

Original article

Analysis of Hydrological and Hydrochemical Factors of Bottom Phytocenosis Transformation near Cape Kosa Severnaya (Black Sea, Sevastopol)

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Abstract

Macrophytes act as important bioindicators of environmental conditions and long-term changes in water quality allowing their use in studying the dynamics of bottom natural complexes. The purpose of the work is to identify the main hydrophysical and hydrochemical factors leading to changes in the biomass of bottom phytocenoses near Cape Kosa Severnaya. The paper analyzes and summarizes literary sources and results of landscape and hydrobotanical studies (summer 1964, 1997, 2006 and 2017) carried out in the coastal zone between Cape Kosa Severnaya and Cape Tolsty. We used data on water temperature, concentrations of nitrates, nitrites, ammonium, phosphates and total suspended matter in water from 1998 to 2021. We also used simulation results of macrophytobenthos biomass dynamics in the area from 1998 to 2002. Several bottom natural complexes were distinguished in the landscape structure of this area at different periods. Their composition and quantity changed over time. In the *Ericaria-Gongolaria* phytocenosis (0.5–5 m), by 2006 there was an increase in the biomass of the dominant species characterized by an increase in the proportion of epiphytes. In 2017, there was a restoration of the dominant species, and the total biomass almost tripled. The *Ericaria-Gongolaria-Phyllophora* phytocenosis (5–10 m) had completely disappeared by 2006, and *Dictyota* spp. took its place in 2017. The *Phyllophora* phytocenosis (depths over 10 m) significantly degraded in 1997, and its biomass decreased almost to zero. In 2006, *Phyllophora crispa* was not recorded at these depths, but by 2017, there appeared separate areas of the bottom where *Phyllophora crispa* was present, with biomass an order of magnitude lower compared to that in 1964. It was concluded that the recorded transformations of benthic communities were caused mainly by changes in water transparency associated with the content of total suspended matter. To monitor the situation, it is advisable to regularly conduct hydrobotanical surveys at intervals of several years.

Keywords: macrophytobenthos, bottom phytocenosis, Black Sea, simulation model, bottom natural complex, eutrophication, water transparency

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Анализ гидролого-гидрохимических факторов трансформации донных фитоценозов в районе мыса Коса Северная (Черное море, Севастополь)

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Аннотация

Макрофиты выступают в качестве важных биоиндикаторов условий окружающей среды и долгосрочных изменений качества воды, что позволяет использовать макрофитов при изучении динамики донных природных комплексов. Цель работы – выявление основных гидрофизических и гидрохимических факторов, приводящих к изменениям биомассы донных фитоценозов в районе м. Коса Северная. Проанализированы и обобщены литературные источники, результаты ландшафтных и гидробиотических исследований (летний период 1964, 1997, 2006 и 2017 гг.) в прибрежной зоне м. Коса Северная – м. Толстый с использованием данных о температуре воды, содержании в воде нитратов, нитритов, аммония, фосфатов и общего взвешенного вещества в 1998–2021 гг., а также результаты имитационного моделирования динамики биомассы макрофитобентоса в этом районе в 1998–2002 гг. В ландшафтной структуре прибрежной зоны района исследования в разные периоды времени выделялись несколько донных природных комплексов, причем с течением времени их состав и количество менялись. В эрикариево-гонголариевом фитоценозе (0.5–5 м) к 2006 г. произошло увеличение биомассы доминирующих видов, характеризующееся ростом доли эпифитов. В 2017 г. наблюдалось восстановление доминирующих видов, а общая биомасса возросла почти в три раза. Эрикариево-гонголариево-филлофоровый фитоценоз (5–10 м) полностью исчез к 2006 г., а на его месте в 2017 г. была зафиксирована *Dictyota* spp. Филлофоровый фитоценоз (глубины свыше 10 м) существенно деградировал в 1997 г., его биомасса сократилась почти до нуля. В 2006 г. *Phyllophora crispa* на этих глубинах не регистрировалась, но к 2017 г. появились отдельные участки дна, где представлена *Phyllophora crispa* с биомассой, меньшей на порядок по сравнению с 1964 г. Сделан вывод, что зафиксированные трансформации донных сообществ были вызваны в основном изменениями прозрачности воды, связанными с содержанием общего взвешенного вещества. Для слежения за развитием ситуации целесообразно регулярно с частотой раз в несколько лет проводить гидробиотические съемки.

Ключевые слова: макрофитобентос, донный фитоценоз, Черное море, имитационная модель, донные природные комплексы, эвтрофикация, прозрачность воды

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на основе контактных измерений и математического моделирования» и FNNN-2024-0012 «Анализ, диагноз и оперативный прогноз состояния гидрофизических и гидрохимических полей морских акваторий на основе математического моделирования с использованием данных дистанционных и контактных методов измерений».

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Introduction

Upper underwater shorefaces and shallow marine areas occupy a very small part of the ocean, but it is here that production processes are most active, with a great diversity of species and ecosystems, habitats of hydrobionts and bottom natural complexes [1].

The bottom natural complex (BNC) is a multicomponent developing system. Even minor changes in one of the components of this system can lead to unpredictable transformations of the environment. In this regard, studies of the landscape and morphological structure of the coastal zone have been and are currently carried out actively in the Black Sea ¹⁾ [2–6]. Thus, physical and geographical zoning was carried out [7–9] and characteristics of deep-sea landscapes of the continental slope were given [10]. In addition, approaches to determining the resistance of the Black Sea bottom landscapes to natural and anthropogenic factors were considered [3, 11], the concept of “marine anthropogenic landscape” was introduced and its typification according to the prevailing types of economic activity was proposed [12]. Material fluxes in the coastal zone of the Crimean Peninsula are actively studied highlighting exogenous and endogenous processes that influence the transformation of BNC components [6, 13].

An analysis of BNC studies conducted in the Black Sea led to the conclusion that a negative transformation of the BNC occurs along the entire Black Sea coast.

In this work, we will focus on the identification of possible causes of bottom phytocenosis negative transformations as the main components of the BNC. Macrophytobenthos is considered to be one of the most important and at the same time vulnerable components of the BNC and plays a leading role in the stabilization of coastal ecosystems ensuring the implementation of a number of ecosystem functions and services. The function of macrophytes in an ecosystem is related to their structural characteristics, such as species composition, distribution, abundance and diversity. In their turn, these characteristics depend on various environmental factors: illumination, water temperature, substrate composition, competitive interactions, water level fluctuations, seawater quality and the concentration of nutrients in water and bottom sediments.

¹⁾ Petrov, K.M., 1969. [Methods of Landscape Research of the Marine Coastal Zone]. In: Manteyfel, B.P., ed., 1969. [*Marine Underwater Research*]. Moscow: Nauka, pp. 136–148 (in Russian).

Macrophytes act as important bioindicators of environmental conditions and long-term changes in water quality, which makes it possible to use them when studying the BNC dynamics [14].

The positive effects of macroalgae and sea grasses on the ecosystem have been well studied. In spring, the growth of established species begins, which leads to a maximum biomass of macrophytobenthos in summer. The primary production of macrophytobenthos is limited mainly by water transparency, epiphyte biomass and nutrient availability, which can act as indicators of increasing anthropogenic load on coastal areas [14–17].

Over the past few decades, a decrease in macrophyte biomass has accelerated due to anthropogenic load on the coast. The main factors resulting in this decrease in biomass are a decrease in illumination caused by an increase in the content of total suspended matter (TSM) and dissolved organic matter in water, as well as pollution by nutrients, mainly nitrates and phosphates. An excess of nutrients causes undesirable changes in the hydrochemical and hydrobiological regimes of water bodies and is the main reason for increasing the level of eutrophication [17]. Under eutrophication conditions, the availability of light in the water column decreases due to an increase in phytoplankton biomass, which leads to macrophytobenthos degradation [14].

Complex interactions among such factors as light availability, nutrient concentrations, storm exposure, macrophyte release and sediment transport can be studied with mathematical modeling. Given the significant role that macrophytes play in marine ecosystems, understanding and quantification of the environmental factors that influence the structure of benthic macrophyte communities are necessary to develop sustainable management practices for these ecosystems.

The purpose of the work is to identify the main hydrophysical and hydrochemical factors leading to changes in the biomass of bottom phytocenosis near Cape Kosa Severnaya.

Materials and methods of study

Changes in macrophytobenthos in 1964–2017

The paper analyzes and summarizes materials from literary sources, landscape and hydrobotanical studies (summer 1964, 1997, 2006 and 2017) carried out in the coastal zone between Cape Kosa Severnaya and Cape Tolsty [18, 19]. Fig. 1 shows the schematic map of the profiles along which observations were made.

Statistical data processing was performed in MS Excel. In the landscape structure of the coastal zone Cape Kosa Severnaya – Cape Tolsty, several BNCs were identified at different periods of time. Moreover, their composition and quantity changed over time. Thus, four BNCs were observed in 1964, only three in 1997. Then, the number of BNCs under study decreased to two in 2006 and increased again to four in 2017. The dominant macrophyte species were *Ericaria crinita* (Duby)

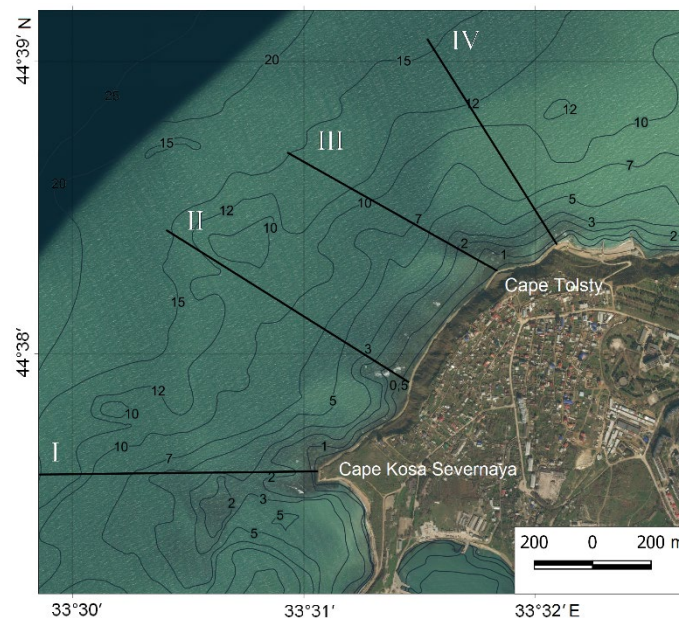


Fig. 1. Schematic map of the location of landscape and hydrobotanical profiles in the coastal zone Cape Kosa Severnaya – Cape Tolsty (Roman numerals stand for profiles). The image is adapted from Bing (available at: <https://www.bing.com/map>)

Molinari & Guiry = *Cystoseira crinita*, *Gongolaria barbata* (Stackhouse) Kuntze = *Cystoseira barbata* and *Phyllophora crispa* (Huds.) P.S. Dixon.

Qualitative and quantitative changes that occurred in the coastal zone BNCs are described in detail in [19]. In our work, we focus on changes in the relative contributions of dominant species, associated species and epiphytes, as such changes accompanied the restructuring of the BNCs during the period under review.

Hydrochemical and hydrophysical indicators of the aquatic environment state (concentration of nutrients, TSM, water temperature, current velocity) affect the growth rate of macrophytes significantly. To identify the connection between the BNC dynamics and changes in the chemical and biological state of the coastal zone near Cape Kosa Severnaya, all available hydrophysical and hydrochemical observation data for 1998–2021 were analyzed. For the purposes of this study, data on water temperature and content of nitrates, nitrites, ammonium, phosphates and TSM in water were used. Based on the available data, the average monthly values of the listed characteristics were calculated. Depth averaging was also carried out; two layers of 0–10 m (upper layer) and 10–20 m (lower layer) were identified.

Determination of illumination at the depth of macrophyte growth

According to existing notions, the most important characteristic for the growth of macroalgae is water transparency, which determines the amount of light energy available for photosynthesis at the depth of algae growth. Standard measurements at coastal stations provide information on TSM content, which can be used to estimate illumination level at depth. *In situ* synchronous measurements of vertical profiles of the 660 nm beam attenuation coefficient (BAC 660) and photosynthetically active radiation (PAR) were carried out at drift stations off Sevastopol Bay using *Kondor* probing hydrophysical complex. The concentration of TSM in water was determined based on the data on BAC 660 using empirical relationship $C_{TSM} = 0.78 \cdot \text{BAC } 660$.

The decrease in the PAR intensity with depth is most realistic when described by exponential function

$$I_z = I_0 \exp(\beta z), \quad (1)$$

where I_0 is sea surface illumination; β is coefficient of light absorption in water depending on the TSM content in water; z is depth. To estimate β as function C_{TSM} , we found the relationship between coefficients β obtained as a result of applying approximation (1) to PAR *in situ* profiles and the average TSM content in the upper mixed layer (Fig. 2, a). The thickness of this layer was determined using the temperature profile data. The least squares method yielded two formulas that can be used to determine the light absorption coefficient β knowing the average TSM content in the upper mixed layer of water (C_{TSM}):

$$\beta = \begin{cases} -1.1818C_{TSM}^3 + 1.6298C_{TSM}^2 - 0.7207C_{TSM} - 0.0264, & C_{TSM} < 1 \text{ mg/L}, \\ -0.6649 \ln C_{TSM} - 0.309, & C_{TSM} > 1 \text{ mg/L}, \end{cases} \quad (2)$$

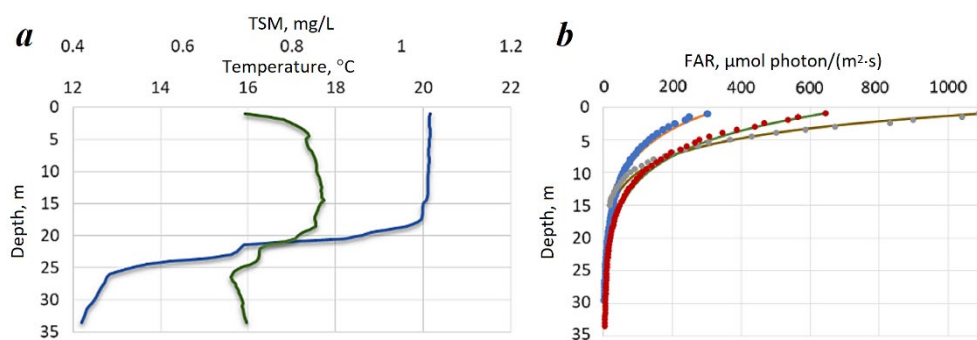


Fig. 2. Example of vertical profiles of water temperature and total suspended matter content at one of the stations (a); vertical profiles of PAR (dots) and their approximations (colour lines) using models (1) and (2) at three profiles (b)

Using these approximations and knowing the intensity of solar radiation at the water surface, it is possible to determine the amount of light reaching the depth of algae growth for given water turbidity in the upper layer. Fig. 2, *b* shows the quality of resulting model (2). Here, the dots represent the *in situ* data on the vertical profiles of PAR at the control stations and lines represent model approximations using expressions (1) and (2). Relative root-mean-square error of the models lies in the range from 7 to 15 % of the average illumination in the 0–25 m layer.

It should be noted that model (2) is regional and cannot claim to be universal. Obviously, to obtain more generalized dependencies, it is necessary to have more data from different water areas. However, to analyze the variability of bottom phytocenosis near Cape Kosa Severnaya, we consider the found dependencies to be sufficiently representative.

Using this model, we can also estimate the potential lower limit of the distribution of a particular alga depending on the average coefficient of light attenuation in water. We will define this limit at a depth where the light intensity is such that the alga photosynthesis rate is equal to its dark respiration:

$$(P_{\max} + R_d) \cdot \operatorname{th}\left(\frac{\alpha I_0 \exp(\beta z)}{P_{\max} + R_d}\right) = R_d,$$

where P_{\max} is maximum photosynthesis rate; R_d is dark respiration; α is slope of the photosynthetic curve in the low light area. From this we get

$$z = \frac{1}{\beta} \ln\left(\alpha \cdot \operatorname{th}\left(\frac{R_d}{P_{\max} + R_d}\right) (P_{\max} + R_d) / \alpha I_0\right). \quad (3)$$

By setting $C_{TSM} = 1$ mg/L, we obtain an estimate of the maximum growth depth of bottom phytocenosis of 10–14 m; the lower limit will move to 25–35 m with a decrease in C_{TSM} to 0.5 mg/L. This estimate is a function of the photosynthetic parameters of the alga, water turbidity and intensity of light at the water surface. This is the potential maximum depth distribution of algae in the sea, but for a more accurate assessment it is necessary to take into account the sufficiency of the concentration of dissolved biogenic substances, as well as the release of organic substances by the alga both during its growth and during the process of thalli dying off or consumption of the alga by marine hydrobionts. It can be said that the observed biomass of algae at a given depth is the result of a balance between its formation during photosynthesis, assimilation of inorganic substances and elimination during excretion, decay or consumption. Therefore, the actual lower boundary of growth of a particular alga will be at a shallower depth than that calculated by formula (3).

Simulation model of the dynamics of bottom phytocenosis

The work uses a model previously tested during studies of the dynamics of macrophyte biomass in Kruglaya Bay and Donuzlav Bay [20, 21]. The proposed

model of dynamic energy balance makes it possible to estimate the growth rate of sea grasses, amount of absorbed biogenic elements, released oxygen, produced and released organic matter, concentration of nitrogen and phosphorus in plant tissues. The dynamics equations of the biomass of macroalgae and sea grasses are written in the form of balance relationship

$$dB/dt = (P_r - eG_r - m)B, \quad (4)$$

where B is biomass of all plant tissues: roots, root stocks and leaves, g DW /m² or g DW/m³; t is time, h; P_r is specific rate of net primary production, 1/h; G_r is specific rate of gross primary production, 1/h; e is ratio of the released dissolved organic matter during the life of the alga to the gross production for the same time; m is coefficient of biomass loss due to mechanical damage, tissue death and consumption by marine animals, 1/h.

Results and discussion

Based on the data of hydrobotanical surveys published in [18, 19], the structure of bottom phytocenoses was studied and the dynamics of the relative distribution of dominant species (basifites), associated species and epiphytes was revealed (Fig. 3).

Structural changes in bottom phytocenosis

The *Ericaria-Gongolaria* phytocenosis on boulder benches up to 1 m deep with an area of 14.7 ha changed quantitatively only in the last observation period of 2006–2017: its biomass increased more than twofold. At the same time, the proportion of epiphytes decreased from 11 to 5%, although their mass increased by 1.3 times. The *Ericaria-Gongolaria* phytocenosis located on a shoreface up to 5 m deep underwent significant changes throughout the entire observation period. From 1964 to 1997, the biomass of the phytocenosis decreased and the proportion of associated species and epiphytes increased to 42 %. These changes continued in 1997–2006 when the proportion of *Ericaria crinita* and *Gongolaria barbata* (basifites) in the phytocenosis decreased to 48 %. Epiphytes made up 50 % of the macrophyte biomass indicating the extreme distress of the ecosystem. After 2006, the situation improved, which led to an increase in the biomass of the entire phytocenosis and an increase in the mass of the dominant macrophytes *Ericaria crinita* and *Gongolaria barbata* to 98%.

The *Erikaria-Gongolaria-Phyllophora* phytocenosis at depths of up to 10 m also degraded throughout the entire observation period. If in 1964 the community included only basiphytes *Ericaria crinita*, *Gongolaria barbata* and *Phyllophora crispa*, then in 1997 a decrease in the total biomass of the phytocenosis was observed and a proportion of epiphytes became noticeable. By 2017, in place of *Ericaria crinita*, *Gongolaria barbata* and *Phyllophora crispa*, a new community had emerged in which the dominant role was played by *Dictyota* spp.

On a gently dipping plain with depths of 10–15 m, the *Phyllophora* phytocenosis that had existed in the middle of the last century with a fairly large biomass (870 g/m²) with a small proportion of associated species and epiphytes (6 and 5 %, respectively) almost disappeared. In 2017, only separate bottom areas were recorded

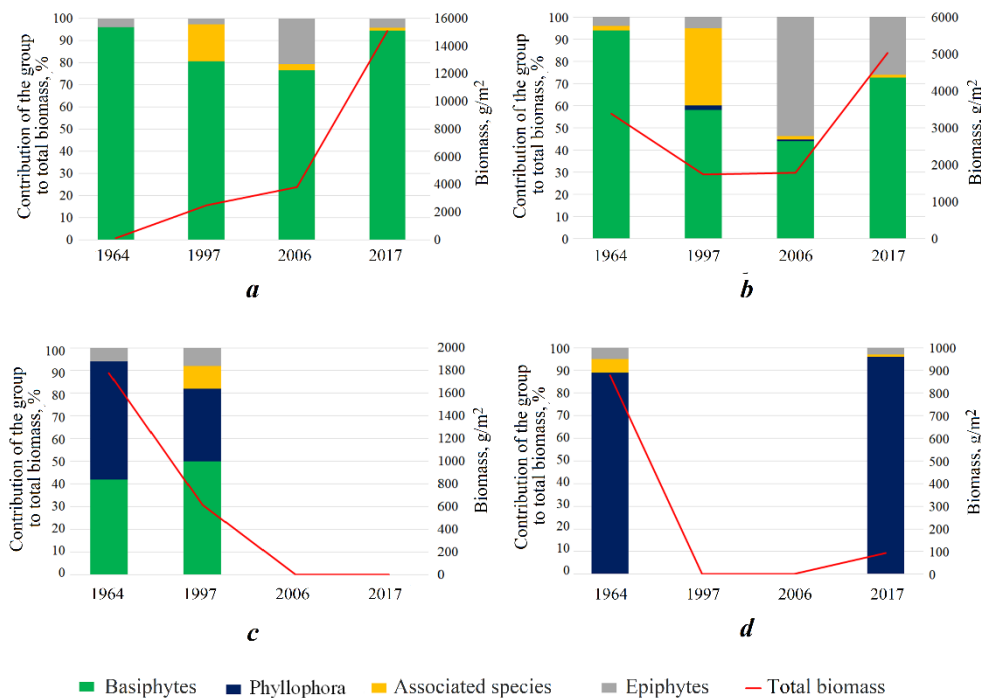


Fig. 3. Dynamics of the total biomass of bottom phytocenosis located near Cape Kosa Severnaya and its structure: *a* – boulder benches with a predominance of *Ericaria crinita* and *Gongolaria barbata* (0.5–1 m); *b* – upper shoreface dominated by *Ericaria crinita* and *Gongolaria barbata* (1–5 m); *c* – upper shoreface with alternating areas dominated by *Ericaria crinita*, *Gongolaria barbata* and *Phyllophora crispa* (5–10 m); *d* – gently dipping plain dominated by *Phyllophora crispa* (10–15 m). The total algal mass of the phytocenosis is shown for 1964–2017

where *Phyllophora crispa* was present with an average biomass of 90 g/m². However, the restoration of the *Phyllophora* phytocenosis indicates the onset of favorable conditions, the main one of which is increased water transparency.

Changes in hydrochemical state of waters

Let us now analyze the data available in the MHI database on the variability of water temperature, as well as measurements of hydrochemical parameters of the aquatic environment near Cape Kosa Severnaya: the content of dissolved inorganic compounds of nitrogen and phosphorus, as well as TSM, in water. Significant heterogeneity in the distribution of observation data over time prevents

us from calculating average annual values of hydrochemical indicators or constructing a reliable series of average monthly observations. To assess their dynamics, we will consider the variability of these indicators in the warm period of the year characterized by the maximum number of observations and the most intensive growth of macrophytes. Fig. 4 shows the TSM content in September during 1998–2021 (in several cases, data for August were used due to the lack of data for September). This month marks the peak of macroalgae biomass and the maximum number of measurements of water hydrochemical parameters in different years. As we can see, from 1998 to 2017, the water turbidity in the upper layer decreased noticeably, which can explain the significantly increased biomass of phytobenthos at depths of up to 5 m. A slight tendency towards decreasing turbidity was observed in the lower layer also, but it was not nearly as pronounced. By 2006, the *Ericaria-Gongolaria-Phyllophora* phytocenosis at depths over 5 m and the *Phyllophora* phytocenosis at depths of 10–15 m had completely disappeared. According to available data, the average TSM content during the vegetation period in 2006 varied within the range of 1.5–2 mg/L, which limited the thickness of the photic layer to 5–7 m according to equation (3).

The analysis of the temporal variability of the hydrochemical state of waters in the area under study showed no significant trends in the content of biogenic substances during the period under consideration. The concentration values of inorganic nitrogen and phosphorus compounds fluctuated within the limits typical for the Sevastopol coastal waters ($[\text{NO}_3] + [\text{NO}_2]$ from 0.03 to 3.54; $[\text{NH}_4]$ from 0.02 to 2.95; $[\text{PO}_4]$ from 0.001 to 0.9 $\mu\text{mol/L}$). As shown by numerical experiments with a phytocenosis model, the average value of phosphate concentration of 0.11 $\mu\text{mol/L}$ is insufficient for the growth of macroalgae. Thus, the content of inorganic phosphorus in water is a limiting factor. With an increase in this aquatic environment parameter, intensive growth of macroalgae is observed.

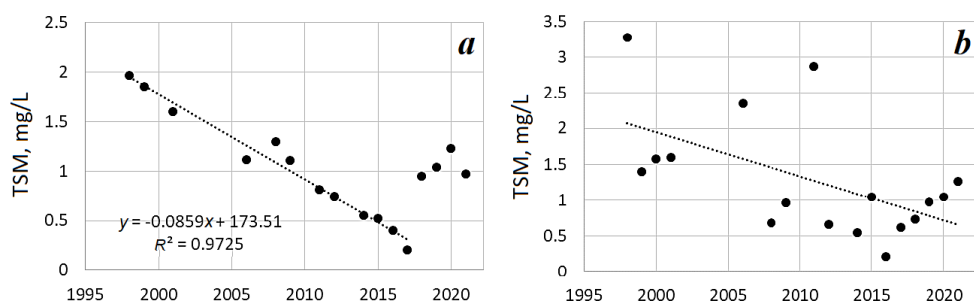


Fig. 4. TSM content in the upper (a) and lower (b) layers of water in September during 1998–2021 near Cape Kosa Severnaya

Model studies

With the available data on the hydrochemical state of waters near Cape Kosa Severnaya, it is impossible to carry out a detailed calculation of the dynamics of phytocenoses biomass throughout the entire period. Therefore, we chose the most data-rich period from May 1998 to February 2002 for our experiments. With a discreteness of one month, the data were interpolated at gaps. The time step of the model was 24 h. In addition to hydrochemical parameters, the model control variables were water temperature in the 0–10 m layer and average daily solar radiation intensity at the sea surface (Fig. 5, *a – c*).

Fig. 5, *d* shows simulation results (at a depth of 4 m) with input variable series. At the beginning of the analyzed period, the content of TSM in the upper layer was

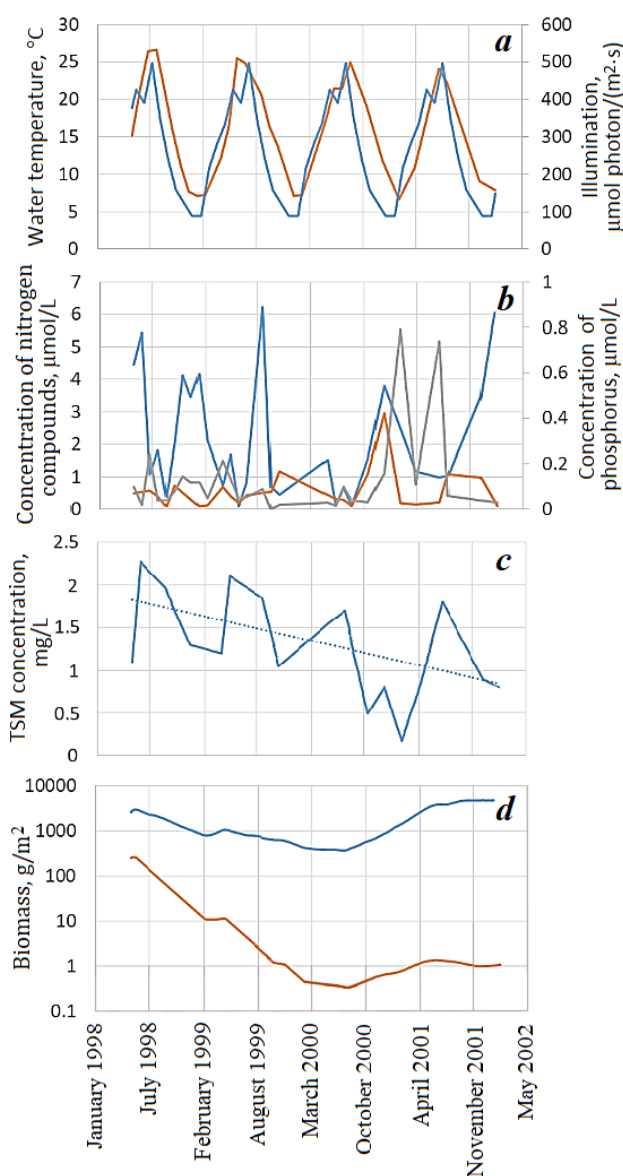


Fig. 5. External conditions of the model and results of model calculations for 4 years in Cape Kosa Severnaya: *a* – water temperature (red line) and illumination of the sea surface (blue line); *b* – concentrations of ammonium compounds (blue line), nitrites and nitrates (red line) and phosphorus (grey line) in water; *c* – TSM concentration (solid line) and trend line (dotted line); *d* – biomass of *Ericaria crinita*, *Gongolaria barbata* (blue line) and *Phyllophora crispa* (red line)

1.5 mg/L or more. With such water turbidity, *Phyllophora crispa* could grow at depths of no more than 4 m. We see that as a result of a slight decrease in the amount of suspended matter, the *Ericaria-Gongolaria* phytocenosis was restored and *Phyllophora crispa* almost completely disappeared over four years of model calculation. According to observations, the *Phyllophora* phytocenosis had begun to recover at depths of 10–15 m by 2017, although in 2017 its biomass reached a value 10 times less than that recorded at the beginning of the observation period. It is safe to assume that the restoration was possible due to the water quality improvement. The concentration of TSM in the warm period of the year has a negative trend (Fig. 4, *a*).

Of interest is the analysis of the variability of model functions reflecting the relative content of nitrogen and phosphorus in the tissues of macroalgae (Fig. 6):

$$f(Q_N) = \frac{Q_N - Q_N^{\min}}{Q_N^{\max} - Q_N^{\min}}, \quad f(Q_P) = \frac{Q_P - Q_P^{\min}}{Q_P^{\max} - Q_P^{\min}}, \quad (5)$$

where Q_P and Q_N , $\mu\text{mol/g}$, are concentrations of phosphorus and nitrogen in alga tissues; Q_P^{\min} , Q_P^{\max} , Q_N^{\min} , Q_N^{\max} , $\mu\text{mol/g}$, are minimum and maximum concentration values (species-specific characteristics of algae). According to the model equations [22], the level of reserves of inorganic nitrogen and phosphorus compounds in algae cells influences the rate of assimilation of biogenic compounds from sea water and the rate of photosynthesis. Thus, functions (5) limit the macroalgae growth. Fig. 6 shows that the limiting effect of nitrogen and phosphorus was manifested alternately over four years of the model time, but phosphorus was the limiting element for macrophytobenthos for most of the time.

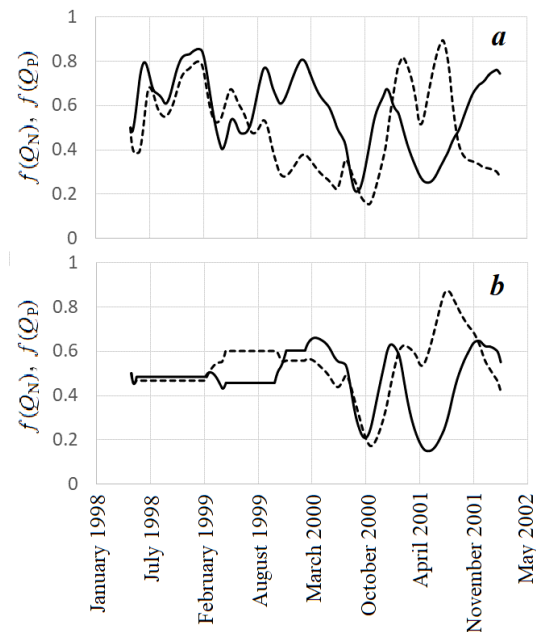


Fig. 6. Temporal variability of functions $f(Q_N)$ (solid line) and $f(Q_P)$ (dashed line) limiting the growth of *Ericaria crinita*, *Gongolaria barbata* (*a*) and *Phyllophora crispa* (*b*) near Cape Kosa Severnaya

Conclusion

Significant changes in the biomass of phytocenosis of the Black Sea dominant species were identified. These changes manifest themselves differently depending on the depth of bottom vegetation growth. In the *Ericaria-Gongolaria* phytoce-
nosis occupying shallow waters with depths of up to 5 m, by 2006 there had been an increase in the biomass of *Ericaria crinita* and *Gongolaria barbata* character-
ized by an increase in the proportion of epiphytes from 5 to 50 %. In 2017, a re-
covery of dominant species was observed while the total biomass increased almost
threefold. At the same time, species of bottom vegetation growing deeper than 5 m
underwent catastrophic degradation. The *Erikaria-Gongolaria-Phyllophora* phyto-
cenosis located at depths of 5–10 m had completely disappeared by 2006, and *Dic-
tyota* spp. took its place in 2017. The *Phyllophora* phytoce-
nosis located at depths
over 10 m degraded significantly in 1997, and its biomass decreased almost to zero.
In 2006, *Phyllophora crispa* was not recorded at these depths. However, separate
areas of the bottom where *Phyllophora crispa* was present, with biomass an order
of magnitude lower compared to that in 1964, had appeared by 2017.

Having analyzed the changes in the hydrochemical regime for 1998–2021, we
came to the conclusion that the recorded transformations of benthic communities
were caused mainly by changes in water transparency associated with the TSM
content. Hydrochemical indicators of water quality varied during the period under
review, but no noticeable trends in changes in the concentrations of biogenic com-
pounds were identified. In 1998–2017, water transparency increased in the summer
period (August–September), but an increase in water turbidity was recorded again
in 2018–2021. The processes of restoration of the biomass of *Phyllophora crispa*
at depths greater than 10 m can stop with further reduction in transparency, which
will lead to the disappearance of this macroalga in the area under study with con-
servation value. The analysis of model functions characterizing the influence
of the concentration of inorganic nitrogen and phosphorus compounds in water
on the growth of macroalgae showed that the growth of macroalgae was alternately
limited by nitrogen and phosphorus inorganic compounds.

To organize monitoring studies of the transformation of bottom phytoceno-
sis, it is advisable to conduct regularly hydrobotanical surveys in combination
with hydrochemical and hydrophysical studies of the coastal zone at intervals of
several years.

REFERENCES

1. Zharikov, V., Bazarov, K. and Egidarev, E., 2017. Use of Remotely Sensed Data
in Mapping Underwater Landscapes of Srednyaya Bay (Peter the Great Gulf,
Sea of Japan). *Geography and Natural Resources*, 38(2), pp. 188–195.
<https://doi.org/10.1134/S187537281702010X>
2. Petrov, K.M., 1989. [*Subaquatic Landscapes: Theory, Research Methods*]. Leningrad:
Nauka, 124 p. (in Russian).
3. Mitina, N.N., 2005. [*Geoecological Studies of Marine Shallow-Water Landscapes*].
Moscow: Nauka, 197 p. (in Russian).
4. Pankeeva, T.V., Milchakova, N.A., Mironova, N.V., Aleksandrov, V.V., Kashirina, E.S.,
Kovardakov, S.A. and Ryabogina, V.G., 2014. [Landscape Approach to Assessment of

- Macrophytobenthos Condition Under Conflict Nature Management]. In: MHI, 2014. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 29, pp. 70–79 (in Russian).
5. Pankeeva, T.V., Mironyuk, O.A. and Pankeeva, A.Ur., 2014. Researches of Bottom Landscapes of the Coastal Zone Tarkhankut Peninsula (Crimea, Black sea). *Geopolitics and Ecogeodynamics of Regions*, 10(1), pp. 800–805 (in Russian).
 6. Agarkova-Lyakh, I.V. and Skrebets, G.N., 2009. Landscapes of the Black Sea Coastal Zone. In: E. A. Pozachenyuk, ed., 2009. *Modern Landscapes of the Crimea and Adjacent Water Areas*. Simferopol: Business-Inform, pp. 250–279 (in Russian).
 7. Mitina, N.N. and Chuprina, E.V., 2012. *Subaquatic Landscapes of the Black and Azov Seas: Structure, Hydroecology, Protection*. Moscow: FGUP “Tipogryfya” Rossel'hoz-akademii, 320 p. (in Russian).
 8. Tamaychuk, A.N., 2009. Landscapes of the Black Sea. In: E. A. Pozachenyuk, ed., 2009. *Modern Landscapes of the Crimea and Adjacent Water Areas*. Simferopol: Business-Inform, pp. 497–529 (in Russian).
 9. Tamaychuk, A.N., 2017. The Space Heterogeneity of Natural Conditions and the Division of the Black Sea. *Proceedings of the Russian Geographical Society*, 149(2), pp. 30–50 (in Russian).
 10. Pasyukova, L.A., 2008. Landscapes of Continental Slope of the Black Sea: Principles of It's Single Out and Description. *Scientific Notes of Tavrida National V.I. Vernadsky University. Geography*, 21(3), pp. 266–273 (in Russian).
 11. Pasyukova, L.A., 2010. [The Problem of Sustainability of Underwater Landscapes in the Yalta Bay Area]. *Scientific Notes of Tavrida National V.I. Vernadsky University. Geography*, 23(3), pp. 331–333 (in Russian).
 12. Pozachenjuk, E. and Penno, M., 2013. To the Substantiation of Highlighting the Marine Anthropogenic Landscapes. In: VSPU, 2013. *Scientific Notes of Vinnytsya State Pedagogical University Named After Michailo Kotzubynsky. Series: Geography*. Vinnytsa. Iss. 25, pp. 142–148 (in Russian).
 13. Bondarev, I.P., 2008. The Problem of Instability of the Underwater Landscape (on the Example of Northern Part of the Black Sea). *Scientific Notes of Tavrida National V.I. Vernadsky University. Geography*, 21(2), pp. 128–133 (in Russian).
 14. Dar, N., Pandit, A. and Ganai, B., 2014. Factors Affecting the Distribution Patterns of Aquatic Macrophytes. *Limnological Review*, 14(2), pp. 75–89. <https://doi.org/10.2478/limre-2014-0008>
 15. Teubner, K., Teubner, I.E., Pall, K., Tolotti, M., Kabas, W., Drexler, S.-S., Waidbacher, H. and Dokulil, M.T., 2022. Macrophyte Habitat Architecture and Benthic-Pelagic Coupling: Photic Habitat Demand to Build Up Large P Storage Capacity and Bio-Surface by Underwater Vegetation. *Frontiers in Environmental Science*, 10, pp. 1–20. <https://doi.org/10.3389/fenvs.2022.901924>
 16. Vila-Costa, M., Pulido, C., Chappuis, E., Calviño, A., Casamayor, E.O. and Gacia, E., 2015. Macrophyte Landscape Modulates Lake Ecosystem-Level Nitrogen Losses Through Tightly Coupled Plant-Microbe Interactions. *Limnology and Oceanography*, 61(1), pp. 1–11. <https://doi.org/10.1002/lno.10209>
 17. Kalra, T., Ganju, N. and Testa, J., 2020. Development of a Submerged Aquatic Vegetation Growth Model in the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST v 3.4) Model. *Geoscientific Model Development*, 13(11), pp. 5211–5228. <https://doi.org/10.5194/gmd-13-5211-2020>

18. Pankeeva, T.V. and Mironova, N.V., 2022. Long-term Dynamics of Underwater Landscapes of the Coastal Zone Cape Kosa Severnaya – Cape Tolsty (Sevastopol). *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 70–85. <https://doi.org/10.22449/2413-5577-2022-2-70-85>
19. Pankeeva, T.V. and Mironova, N.V., 2023. Spatio-Temporal Changes of Macrophyto-benthos in Coastal Landscapes at Cape Kosa Severnaya (Sevastopol). *Theoretical and Applied Ecology*, (2), pp. 66–72. <https://doi.org/10.25750/1995-4301-2023-2-066-072> (in Russian).
20. Vasechkina, E.F. and Filippova, T.A., 2020. Simulation of Bottom Phytocenosis in the Crimean Coastal Zone. *Physical Oceanography*, 27(3), pp. 317–334. <https://doi.org/10.22449/1573-160X-2020-3-317-334>
21. Filippova, T.A. and Vasechkina, E.F., 2022. Simulation of Chemical and Biological Processes of Seagrass Growth. *Physical Oceanography*, 29(6), pp. 674–687. <https://doi.org/10.22449/1573-160X-2022-6-674-687>
22. Vasechkina, E.F. and Filippova, T.A., 2019. Modeling of the Biochemical Processes in the Benthic Phytocenosis of the Coastal Zone. *Physical Oceanography*, 26(1), pp. 47–62. <https://doi.org/10.22449/1573-160X-2019-1-47-62>

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Aleksandr A. Latushkin – expeditionary hydro-optical studies, data processing and analysis

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