Autumn dynamics of phytoplankton, zooplankton and nutrients contents in the Novorossiysk harbour, the northeastern Black Sea

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Abstract. Nutrients contents, dissolved oxygen, numerical density, abundance of phytoplankton, holoplankton and meroplankton were obtained in the harbour of Novorossiysk Bay in the autumn season. At the beginning of the autumn 2015, the optimal water temperature in the upper layer of water and the absence of zooplanktonophagous (ctenophore predators) led to the intensive development of plankton communities. The phytoplankton was represented mainly by diatoms algae and zooplankton – by cladoceran, copepods and larvae invertebrates. However, at the beginning of autumn no meaningful relationship between plant and animal components, contents of nutrients and phytoplankton can be found. The zooplankton contained metazoan organisms with a wide range of nutrition including detritophagous. During the autumn season, the phytoplankton community began to transit at the mixotrophic-heterotrophic phase of the annual cycle of development. Probably in the Novorossiysk harbor, the detritus is the most important component in the biotic cycle of matter and energy.

1. Introduction
The development of the coastal northeastern Black Sea plankton communities has a well-pronounced seasonal character, the majority of the most important events being recorded in autumn [1, 2, 3]. At the turn of August – beginning of September, the biomass of Mediterranean ctenophore Beroe ovate Bruguière reaches the dense aggregations in the plankton. This specialized carnivorous animal is fed on the ctenophore Mnemiopsis leidyi (A. Agassiz). As a result, the biomass of zooplanktonophagous M. leidyi decreased and, consequently, the biomass of holoplankton, meroplankton and planktophagous fishes increased. Thus, a set of principal biotic factors may influence and explain...
periodicities changes in the coastal plankton communities of the Black Sea. The development and management of shelf-sea ecosystems require a holistic understanding of the factors that influence the plankton structure and dynamics. The polluted area of the Novorossiysk harbor is an example of areas that are influenced by anthropogenic eutrophication and intensive shipping. Therefore, in autumn, when in zooplankton the pressure of predatory comb jelly is absent, we are primarily concerned with research of planktonic links of the food chain of ecosystems, such as nutrients contents – phytoplankton – zooplankton.

The goal of the paper was to study autumn dynamics of phytoplankton, zooplankton and nutrients contents in the Novorossiysk harbour.

2. Material and Methods
The Novorossiysk Bay is one of the biggest bays of the northeastern part of the Black Sea. It represents an elongated bay with the southeastern part adjacent to the open sea. The area of the Novorossiysk harbour (port) occupies the head of the bay having a complicated coastline and weak water exchange with outside the harbour, which facilitates water eutrophication and heavy pollution of bottom sediments. The samples of plankton and water were collected at the sampling stations in September – November 2015 (Figure 1). During sampling, the sea surface temperature varied between 24.5°C (in September) and 15.0°C (in November).

![Figure 1](image-url)

Figure 1. The map of the sampling survey in the Novorossiysk harbour: a – harbour (port), b – outside harbour

Phytoplankton were sampled from the surface by a plastic bucket and concentrated using the funnel by Sorokin for inverse filtration in the Nucleopore filtering membrane. Samples were fixed with neutral formalin to a final concentration of 1–2% for species identification. Living cells were also observed before sedimentation depending on the cell density [4]. The samples were analyzed in a Nageotte counting chamber using a microscope. Cells were counted in 0.1 to 0.5 of the volume of the concentrated sample depending on cell abundance. Algal biomass was calculated by a volumetric technique based on the cell size and shapes that are the most similar to specific geometric shapes [5].

Holoplankton and meroplankton (crustaceans, larvae of benthic organisms, rotifers and other organisms > 200–500 μm) were sampled throughout the water column using a medium-sized Juday net with an opening diameter of 25 cm (mesh size – 100 μm) by total catch. The material was fixed by 2–4% neutral formaldehyde and processed in the laboratory by the conventional procedure. Calculations of biomass were made using Petipa [6].

Water-bottle samples were taken, and subsamples for ammonium analysis and oxygen were fixed immediately after sampling on board the research vessels. Subsamples for other nutrient determinations were taken with 0.5-liter plastic bottles without fixation. The sampling and processing
of samples of nitrates, ammonium, silicates and phosphates were performed by standard methods, referred to as RD 52.10.243-92 [7]. Phosphates were determined by the method of Hansen & Koroleff [8]. Absorbance was measured at 885 nm in a 50-mm cell. For silicates, the method by Koroleff [9] based on the formation of B-1:12 silicomolybdic acid and its partial reduction to a blue heteropoly acid was used. Absorbance was measured at 880 nm with a 10-mm cuvette. Nitrites were measured on deck to avoid contamination of NH3 from the air inside the ship. The reagents (phenol and hypochlorite solutions) were added on deck to avoid contamination of NH3 from the air inside the ship.

Dissolved oxygen in seawater was determined by the iodometric method (Winkler method) according to RD 52.10.243-92 MU. Seawater samples were fixed immediately after sampling on board the research vessels and put in a dark place. The iodometric determination was carried out in the ship’s laboratory using a semi-automatic titration unit “Digitrate” no later than 4 hours after fixation.

3. Results and Discussion

Nutrients contents. The analysis of seasonal dynamics of nutrients all over the study area indicates an increase of average contents of nitrates, nitrites, ammonium, phosphates, silicates, dissolved inorganic nitrogen and a decrease of dissolved oxygen in late autumn (November) (tables 1 and 2).

### Table 1. Average nutrients contents (mg/l) at seven stations in the Novorossiysk harbour, DIN – dissolved inorganic nitrogen; dates are given as day/month

| Nutrients | 22/09 | 20/10 | 18/11 | Mean    |
|-----------|-------|-------|-------|---------|
| O2        | 10.9±0.12 | 8.49±0.21 | 7.95±0.2 | 9.1±1.3 |
| N-NO2     | 0.002±0.0016 | 0.0018±0.009 | 0.0064±0.002 | 0.003±0.002 |
| N-NO3     | 0.0057±0.002 | 0.024±0.012 | 0.198±0.095 | 0.07±0.1 |
| N-NH4     | 0.032±0.039 | 0.028±0.017 | 0.084±0.026 | 0.048±0.038 |
| P-PO4     | 0.0048±0.003 | 0.004±0.002 | 0.011±0.036 | 0.011±0.036 |
| Si-SiO3   | 0.032±0.028 | 0.057±0.024 | 0.18±0.09 | 0.09±0.09 |
| DIN       | 0.04±0.04 | 0.05±0.02 | 0.28±0.1 | 0.12±0.12 |

### Table 2. Nutrients contents (mg/l) at station 8 outside the Novorossiysk harbour, DIN – dissolved inorganic nitrogen; dates are given as day/month

| Nutrients | 22/09 | 20/10 | 18/11 | Mean    |
|-----------|-------|-------|-------|---------|
| O2        | 10.21 | 8.45 | 8.15 | 8.9±0.55 |
| N-NO2     | 0.000 | 0.000 | 0.008 | 0.002±0.002 |
| N-NO3     | 0.003 | 0.011 | 0.315 | 0.11±0.09 |
| N-NH4     | 0.011 | 0.01 | 0.07 | 0.03±0.017 |
| P-PO4     | 0.001 | 0.003 | 0.011 | 0.005±0.002 |
| Si-SiO3   | 0.003 | 0.023 | 0.304 | 0.11±0.084 |
| DIN       | 0.014 | 0.021 | 0.39 | 0.14±0.1 |

Outside the port area, the average nutrients were comparable to their contents in the harbour of Novorossiysk. At the same time, the contents of nitrates, silicates and dissolved inorganic nitrogen averaged higher compared to the intensively polluted harbour area. Thus, the average contents of nitrates ranged from 0.07±0.1 in the harbour to 0.11±0.09 mg/l outside the harbour (see table 2).

Phytoplankton. Totally, 64 taxa were found in the autumn phytoplankton, including 24 of Bacillariophyta, 34 – Dinophyta, 2 – Cyanophyta, 1 – Cryptophyta, 2 – Euglenophyta, 1 – Chrysophyta. The mean values of phytoplankton abundance during the study period in the harbour were 86±53×10³ cells/l, biomass – 226.6±71.2 mg/m². These values were 1.4 times lower outside the
harbour area. In the Novorossiysk harbour, the maximal values of abundance and biomass were recorded at the beginning of autumn (228±×10^3 cells/l and 550 mg/m^3 respectively), minimal values – in late autumn (16±×10^3 cells/l, 58 mg/m^3) (figure 2).

Figure 2. Dynamics of phytoplankton: numerical abundance (N, 10^3 cell/l), biomass (B, mg/m^3) and share of taxonomic groups in total number (a) and biomass (b) of phytoplankton in the Novorossiysk harbour

The autumn phytoplankton was represented mainly by diatoms algae (Bacillariophyta), containing 31–75 % of the total phytoplankton abundance and 74–88 % of the total phytoplankton biomass. In September phytoplankton abundance (164±×10^3 cells/l) was due to diatoms algae, such as Cerataulina pelagica (Cleve) Hendey, Leptocylindrus minimus Gran, L. danicus Cleve, Skeletonema costatum (Greville) Cleve, Nitzschia palea var. tenuirostris Grunow. There were species of genera Chaetoceros and Thalassiosira and in November (12±×10^3 cells/l) – Proboscia alata (Brightwell) Sundström, N. palea var. tenuirostris Grunow, Skeletonema costatum (Greville) Cleve, Pseudonitzschia pseudodelicatissima (Hasle) Hasle and others.

A significant fraction of diatom biomass (94 %) was formed by species P. alata. The biomass of dinoflagellates algae (Dinophyta) of the total biomass of phytoplankton varied in October – November from 21 to 15 % (72–8.7 mg/m^3 respectively). Among the dinoflagellates we noted genera Gymnodinium, Gyrodinium, Protoperidinium, Proorocentrum micans Ehrenberg, Diplopsalis lenticula Bergh, Gyrodinium fusiforme Kofoid & Swezy, Ceratium furca (Ehrenberg) Claparède & Lachmann, C. fusus (Ehrenberg) Dujardin and other species. During the course of the study, 14–23 % of the total phytoplankton abundance was formed by cryptophyte algae Plagioselmis prolonga (Butcher ex G. Novarino, I.A.N. Lucas & S. Morralland). 1–3 % of the total phytoplankton abundance was euglenic algae and cyanobacteria genera Eutreptia, Euglena (Euglenophyta), Oscillatoria, Lyngbya (Cyanophyta). The presence of these species indicates a higher nutrient status and eutrophication of waters of the Novorossiysk harbour. The maximal density of coccolithophorids algae Emiliania huxleyi (Lohmann) W.W. Hay & H.P. Mohler (Chrysophyta) (31±1.7×10^3 cells/l) was recorded in October.

Beyond the port, the high phytoplankton abundances were also due to diatoms. However, the coccolithophorids abundance of E. huxleyi in October was almost three times higher than that in the harbour (119×10^3 cells/l) (see figures 2 and 3). In November, coccolithophorids reached up to 34 % of the total phytoplankton abundance. Outside the harbour area, during autumn the summarized abundance of diatom mainly P. alata constituted up to 4–61 % of the total phytoplankton abundance and 38–96 % of total phytoplankton biomass. Dinoflagellates were dominant in October – November (47–25 % of the total phytoplankton biomass) and the total phytoplankton abundance was 39 %
Among the dinoflagellates, we noted genera of Gymnodinium, Protoperidinium, Prorocentrum, Diplopsalis lenticula Bergh, C. furca, C. fusus and other species. On the whole, the most abundant number of sum phytoplankton (213×10^3 cells/l) throughout the whole sampling period outside the harbour area was noted in October. Biomass planktonic algae reached maximum in September (391 mg/m^3).

**Figure 3.** Dynamics of phytoplankton: numerical abundance (N, 10^3 cell/l), biomass (B, mg/m^3) and the share of taxonomic groups in the total number (a) and biomass (b) of phytoplankton outside the Novorossiysk harbour

**Holoplankton.** Totally, 15 taxa were found in the holoplankton, including: 8 – Copepoda, 4 – Cladocera, 1 – Dinophyceae (Noctiluca scintillans (Macartney) Kofoid & Swezy), 1 – Chaetognatha, 1 – Appendicularia. During the study period in the harbour the average abundance ranged from 18.9±0.7 to 36.3±5.2×10^3 ind./m^3 and the biomass ranged from 100.8±2.8 to 164.1± mg/m^3 (figures 4 and 5). The number of holoplankton during the research period averaged 27±5.1×10^3 ind./m^3, biomass – 141.3±24.8 mg/m^3. The peak in the dynamics of the number and biomass was registered in September. In this time, 88.69 % of the total holoplankton abundance and 76.5 % of the biomass consisted of cyclopoid copepods Oithona davisae Ferrari F.D. & Orsi (32.2±1.4×10^3 ind./m^3, biomass – 125.6±12.5 mg/m^3). Among holoplankton crustaceans, we noted calanoid copepods Centropages ponticus Karavaev, Acartia tonsa Dana, Paracalanus parvus (Claus). In November, the abundance dropped up to 18.9±7.6×10^3 ind./m^3, the biomass – up to 100.8±9.9 mg/m^3. The abundance and biomass of sum holoplankton outside the harbor area were respectively 1.4‒2 times higher than those in the port area were. The maximal values of abundance and biomass were recorded at the beginning of autumn (49.3×10^3 ind./m^3, 442.6 mg/m^3) (see figure 5).

The autumn peak of the number was mostly due to the cyclopoid copepods. In September their density reached 37.1×10^3 ind./m^3, while their contribution to the total zooplankton was about 75%. In October and November O. davisae comparised from 52 to 61%, respectively, of the total holoplankton abundance. High biomass of holoplankton at the beginning of autumn also was determined by the considerable density of cladocerans Penilia avirostris Dana (24% of the total number) and Pseudovadne tergestina Claus (12 %). In October, a significant part of the total biomass holoplankton (66.5 %) was composed of copepods O. davisae (23 %), C. ponticus (29%), A. tonsa (22 %), P. parvus (15 %). Late in autumn, mostly copepods P. parvus (12.9×10^3 ind./m^3, 52.8 mg/m^3) and O. davisae (21.2×10^3 ind./m^3, 82.8 mg/m^3) were observed in the plankton.

**Meroplankton.** The larvae of bottom invertebrates comprised 14 taxa, including 2 taxa of Polychaeta, 1 – Cirripedia, 1 – Phoronida, 3 – Decapoda, 5 – Bivalvia, 1 – Gastropoda, and 1 – taxa of
Hydrozoa. The number of meroplankton during the research period in the harbour averaged $0.2\pm0.08 \times 10^3$ ind./m$^3$, biomass – $3.3\pm0.09$ mg/m$^3$. The density of the meroplankton ranged from $0.06–0.7\times 10^3$ ind./m$^3$, biomass – from 1–8 mg/m$^3$ (figure 6).

**Figure 4.** Dynamics of holoplankton abundance (a) and biomass (b) in the Novorossiysk harbour: 1 – *Acartia tonsa*, 2 – *Centropages kroyeri*, 3 – *Paracalanus parvus*, 4 – *Oithona davisae*, 5 – total holoplankton

Beyond the harbour, the average density was $1.2\pm1.1 \times 10^3$ ind./m$^3$, biomass – $14.5\pm14.1$ mg/m$^3$, which is four time higher than that in the harbor area. The contribution of meroplankton to the overall zooplankton density averaged 0.7–3%. The well-pronounced peak of the meroplankton density was recorded at the beginning of autumn (September). In the open part, the number of meroplankton ($3.4\times 10^3$ ind./m$^3$) was five times higher than that in the harbour. In September a significant contribution to the overall density was provided by the larvae of hydroids *Sarsia tubulosa* (M. Sars) (69–44 % of total zooplankton density) and bivalves *Chamelea gallina* (Linnaeus), *Anadara inaequivalvis* (Bruguière), *Mytilaster lineatus* (Gmelin).

The overall density of bivalves ranged from $0.19$ to $1.8\times 10^3$ ind./m$^3$ (28–55 % of the total zooplankton density). The share of other organisms, such as decapods crustaceans *Upogebia pusilla* (Petagna), gastropod and bivalve mollusk, cirripede barnacles, polychaetes was negligible. The density of the meroplankton was the lowest in November ($0.01–0.06\times 10^3$ ind./m$^3$). At that time, its share in the zooplankton did not exceed 0.03–0.3 %. In late autumn, the meroplankton mostly consisted of the larvae of bivalve mollusks *Mytilus galloprovincialis* Lamarck, polychaetes *Polydora cornuta* Bosc, and the cirripede barnacle *Amphibalanus improvisus* (Darwin).
Figure 6. Dynamics of the meroplankton density ($10^3$ ind./m$^3$) in the Novorossiysk harbour (a) and outside harbour (b): 1 – hydroids, 2 – bivalves, 3 – barnacles, 4 – polychaetes, 5 – total meroplankton

During our survey outside the harbour area we revealed that the contents of nitrates, silicates and dissolved inorganic nitrogen, as well as abundance and biomass of holoplankton and meroplankton averaged higher compared to the intensively polluted port area. At the same time, the average amount of phytoplankton was lower. Obviously, the high content of nutrients is associated with their weak consumption by phytoplankton. Analysis of the relationship between nutrients contents and phytoplankton biomass, and between the biomass of phytoplankton and zooplankton at various points in the autumn season showed the following (figure 7). In September, the changes of values of phytoplankton biomass were not determined by the variability of contents of nitrites and other nutrients as well as biomass zooplankton (figure 7 a).

In October, the value of phosphates and silicates was more dependent on a level of biomass phytoplankton (figure 7 b, c). However, the obtained coefficients of correlation $P$-$PO_4$ ($r = 0.3147$) and $Si$-$SiO_3$ ($r = 0.5475$) are not significant values. The determination of coefficients $S_{x,y} = r^2 = 0.3147$ (1) and $S_{x,y} = 0.5475$ (2) shows that only 10–30% of changes in the phytoplankton biomass depend on the contents of phosphates and silicates, and 70–90% are due to other factors. In November the same relationship was determined for $N$-$NO_3$ ($r = 0.5115$) and for dissolved organic nitrogen ($r = 0.4085$) (Figure 7 d, e). A high correlation between the biomass of phytoplankton and zooplankton was noted upon decrease in the water temperature. The decline in the amount of phytoplankton and zooplankton occurred along with an increase in the contents of nitrates, nitrites, ammonium, phosphates, silicates and dissolved inorganic nitrogen ($r = 0.9160$) (figure 7 i).

The obtained trends of values that characterize the dynamics of nutrients contents, phytoplankton and zooplankton, suggest that in September 2015, the Novorossyisk harbour experienced an intensive development of plankton communities. Probably the optimal water temperature in the upper layer and the absence of zooplanktonophagous (ctenophore predators) led to this process. After the peak of the abundance of phytoplankton and zooplankton, their quantitative decline and termination of the growing season were observed during the following autumn months. In the meroplankton, there was practically no larvae invertebrates.

In the holoplankton, there were not Cladocera crustaceans. During the autumn season the phytoplankton was represented mainly by diatoms algae. According to the paper [11], the most efficient functioning of the food chain was with the phytoplankton represented by diatoms, and zooplankton – by copepods. In the Novorossiysk Bay, the diatom association exists during mainly the year [12]. However, no good relationship between plant and animal components, between contents nutrients and phytoplankton at the beginning of autumn could be found. During the autumn season, the phytoplankton community transits in the mixotrophic-heterotrophic phase of the annual cycle of
development. At this time, probably autotrophic phytoplankton (diatoms) is not active and destruction (respiration) prevails over production [13].

![Graphs showing nutrient content and phytoplankton biomass relationships](image)

**Figure 7.** Relationship between nutrients contents and phytoplankton biomass (a–g) and phytoplankton and zooplankton biomass (h, i) in the Novorossiysk harbour in September (a), October (b, c, h) and November (d–g, i)

The number of mixo- and heterotrophic dinoflagellates that feed on organic dissolved matter (DOM) increases. As a result, there is no correlation between phytoplankton and nutrients contents. In September, the zooplankton contained metazoan organisms with a wide range of nutrition including detritophagous (Cladocera crustaceans, neritic copepods and benthic larvae).

It is known that the bulk of the primary substance produced by phytoplankton becomes available to planktonic animals as a food source only after its death and bacterial decomposition, i.e. in the form of detritus [2]. The main consumers of phytoplankton in coastal areas are heterotrophic nanoplankton and microzooplankton. Protozoa, as well as mixotrophic and heterotrophic flagellates are able to eat from 57 to 90% of the primary production [13].

This leads to the formation of an intermediate link in the food chain – the microheterotrophs, which transform DOM. In this case, the value of algae for feeding planktonic animals is not the only factor of importance.

### 4. Conclusion
At the beginning of the autumn in 2015, the optimal water temperature in the upper layer of water and the absence of zooplanktonophagous (ctenophore predators) led to the intensive development of plankton communities. The phytoplankton was represented mainly by diatoms algae and zooplankton – by cladoceran, copepods and larvae invertebrates. However, no good relationship between plant and animal components, between contents nutrients and phytoplankton could be found at the beginning of the autumn. The zooplankton contained metazoan organisms with a wide range of nutrition including detritophagous. During the autumn season, the phytoplankton community began its transition to the mixotrophic-heterotrophic phase of the annual cycle of development. Probably in the Novorossiysk harbor, the detritus is the most important component in the biotic cycle of matter and energy. This biocenological mechanism is reflected in the functioning of the pelagic ecosystem of the Novorossiysk harbor as a whole.

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