outlets of larger rivers and urban agglomerations, it is distinguished by its good environmental conditions. On the other hand, the distance from research and scientific centers means that comprehensive biological research in this part of the Baltic Sea is not undertaken very often. Therefore, the main objective of the study was to research the biodiversity of the coastal zone of the open part of the Polish coast near the town of Poddabie by specifying the spatial and temporal structure of phytoplankton. In addition, the only research and available studies on phytoplankton in these shallow-water central coast zones are conducted by IMWM as part of the HELCOM Baltic Sea Monitoring at station P16, which is located the closest to the studied area (about 10 km) (Figure 1) [21], [23-28], [31-33] [59-61].

STUDY AREA

The research area comprises the coastal waters in the vicinity of the Poddabie village, located in close proximity to the Ustka Bay, which in its entirety covers a 34-kilometer section of the coast (extends between the 218th and 252nd km of the Polish shore) [40], [44]. In the west, the bay begins near the Wicko Morskie village (1 km to the east of Jaroslawiec), its eastern end is a peninsula near the village of Rowy. 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 and further to the east, it continues with a cliff section. The height of the cliffs varies from 3-5 m in Ustka (at the 236th – 233rd km of the Polish shoreline), through 12-15 m in the area of Orzechowo-Poddabie (at the 230th – 225th km), 25 m in Debina (at the 222nd km) to 4-5 m in Rowy (at the 220th – 217th km) [3], [6]. In the period from November 2014 to September 2016, the research on phytoplankton as well as physical and chemical parameters of water was carried out at the Baltic central coast in the area of Poddabie at the P1, P2 and P3 measurement stations. (Table 1).

METHODS

The samples were collected in the years 2014-2016 within the area of Poddabie in the southern Baltic where three measuring stations P1, P2, and P3 were located (Figure 1). In addition, measurements of salinity, temperature and transparency of water were carried out at each measurement station in the Poddabie area and are shown in (Table 2).

Physical and chemical measurements were made using a CTD probe (Conductivity, Temperature, Density), produced by SAIV A/S (model SD204). It is used to measure vertical changes in temperature and pressure as a function of depth and on this basis calculates the density and salinity of water. Measurements were carried out vertically, from the surface of the water to the bottom, with the record taken every second. At each station, waster transparency was also measured using the Secchi disc (white disc of 0.3 m diameter) [11]. The disc was lowered into the water column, and the maximum depth of its visibility was a measure of water transparency at a given research station. Measurements were carried out with an accuracy of 0.25 m.

Water samples for phytoplankton measurements were collected and analyzed in accordance with the HELCOM COMBINE guidelines [11] and the adopted methodology of phytoplankton field of in transitional and coastal waters of the Polish marine areas [29]. According to this methodology, quantitative samples were taken using a bathometer from measurement levels depending on the depth at the station (Table 1) 0.5-1 m, 2.5 m or 1 m above the seabed. Samples for qualitative analysis

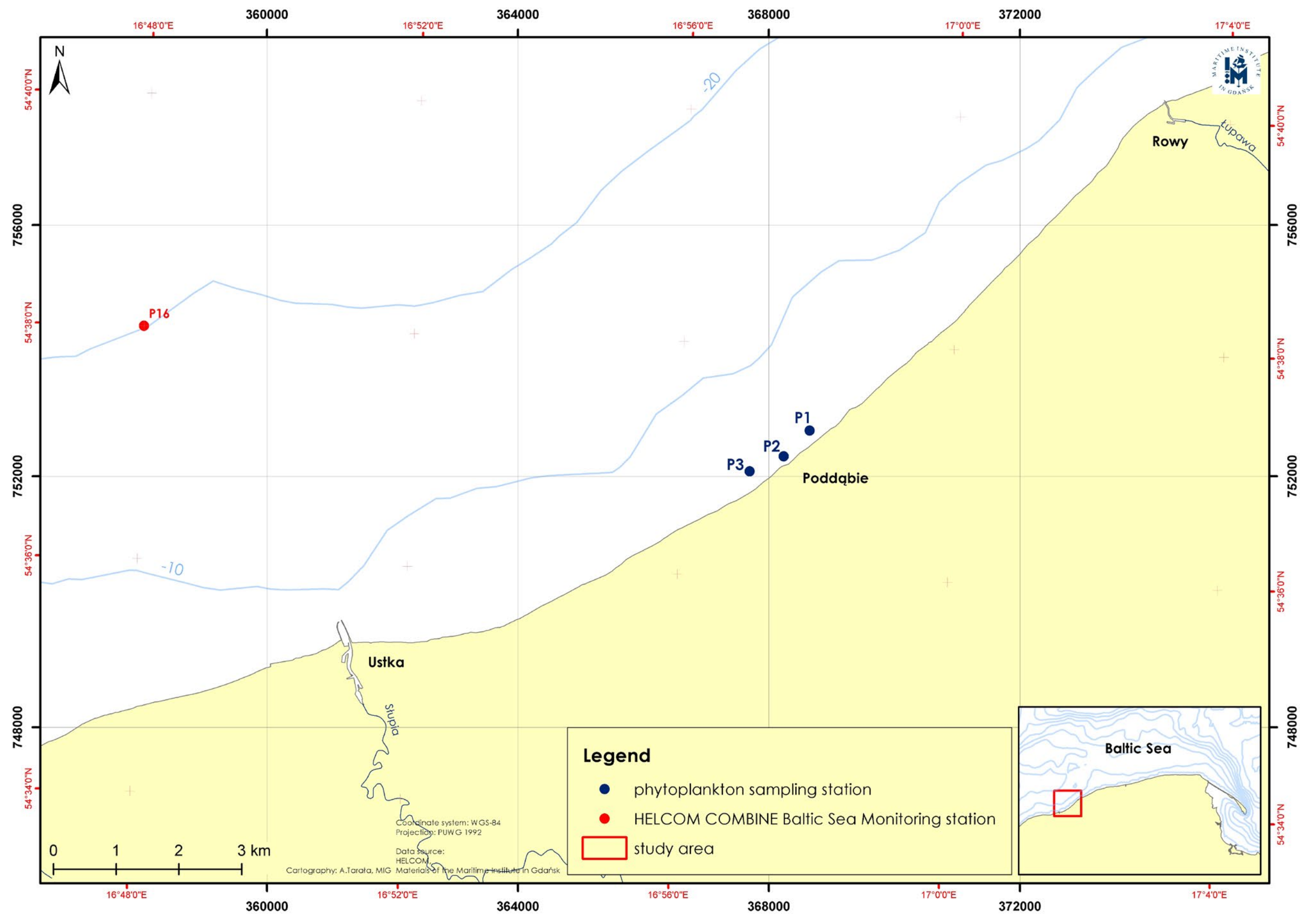

Fig. 1. Distribution of phytoplankton stations surveyed in 2014-2016 in the Poddabie area in the southern Baltic Sea and the IMWM station under HELCOM Baltic Sea Monitoring at station P16 [prepared by A. Tarała].

Tab. I. Geographic coordinates and depth of phytoplankton stations between 2014 and 2016 in the Poddabie area in the southern Baltic Sea.

NO.	STATION	GEOGRAPHIC COORDINATES (WGS 84)	GEOGRAPHIC COORDINATES (WGS 84)	DEPTH [M]
1.	P1	16,9650333°E	54,6211833°N	2,7
2.	P2	16,9588333°E	54,6174000°N	3,4
3.	P3	16,9505333°E	54,6151167°N	2,8

of phytoplankton, seston (a suspension in water) were taken with a plankton net with a mesh diameter of 25 µm. Both quantitative and qualitative tests were poured into 250 ml containers, after which they were preserved with Lugol iodine solution and transported to the laboratory where they were stored at <10°C. In total, 30 quantitative and 30 qualitative samples of phytoplankton were obtained at three measurement stations during the period of November 2014-September 2016 [29].

Laboratory analyses involved qualitative (taxonomic composition) as well as quantitative (abundance and biomass) analysis of phytoplankton. Qualitative analysis aimed at determining the taxonomic composition of phytoplankton organisms and was carried out using the latest available keys for taxonomic identification of phytoplankton. 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. 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 [11]. 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 100 µm. 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

Tab. II. Measurement results of temperature, salinity and transparency of waters around measurement stations in the area of Poddabie 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
Temperature [°C]	P1	10,80	3,80	4,23	9,64	15,53	7,09	5,63	9,63	18,38	18,64
	P2	10,68	3,79	4,34	9,43	15,47	6,94	5,57	9,71	18,35	18,43
	P3	10,75	3,77	4,38	9,71	15,56	6,98	5,57	9,79	18,48	18,48
Salinity [PSU]	P1	7,29	7,64	7,64	7,46	7,55	7,57	6,89	7,83	7,86	7,47
	P2	7,31	7,71	7,63	7,43	7,55	7,54	6,88	7,66	7,84	7,46
	P3	7,31	7,70	7,50	7,41	7,55	7,53	6,88	7,57	7,80	7,47
Transparency [m]	P1	2,4	3,0	3,0	2,6	2,2	1,5	2,2	2,8	2,5	2,5
	P2	3,5	3,0	2,5	3,2	3,5	1,5	2,7	3,	3,9	2,3
	P3	3,2	2,0	2,0	2,2	2,0	2,0	3,0	3,5	2,7	2,5

Tab. III. Periods of phytoplankton development in the area of Poddabie based on water temperature [°C].

NO.	STATION	GEOGRAPHIC COORDINATES (WGS 84)	GEOGRAPHIC COORDINATES (WGS 84)	DEPTH [M]
November 2014	10,80	10,68	10,75	Autumn 2014
January 2015	3,80	3,79	3,77	Winter 2015
March 2015	4,23	4,34	4,38	
May 2015	9,64	9,43	9,71	Spring 2015
September 2015	15,53	15,47	15,56	Late Summer 2015
November 2015	7,09	6,94	6,98	Late Autumn 2015
April 2016	5,63	5,57	5,57	Early Spring 2016
May 2016	9,63	9,71	9,79	Spring 2016
July 2016	18,38	18,35	18,48	Summer 2016
September 2016	18,64	18,43	18,48	

Commission) [11]. The study adopted average abundance and average biomass from all measurements at three stations in the Poddabie area. The dominance of individual taxa was calculated both on the basis of the biomass criterion and abundance, which made it possible to precisely determine the nature of the accumulation [61].

RESULTS

The water temperature gradually increased from March 2015 to September 2015. In November 2015, the seawater temperature dropped significantly. From April 2016 to July 2016, the water gradually warmed up to 18°C. This temperature remained at the same level in September 2016. As is so often the case, the highest water temperature was recorded in September 2016 at the P1 measurement station and amounted to 18.64°C. The lowest temperatures were recorded in January when the temperature in the water column at the P3 station dropped to 3.77°C.

Salinity in the Poddabie area at all three measurement stations reached very similar values. There was also a slight change in salinity depending on the season of the year. From November 2014 to September 2016, the highest water salinity was recorded in July 2016 (7.84 PSU), while the lowest salinity in April 2016 (6.88 PSU).

Transparency was good due to the small depths of the measurement stations for most of the period from November 2014 to September 2016 and the Secchi discs reached the seabed. Only in January, March and November 2015, transparency was less than the depth of the station. The lowest Secchi depth values were observed in November 2015 and were 1.5 m at the P1 and P2 stations, up to 2 m at P3.

One of the main factors influencing the development of primary production is the water temperature. On the basis of this parameter and the dominant organisms in water, distinct periods (seasons) of phytoplankton development have been identified [57]. Thanks to this, it was possible to analyze the succession of seasonal phytoplankton in the period from autumn 2014 to summer 2016. On the basis of detailed quantitative and qualitative analysis of phytoplankton samples, it was possible to observe taxa characterized by high abundance and biomass, which are widely recognized in the literature as dominants typical for a given season [47], [53]. Of the 10 phytoplankton measurements, 8 development periods were distinguished (Table 3). The following results show changes in the dominance structure of individual phytoplankton groups during the entire study period [57].

In the area of Poddabie, a total of 90 taxa of phytoplankton were identified from the top 10 phytoplankton groups. In addition, indeterminate flagellates and small unicellular (unicell)

Tab. IV. Taxonomic composition of phytoplankton in the area of Poddabie from November 2014 to September 2016.

TAXON / STATION SYMBOL	P1	P2	P3
CHLOROPHYTA			
Actinastrum hantzschii	+		+
Desmodesmus sp.	+	+	+
Desmodesmus armatus var. armatus	+	+	+
Desmodesmus communis	+	+	+
Desmodesmus maximus		+	+
Lagerheimia cf. subsalsa	+	+	+
Monoraphidium contortum	+	+	+
Monoraphidium griffithii	+	+	
Monoraphidium minutum	+		+
Oocystis sp.	+	+	+
Pediastrum boryanum var. Boryanum	+	+	+
Planctonema lauterbornii	+	+	+
Pyramimonas	+	+	+
Scenedesmus sp.			+
Scenedesmus ellipticus	+	+	+
Staurastrum sp.			
Tetrastrum sp.	+		
CHRYSOPHYTA			
Apedinella radians			+
Pseudopedinella sp.	+	+	+
CILIOPHORA			
Mesodinium rubrum	+	+	+
CRYPTOPHYTA			
Cryptomonadales		+	+
Hemiselmis sp.	+	+	+
Katablepharis sp.	+		+
Leucocryptos marina	+		
Plagioselmis prolonga	+	+	+
Teleaulax acuta	+	+	+
CYANOPHYCEAE			
Aphanizomenon flos-aquae	+	+	+
Aphanocapsa sp.	+	+	+
Aphanocapsa delicatissima	+	+	+
Aphanothece sp.		+	+
Aphanothece paralleliformis	+	+	+
Coelosphaerium minutissimum	+	+	+
Cyanodictyon sp.	+	+	+
Cyanodictyon planctonicum	+	+	+
Dolichospermum flos-aquae	+		+
Lemmermanniella sp.	+	+	+
Limnothrix sp.	+	+	+
Merismopedia sp.	+	+	+
Oscillatoriales			+
Planctolyngbya contorta	+	+	+
Planktolyngbya sp.	+	+	

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

TAXON / STATION SYMBOL	P1	P2	P3
Pseudanabaena limnetica	+	+	+
Snowella sp.		+	+
Snowella septentrionalis	+	+	+
Woronichinia sp.	+	+	+
BACILLARIOPHYCEAE			
Actinocyclus sp.		+	+
Amphiprora paludosa var. paludosa		+	
Amphora sp.		+	+
Asterionella formosa	+	+	
Centrales	+	+	+
Ceratoneis closterium	+	+	+
Chaetoceros sp.	+	+	+
Chaetoceros danicus	+	1	+
Chaetoceros decipiens	+	+	+
Chaetoceros simplex	+	+	+
Coscinodiscus sp.	+	+	
Coscinodiscus granii	+	+	+
Cyclotella sp.	+	+	+
Cyclotella choctawhatcheeana	+	+	+
Diatoma tenue	+	+	+
Diploneis didyma	+	+	+
Licmophora sp.		+	
Melosira arctica			+
Navicula sp.	+	+	+
Nitzschia sp.		+	+
Nitzschia acicularis		+	
Pennales		+	+
Rhoicosphenia abbreviata		+	
Skeletonema marinoi	+	+	+
Synedra acus var. acus		+	
Synedra ulna var. ulna	+	+	+
Thalassiosira baltica	+	+	+
DINOPHYCEAE			
Amphidinium crassum			+
Dinophysis sp.			+
Dinophysis acuminata	+	+	+
Dissodinium pseudolunula	+	+	
Gymnodiniales		+	
Gymnodinium sp.	+	+	+
Gymnodinium simplex	+		+
Gymnodinium vestificii	+		
Heterocapsa rotundata	+	+	+
Heterocapsa triquetra	+	+	+
Katodinium glaucum		+	
Oblea rotunda	+	+	+

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

TAXON / STATION SYMBOL	P1	P2	P3
Peridiniales	+		
Prorocentrum micans	+		
Prorocentrum minimum	+	+	+
EUGLENOPHYTA			
Eutreptiella sp.	+	+	+
DISCOMITOCHONDRIA			
Flagellates	+	+	+
HAPTOPHYTA			
Chrysochromulina sp.	+	+	+
OTHERS			
Unicell	+	+	+
ZOOMASTIGOPHORA			
Ebria tripartita	+	+	+

Tab. V. Number of taxa of individual groups in the area of Poddabie recorded between November 2014 and September 2016.

GROUP	STATION SYMBOL		
	P1	P2	P3
Chlorophyta (green algae)	14	12	14
Chrysophyta (golden algae)	1	1	2
Ciliophora (ciliates)	1	1	1
Cryptophyta (cryptophytes)	5	4	5
Cyanophyceae (cyanobacteria)	16	17	18
Bacillariophyceae (diatoms)	17	26	20
Dinophyceae (dinoflagellates)	11	9	9
Euglenophyta (euglenids)	1	1	1
Haptophyta (haptofity)	1	1	1
Zoomastigophora	1	1	1
Total	68	73	72

were reported. At the P1 measurement station 68 taxa were recorded, at the P2 station - 73, and 72 taxa at the P3 station. The greatest variety of species at all three stations in the studied area belonged to Bacillariophyceae, followed by Cyanophyceae and Chlorophyta (Table 4). The largest diversity of diatoms was recorded at the P2 station - as many as 26 taxa (Table 5). They belonged mainly to the genus Chaetoceros, Coscinodiscus, Cyclotella, Thallassiosira, and these were the centric diatoms. In the samples, taxa belonging to Pennales such as Synedra sp., Nitschia sp. and Diatoma tenue were also marked. The smallest diversity of diatoms was observed at the P1 measurement station. Among the cyanobacteria in the Poddabie area, nanoplankton species predominated and belonged mainly to the genus Aphanocapsa, Aphanothece, Cyanodictyon, Coleosphaerium, and Merismopedia. There were also observed species of filamentous cyanobacteria: Aphanozomenon flos- aquae, Dolichospermum flos-aquae, Planktolyngbya sp. Pseudoanabena limnetica and Limnothrix sp. Among chlorophytes there were 17 taxa identified. The observed taxa mostly appeared in the form of a cenobium, for example from the Desmodesmus or Scenedesmus genus. Pseudopediastrum boryanum, Ocystis sp. and Planctonema lauterborni were recorded at each station. Dinoflagellates were represented mainly by Gymnodinium simplex, Gymnodinium sp, Oblea rutunda, Prorocentrum minimum, Dinophysis acuminata, Disssodinium pseudolunula or Amphidium crassum. The lowest variation was found among Cryptophyta and these were mainly taxa: Hemiselmis sp., Plagioselmis prolonga and Teleauax acuta. There was also one species of Haptophyta: Chrysochromulina sp., as well as one that belonged to Zoomastigophora. The measurements also included Chrysophyta represented by the species Pseudopediniella sp. and Apediniella radians as well as the ciliates - Mesodinium rubrum. The qualitative structure of phytoplankton was similar at all three measurement stations in this area (Table 4).

The average abundance of phytoplankton in the Poddabie area was 344,379 N · dm-3. The total abundance of phytoplankton ranged from 300,541 at the P3 measurement station to 410,885 at the P2 station (Table 6). High abundance of phy-

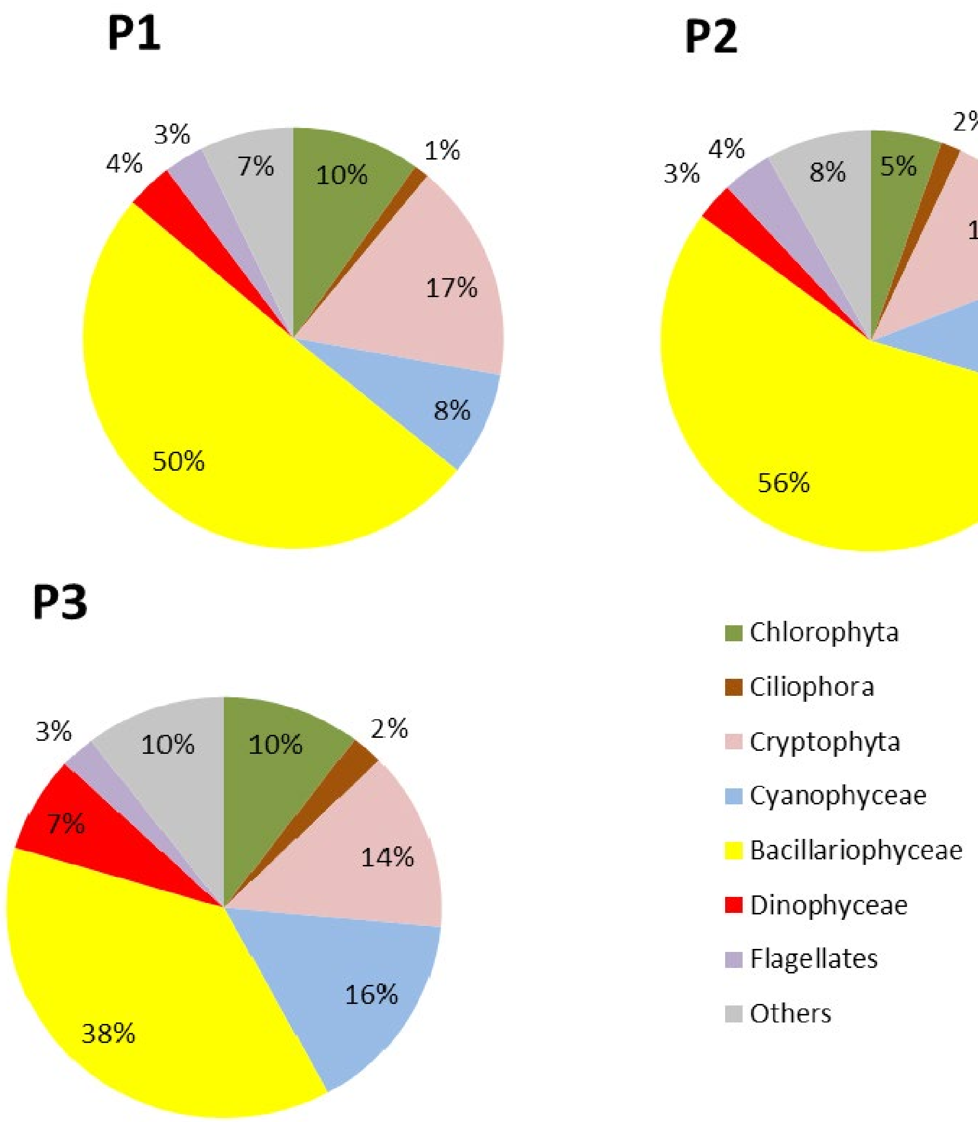

Fig. 2. Percentage share of the average abundance of phytoplankton in the area of Poddabie at three measurement stations from November 2014 till September 2016

Tab. VI. Average abundance of phytoplankton in [N · dm-3] in the area of Poddabie from November 2014 till September 2016.

GROUP	STATION SYMBOL		
	P1	P2	P3
Chlorophyta (green algae)	31685	22338	30864
Chrysophyta (golden algae)	1458	2990	2570
Ciliophora (ciliates)	3768	6502	7215
Cryptophyta (cryptophytes)	53992	49781	41431
Cyanophyceae (cyanobacteria)	25713	42832	46835
Bacillariophyceae (diatoms)	162040	228268	112848
Dinophyceae (dinoflagellates)	11456	11957	22277
Euglenophyta (euglenids)	1730	6820	3805
Flagellates (flagellates)	9975	15747	7698
Haptophyta (haptophytes)	49	247	99
Zoomastigophora	18887	22214	23386
Unicell (others)	958	1189	1514
Total	321711	410885	300541

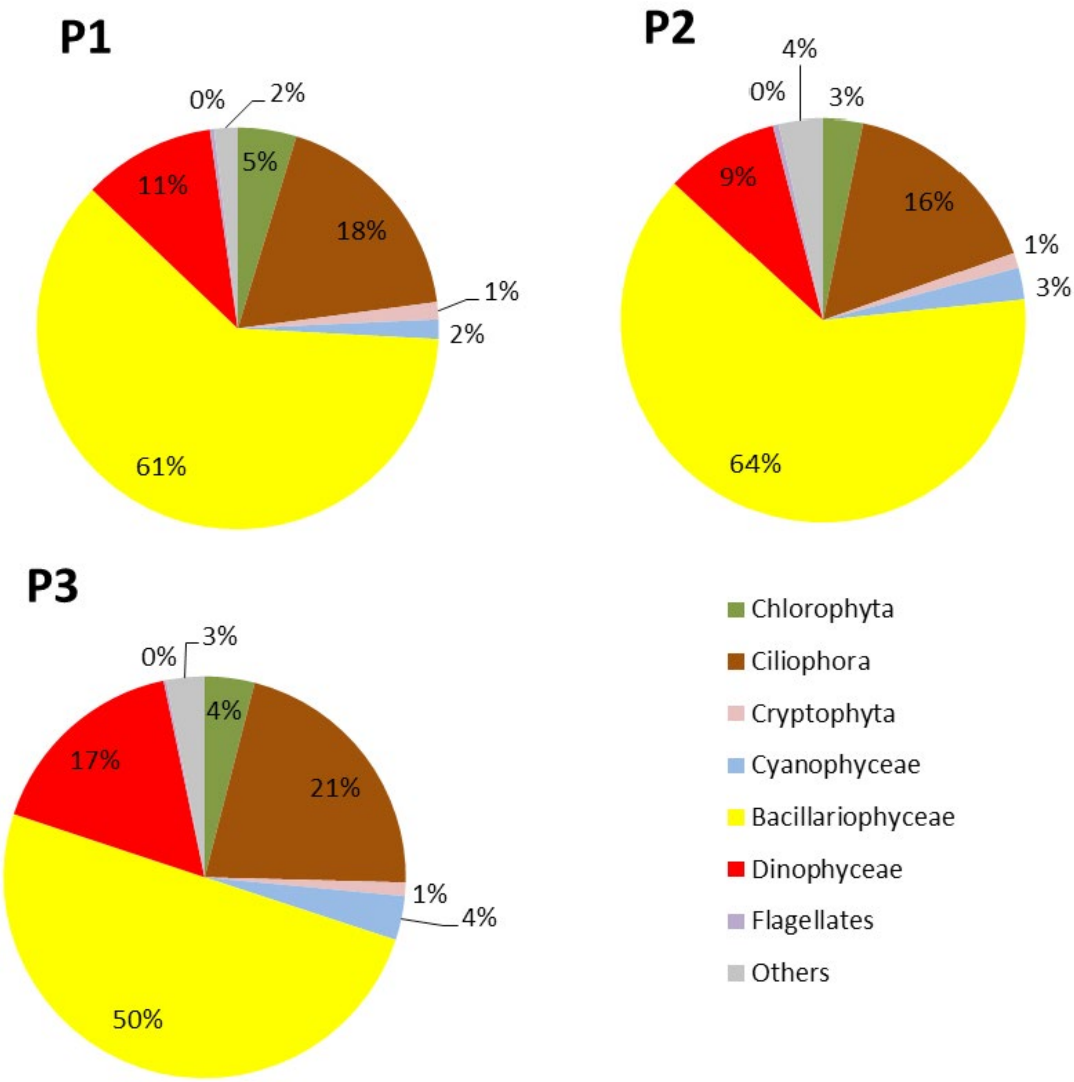

Fig. 3. Percentage share of the average value of phytoplankton biomass in the area of Poddabie at 3 measurement stations from November 2014 to September 2016.

Tab. VII. Average biomass of phytoplankton [mm3 · m-3] in the area of Poddabie from November 2014 till September 2016.

GROUP	STATION SYMBOL		
	P1	P2	P3
Chlorophyta (green algae)	17,91	13,78	14,72
Chrysophyta (golden algae)	0,38	0,70	0,71
Ciliophora (ciliates)	69,12	70,58	78,59
Cryptophyta (cryptophytes)	5,27	5,21	4,04
Cyanophyceae (cyanobacteria)	5,97	11,03	13,01
Bacillariophyceae (diatoms)	232,94	273,88	183,79
Dinophyceae (dinoflagellates)	40,50	39,11	61,10
Euglenophyta (euglenids)	0,45	6,43	1,81
Flagellates (flagellates)	1,28	2,03	0,79
Haptophyta (haptophytes)	0,01	0,03	0,01
Zoomastigophora	1,15	2,07	1,05
Unicell (others)	5,17	6,06	7,64
Total	380,14	430,91	367,27

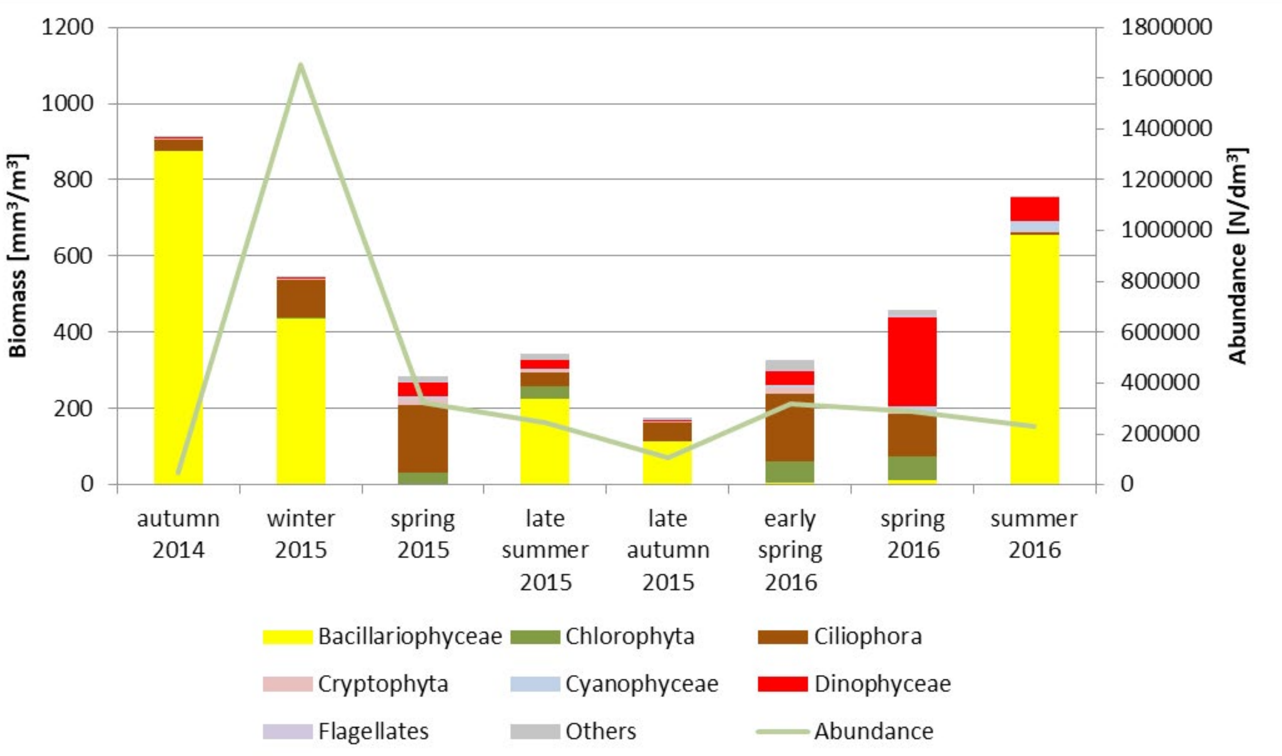

Fig. 4. Share of biomass and abundance of major phytoplankton groups in the P1 area in the selected seasons in 2014-2016.

toplankton at the P2 station resulted from diatoms with the largest share in the abundance of phytoplankton in the Poddabie region, constituting 56% of the total at the P2 station, decreasing to 38% at the P3 station. Cryptophytes and cyanobacteria played a smaller but significant role as well, making from 12% up to 17% of the total abundance of phytoplankton at individual stations. At the P3 station, the abundance of cyanobacteria was also high, constituting 16% of the total phytoplankton population (Figure 2).

The average annual biomass of phytoplankton in the Poddabie area amounted to 312.77 · mm3 · m-3. Phytoplankton biomass was the highest at the P2 measurement station and the lowest at P3 (Table VII). Diatoms played an important role in biomass in the Poddąbie area. Their average percentage made 64% of the total phytoplankton biomass at the P2 station, 61% at the P1 station, and 50% at the P3 station. The presence of Mesodinium rubrum, a ciliate, was also significant, and accounted for as much as 21% of the total phytoplankton biomass at the P3 station, along with dinoflagellates - 17% (Figure 3).

Based on the abundance or biomass of phytoplankton, typical species dominating during seasonal succession were distinguished. This allowed to fully characterize the structure of particular phytoplankton groups in a given season. Studies of seasonal changes in the domination of individual phytoplankton groups in the period of 2014-2016 have shown that the dominance structure of individual taxa changed over the entire study period and was similar at all measurement stations: P1, P2, and P3. Cryptophytes and dinoflagellates, which accounted for about 40% each of the total abundance of phytoplankton, had a significant impact on the numbers in autumn 2014. In the winter of 2015, the predominant species were diatoms and accounted for about 90% of the total abundance. In the late autumn of 2015, cryptophytes dominated, and the dominants in this group were the taxa of species Teleaulax acuta and Prolonga prolonga. In late spring 2015, late summer 2015, early spring 2016 and summer 2016, there was a clear dominance of cyanobacteria, cryptophytes and green algae in the total abundance of phytoplankton. The share of these groups ranged from 25% to 40% depending on the measurement period. The abundance structure of individual phytoplankton groups at three stations in the Poddabie area in the years 2014-2016 was similar at the P1 and P2 stations. Only the P3 measurement station displayed no characteristic increases in the number of blooms during the blooming season. The highest abundance of 1,200 [N / dm3] at station P1 was noted in winter 2015, which was caused by the large abundance of cryptophytes from the species Plagioselmis prolonga and Teleaulax acuta and in spring 2016, where an increase in the abundance of Skeletonema marinoi diatoms could be observed. The lowest abundance of phytoplankton was recorded in autumn 2014, when phytoplankton biomass was the highest and in late autumn 2015, when phytoplankton biomass was the lowest. The achieved results indicate that the 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. In the spring of 2015, there was a decrease in abundance by around 1,000 [N / dm3] at all stations, and the main groups responsible for the value

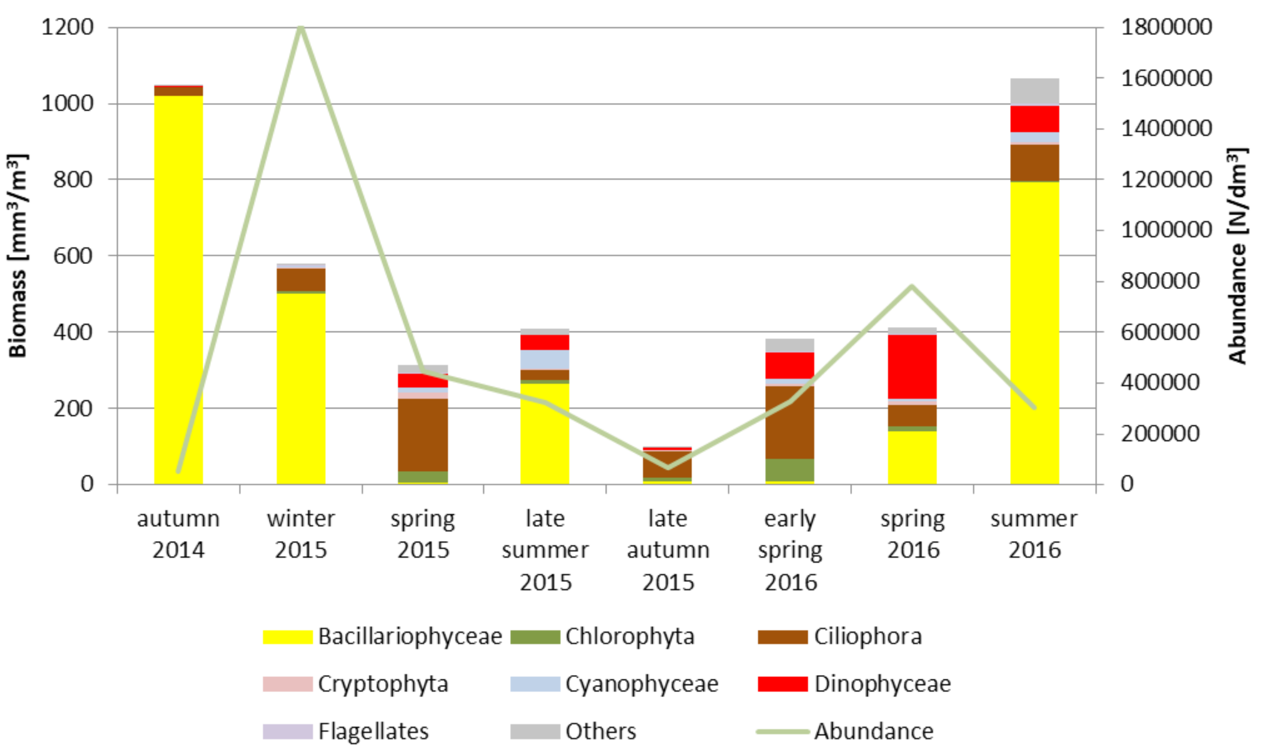

Fig. 5. Share of biomass and abundance of major phytoplankton groups in the P2 area in the selected seasons in 2014-2016.

of abundance were cryptophytes, a species of green algae: Planktonema lauterborni and cyanobacteria Cyanodictyon and Coelasphaerium. In late summer of 2015, the number of cyanobacteria, green algae and cryptophytes increased. In early spring 2016 and spring of 2016, the abundance was dominated by Aphanocapsa sp., Aphanothece paralleliformis, Coelosphaerium minutissimum, Cyanodictyon sp., Merismopedia sp. In the Poddabie area, the highest average biomass at each measurement station was recorded in autumn 2014 due to the presence of large diatoms of the Coscinodiscus genus. The lowest biomass in the Poddabie area was recorded in late autumn 2015, which might be caused by the depletion of biogenic nutrients after the probable autumn maximum. In winter 2015, diatoms' predominance in biomass was also noted due to the blooms of Coscinodiscus granii species, Chaetoceros sp., and Diatoma tenuis; the largest biomass of this group was recorded at the P2 station. In the spring of 2015 there was a clear dominance of the ciliate species Mesodinium rubrum and the green algae Pseudopediastrum boryanum and dinoflagellates Oblea rotunda at the P1 station. In the spring season, biomass was around 300 mm3 · m-3 at all stations. In late summer of 2015, the diatoms from the Coscinodiscus granii genus dominated in the biomass once more. A smaller but significant part of the biomass was Dinophysis acuminata, Aphanizomenon flos-aquae t the P1 station, green algae of the Pyramimonas genus at P2 and Aphanizomenon flos-aquae and Dinophysis acuminata at the P3 station. In late autumn of 2015, diatoms of the Coscinodiscus grania were recorded only at the P1 station. Ciliates dominated in other stations once more. In early spring 2016 and spring of 2016, the distribution of biomass and the qualitative structure were similar at each station. Beside the ciliates in these seasons, at each station there were blooms of dinoflagellates Heterocapsa triquetra and Oblea rotunda and diatoms from Skeletonema marinoi species.

DISCUSSION

Clusters and taxa recorded in the areas of Poddabie were typical of the coastal waters of the southern Baltic [7], [9], [42], [61]. The qualitative structure of phytoplankton changed during the period under consideration 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, including the Baltic, two distinct abundance and biomass maxima are usually observed - spring and autumn [5], [22], [50]. In a temperate climate, seasonal succession in coastal waters usually starts with winter-spring blooms of 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, which results from similar environmental requirements of these two phytoplankton groups [16]. The situation is similar in the studied area. In spring 2016, a high number of Skeletonema marinoi diatoms as well as high biomass of dinoflagellates Dinophysis acuminata and Heterocapsa triquetra

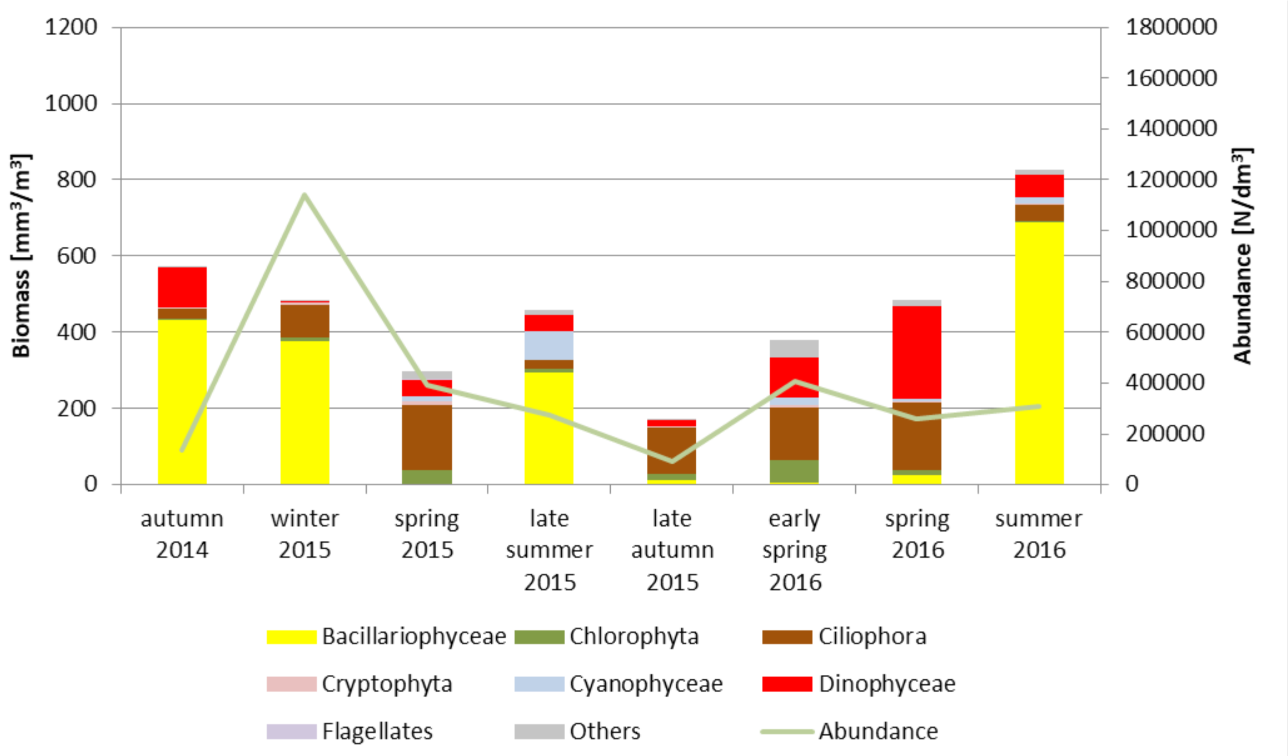

Fig. 6. Share of biomass and abundance of major phytoplankton groups in the P3 area in the selected seasons in 2014-2016.

was observed at the P2 measurement station in one sample. During the research, clear maxima for biomass were observed - in autumn 2014 and late summer 2015, when diatoms dominated in the entire water basin, mainly from the Coscinodiscus granii genus. In connection with the development of various species characteristic for a given season, it can be observed that fluctuations in the abundance values in most phytoplankton groups do not coincide with the biomass values. Therefore, the maximum abundance 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. A good example is the Skeletonema marinoi diatom bloom at the P2 station in winter 2015, which caused high abundance at this station. The blooms large size organisms, for example, Coscinodiscus grania diatoms, which occurred in November 2014 and in summer 2016, when the abundance of other phytoplankton groups in this season was very low. Therefore, maximum abundance and biomass can be observed at different times during the whole annual cycle of phytoplankton development, which is more accurately described in the section "Results" of this article (Fig.4, Fig.5, Fig.6). During the entire study period, the autotrophic ciliates, species of Mesodinium rubrum, constituted a significant contribution to biomass. 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 Mesodinium rubrum ciliate in the coastal waters of the South Baltic conducted in the years 2006-2008 near Ustka [45] indicate that the highest abundance of ciliates was recorded in April-June. The same tendency was recorded in the area of Poddabie. The biomass of this species was higher than in the other analyzed areas in the coastal zone of the Baltic Sea [61]. Data in the literature indicate that high ciliate biomass is characteristic for more eutrophic regions of the Baltic Sea, e.g., for Gdańsk or the Arkonski Basin [45].

The study results also confirm the significant share of diatoms in biomass and abundance of spring and autumn phytoplankton of the genus Coscinodiscus sp., Chaetoceros sp., Skeletonema marinoi, Diatoma tenue and ciliates Mesodinium rubrum and is consistent with the observed general trend of the growing share of these organisms in the Baltic waters [1], [10], [13], [15], [52], [55], [61]. In the early spring and spring of 2016, blooms were caused mainly by plankton from the genus Dinophysis, Heterocapsa and Oblea. In autumn and winter, small cryptophytes (Plagioselmis prolonga, Teleaulax acuta) predominated in the entire water in terms of abundance in phytoplankton. If during the spring blooms of diatoms and dinoflagellates, phosphorus in water is not used, in combination with, for example, a long period of warm sunny weather in summer and a lot of nutrients in the water, cyanobacteria bloom that season. The intensity and type of blooms is determined mainly by the amount of nutrients accumulated during winter and the temperature of water [8], [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 blooms of Cyanophyceae assimilating atmospheric nitrogen are a natural phenomenon, however, as a result of eutrophication in many regions of the Baltic Sea they became more intense and appear more frequently [14]. Since the late 1980s, the main components of these blooms have been the toxic Nodularia spumigen, which produce toxic substances (the second species causing summer blooms of cyanobacteria in the Baltic is non-toxic Aphanizomenon flos-aquae [35-38]. There also occur such species as Dolichospermum sp., Planktolyngbya contorta, Snowella sp., and single-cell cyanobacteria that belong mainly to the genus Synechococcus [38, 39]. The area of Poddabie displayed an increase in the number of cyanobacteria in spring and summer - mainly small colony species of the genus Cyanodictyon, Coelosphaerium, Merismopedia, Aphanocapsa and Anathece. Owing to these nanoplankton cyanobacterial species, abundance in the summer months was high but lower than at the station. Aphanizomenon flos-aquae dominated in the biomass; this is a natural phenomenon according to the literature [36]. There was no toxic species of Nodularia spumigena, which may be caused by the average water temperature of 18 in 2016. According to the literature [37], the optimal salinity for the bloom of Nodularia spumigena falls 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 was not found during sampling. The total biomass and abundance of phytoplankton in the course of the seasonal succession at the three stations in the Poddabie area was two times lower than in the Ustka area [61] and the species composition and seasonal variability were similar.

The results obtained as part of the conducted studies confirm typical changes of phytoplankton in the examined three areas depending on the season of the year. There were no significant species differences between stations, but significant differences in biomass and abundance values compared to other areas in the South Baltic area [61]. Comparing the results obtained in this study to data from the IMWM annual reports for the last decade, it can be observed that the size and fluctuations of total biomass and phytoplankton abundance in the three studied regions are typical for the South Baltic coastal area [21], [23-28], [31-34]. The average values of phytoplankton abundance and biomass for the studied regions were typical for this type of coastal waters. This is confirmed by the annual research conducted as part of the IMWM monitoring, which in the previous years 2016 and 2017 shows similarity among particular phytoplankton groups dominating in the coastal zone. The qualitative and quantitative distribution of phytoplankton at the P16 station in 2016 and 2017 was similar to the distribution in the area of Poddabie [47-49].

Due to the variable nature of this parameter and the possibility of missing the bloom in a given season, fluctuations in both abundance and biomass may be different in subsequent years of research depending on the place and time of sampling, as noted in the literature [56], [61]. Each of the three tested stations display the same dominants in abundance and biomass . The total low abundance and biomass of phytoplankton in the Poddabie area may result from the location of this region. There is no nearby inflow of fresh waters from rivers, and thus the inflow of nutrients causing blooms.

The only research (and available studies) of phytoplankton in the shallow central waters is carried out regularly by IMWM as part of the HELCOM Baltic Sea Monitoring at station P16, which is located the closest to the studied area, and is also situated in the 0-10 m layer. The waters of the studied regions were characterized by moderate salinity stability (6.88 - 7.9 PSU), and the recorded fluctuations were negligible and had no limiting influence on the commonly occurring species.

All changes in the quality structure of phytoplankton and seasonal succession are related to various factors, e.g., climate change or human activity and introduction of alien species [41]. Phytoplankton seasonality analyses show that increasing the cyanobacteria biomass may contribute to the eutrophication of the water basin, which can lead to comprehensive changes in the ecosystem. It seems that the biomass of cyanobacteria in the Baltic Sea has been increasing for at least 60 years [51]. Another group of phytoplankton appearing in mass amounts in the Baltic Sea are diatoms. During the blooms, they quickly reach high biomass, as they intensively absorb the nutrients needed for growth. Due to their sedimentation properties, their quantity in the water rapidly decreases, and they are also food for benthic organisms at the bottom [12]. Dinoflagellates grow slower than diatoms and due to their ability to migrate vertically in the water, they can use nutrients from the lower layers of water. Recent reports indicate that the ratio of the abundance of diatoms to dinoflagellates reflects the state of the ecosystem and the quality of the phytoplankton group as food for other elements in the food chain [22], [53]. This proves the validity and necessity to study seasonality and temporal and spatial structure of phytoplankton occurrence, including the study of biodiversity of the phytoplankton composition in the Baltic Sea.

CONCLUSIONS

During the research conducted in November 2014 - September 2016, the species composition of phytoplankton was determined in the area of the southern Baltic and its temporal and spatial structure was characterized, which was the main purpose of this work. The seasonality structure of individual phytoplankton groups in the Poddabie area was determined by the water temperature for individual development periods. Comparison of the obtained results with the available data from recent years shows that the species diversity as well as the size and fluctuations of total biomass and phytoplankton abundance in the three studied regions are typical for the South Baltic coastal area [23-28], [31-34], [59-61].

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