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Article

Long-term changes in the composition and structure of the pseudolittoral macrophytobenthos in the intense eutrophication environment of the Southern Coast of Crimea (Black Sea)

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Abstract. As a result of monitoring studies in 1991–2022, carried out in the marine pseudolittoral (PSL) of one of the recreational and tourist centers of the Southern Coast of Crimea (SCC), it was established that the summer plant communities of macrophytobenthos differed in composition and structure from year to year. It was shown that this is due to changes in the level of eutrophication of the coastal marine water area by wastewater, the amount of which and extent of pollution from which depend on the number of tourists and the damage to the sewage treatment plants (STP). In the 1990s, during a threefold decrease in the number of tourists, communities of mesosaprobic brackish-water-marine representatives of Chlorophyta, typical of moderately eutrophic waters, were replaced by polydominant communities formed mainly by oligosaprobic marine representatives of Rhodophyta. As a result, the composition of the flora and the nature of the vegetation cover of the PSL came as close as possible to those characteristic of the natural or slightly transformed water areas of the Southern Coast of Crimea.

Keywords: monitoring, macrophyte algae, eutrophication, species composition, biomass, ecological-floristic groups

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Научная статья

Многолетние изменения состава и структуры псевдолиторального макрофитобентоса в условиях интенсивного эвтрофирования у Южного берега Крыма (Черное море)

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Аннотация. В результате мониторинговых исследований 1991–2022 гг., выполненных в морской псевдолиторали (ПСЛ) одного из рекреационно-туристических центров Южного берега Крыма (ЮБК), установлено, что летние растительные сообщества макрофитобентоса в разные годы отличались составом и структурой. Показано, что это обусловлено изменением уровня эвтрофирования прибрежно-морской акватории сточными водами, объем и степень загрязнения которых зависят от количества рекреантов и износа канализационных очистных сооружений (КОС). В 1990-х гг. на фоне трехкратного снижения числа рекреантов на смену сообществам мезосапробных солоноватоводно-морских представителей Chlorophyta, характерным для умеренно эвтрофированных вод, пришли полидоминантные сообщества, сформированные преимущественно олигосапробными морскими представителями Rhodophyta. В результате состав флоры и характер растительного покрова ПСЛ максимально приблизились к характерным для естественных и слабо трансформированных акваторий ЮБК. Двукратный рост числа рекреантов в конце 2000-х гг. в совокупности с прогрессирующим износом КОС обусловили смену растительного покрова ПСЛ, который с тех пор и доныне формируют моно- и олигодоминантные сообщества преимущественно полисапробных солоноватоводных космополитных представителей Chlorophyta. Сокращение объемов и качественная очистка сточных вод, поступающих в прибрежную акваторию, может способствовать восстановлению сообществ, типичных для южнобережной ПСЛ.

Ключевые слова: мониторинг, водоросли-макрофиты, эвтрофикация, видовой состав, биомасса, эколого-флористические группировки

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Introduction

The Southern Coast of Crimea (SCC) is a physical-geographical region stretching across the extreme south of the Crimean Peninsula from Cape Fiolent in the west to Cape Ilya in the east (Ena, 1983). It stands out from the rest due to the diversity of natural and climatic conditions that determine the richness of the phytobiota, which fully applies to the adjacent coastal waters of the eponymous hydrobotanical region of the Black Sea (Kalugina-Gutnik, 1975; Minicheva et al., 2014). On the other hand, traditional recreational and tourist use determines a high degree of urbanization and the presence of developed infrastructure. More than 70% of the total length of the coastline has been transformed and now consists mainly of artificial beaches, and the already high population density (235.5 people/km²) increases several times in the summer (Soveremennye landshafty..., 2009). The sewage treatment facilities (STP) of the South Coast of Crimea were originally designed as a system for deep-water discharge of treated wastewater. Their original capacity has since been exceeded, the outdated collectors are in a state of emergency, and more than half of the total volume of wastewater now entering the sea is untreated or insufficiently treated (Pupyrev, 2015). Therefore, one of the most acute problems of the SCC is the long-term eutrophication of coastal sea waters, which is highest near the emergency collectors.

In coastal areas the primary producers, the main consumers of organic matter, are macrophyte algae. They form one of the key links in the homeostasis system of coastal ecosystems and, at the same time, the most important factor in the self-purification processes of sea waters (Egorov et al., 2021). The macrophytobenthos responds to an increase in the trophic level of the environment by adaptively restructuring the composition and structure of communities, while changes in biomass and, accordingly, the functional (including purification) role of some species are compensated by opposite changes in other species (Kovardakov and Firsov, 2008; Minicheva, 1998; Minicheva et al., 2013; etc.). Therefore, the composition and structure of macrophytobenthos communities are important indicators of the state of the coastal ecosystem, and their dynamics (up to a certain limit, beyond which vegetation degradation inevitably occurs) reflects the intensity and direction of the changes taking place. However, there have been relatively few studies of this subject on the South Coast of Crimea (Evstigneeva and Tankovskaya, 2020a, b; Maslov, 1988, 1992). Stationary observations are of particular interest. Therefore, in 1991, a hydrobotanical station was established in Gurzuf, a popular center of seasonal tourism in the SCC, to monitor the macrophytobenthos of the pseudolittoral zone.

The purpose of this work is to characterize long-term changes and the current state of the composition and structure of pseudolittoral macrophytobenthos under conditions of local chronic eutrophication based on hydrobotanical studies in the coastal marine waters of Gurzuf.

Objects and methods of research

The monitoring hydrobotanical station (coordinates N 44°31'41.7" E 34°16'23.8") is located within the boundaries of Gurzuf on a stretch of the coastal zone, including the postponed construction of a recreational complex and the Vodokanal Wastewater Treatment Plant. Concrete walls holding back a relatively gentle landslide bank, are bordered by a narrow boulder beach. In the benthal from the waterline and down to a depth of 5–6 m, the bottom soil is a block and block-boulder heap – a product of the destruction of the original bank with an admixture of concrete structures and their fragments (Fig. 1). The STP plant, commissioned in 1973, has a short and shallow underwater outlet ending approximately one kilometer from the shore at a depth of less than 40 m. The volume of wastewater entering the treatment facility is 3.5–7.0 thous. m³/day and is predominantly of domestic origin (housing,



Fig. 1. Location of the hydrobotanical station (N 44°31'41.7" E 34°16'23.8") and general view of the surveyed area of the coastal zone (Gurzuf, Southern Coast of Crimea).

catering, accommodation and recreational services), and therefore, in accordance with the seasonal recreational and tourist load, is at its maximum in the summer. Having been designed according to the 1960s threshold limit values, the STP does not comply with modern standards and is 98% worn out, and the damaged collector regularly produces large-scale emergency emissions along its entire length (Gruzinov et al., 2018; Pupyrev, 2015).

The studies were conducted in the pseudolittoral (PSL) part of the benthic zone, the existence of which in the non-tidal Black Sea, unlike the true tidal littoral, is due to non-periodic (wind and baric) fluctuations in the level (Arnoldi, 1948), reaching 0.40–0.60 m (\pm 0.20–0.30 m above and below the mean water level) on the South Coast of Crimea (Belich et al., 2018; 2019, etc.).

The object of the study is benthic macrophytes. In 1991–1992, in order to more fully identify the species composition and structure of communities, the material was collected seasonally, and in the following years of 1997, 1998, 2010, 2020 and 2022 – in the summer. Summer was chosen as the optimal season for long-term observations, since at this time there are no strong storms that can damage or even destroy the vegetation of the PSL, which could make the comparison of the obtained data be incorrect or even impossible. Quantitative samples were collected using a 0.10×0.10 m frame with ten replicates, according to the generally accepted method (Kalugina-Gutnik, 1975), modified in accordance with the specifics of the PSL (Belich, 1993). The nomenclature within the phyla Chlorophyta, Ochrophyta, Rhodophyta follows "AlgaeBase"¹ the names of the authors of taxa are in standard abbreviations in accordance with the recommendations of IPNI². Where necessary, additional combinations are given (in brackets) according to the identifier (Zinova, 1967), which is used as a basic guide for identifying species. Ecological and floristic characteristics of algae follow Kalugina-Gutnik (1975), saprobiological and halobitic characteristics follow the unpublished data of A.A. Kalugina-Gutnik and T.I. Eremenko. For each species separately, the wet weight was determined, the results were recalculated per m², then the average biomass value was calculated $\bar{x} \pm S$ (BM). Dominant species were identified taking into account BM. The projective cover (PC) was determined visually. The Jaccard similarity index (JSI) was calculated according to Schmidt (1984). Using the same methods facilitates reliable comparison of the results obtained over the entire observation period (1991–2022).

¹ AlgaeBase, World-wide electronic publication, National University of Ireland, Ireland. Web page. URL: <http://www.algaebase.org> (accessed: 22.05.2023).

² The International Plant Names Index (IPNI), 2019. Web page. URL: <http://www.ipni.org> (accessed: 22.05.2023).

Results and discussion

At the monitoring station, the PSL vegetation on a hard substrate forms a belt up to 0.50 m (\pm 0.25 m) wide, not divided into tiers and subzones. At the initial stage of the study (1991–1992), the seasonal dynamics of the composition and structure of the microphytobenthos of PSL were examined (Belich, 2002). During this period, 42 species³, were recorded, with their number (NS) varying from 14 in summer to 24 in winter. There was a seasonal change of dominants, leading to a series of communities that cyclically replaced each other, usually characterized by mosaicism and polydominance. BM in them fluctuated from 0.5–0.7 kg/m² at PC 50% in the autumn-winter period to more than 2 kg/m² at PC up to 90–100% in the spring. In spring, *Ulva intestinalis*⁴, dominated on coastal boulders, resulting in Chlorophyta accounting for over 90% of total BM of macrophytes. In summer and autumn, along with *U. intestinalis*, the dominant species included *Ceramium ciliatum*, *Dictyota fasciola*, *Lophosiphonia obscura*, and some species of the genus *Cladophora* Kütz. By the end of summer – in the first half of autumn, under the influence of insolation, most of the thalli of *U. intestinalis* and *C. ciliatum* became discolored and inviable. In winter, *Scytosiphon lomentaria*, *Ceramium virgatum* and *Cladophora albida* became dominant. Due to the low height of the vegetation cover, rarely exceeding 5–7 cm, the tiering in PSL communities was not expressed. During wind or baric drops in water level, the thalli of relatively large-sized species (*U. intestinalis*, *Scytosiphon lomentaria*, etc.) were exposed and lay on the substrate. It is noteworthy that strong storms observed from autumn to spring often damaged, and in winter in some places completely removed, the vegetation in PSL.

During long-term observations (1991–2022), 39 species of macroalgae were recorded in seasonal summer PSL communities (Table 1), which in different years, with a stable PC value of 75–80%, formed plant communities that differed in species composition, CB, BM, and the ratio of ecological-floristic groups.

In 1991, the community *Cladophora sericea* + *Ceramium ciliatum* + *Ulva intestinalis* was registered, and in 1992, the community *Cladophora vadorum* + *Cladophora sericea* + *Cladophora albida* + *Ulva intestinalis*. With the same NS of 15 units, the species composition changed, but the JSI between communities was quite high – 0.76 (Table 2). In addition, the species (including dominants) were similar in aspect and in terms of a set of ecological and floristic indicators, which determined the structural similarity of these two communities. In them, short-vegetation (annual and seasonal) marine (60%) warm-water (60%) representatives of Rhodophyta, mainly related to oligosaprobies (53–60%), prevailed in NS (Table 3). Although the total BM of the community in 1992 was significantly higher, the ratios of ecological-floristic groups by BM in both years were similar. Brackish-marine cold-water (50% each) annual Chlorophyta (70% each), mainly related to mesosaprobies (> 50%), dominated (Table 4).

In 1997, the community *Ceramium ciliatum* + *Lophosiphonia obscura* + *Dictyota fasciola* + *Ulva intestinalis* was recorded, and in 1998, the community *Ceramium ciliatum* + *Dictyota fasciola* + *Cladophora albida*. At NS 14 and 18, respectively, the JSI between them was only 0.39 (Table 2), but the ratio of eco-floristic groups was similar. According to N, short-vegetating oligosaprobic (64–50%) warm-water (57–61%) marine (57–56%) representatives of Rhodophyta (43–50%) prevailed (Table 3). The total BM of the communities in 1997 and 1998 were identical; the ratios of eco-floristic groups were also close. The BM of the communities was mainly (> 50%) formed by oligosaprobic seasonal summer warm-water Rhodophyta belonging to the marine group (Table 4).

In 2010 and 2020, a monodominant community of *Ulva intestinalis* was recorded, and in 2022, an oligodominant community of *Ulva intestinalis* + *Cladophora albida*. At NS 14 and 20, respectively, the JSI with communities of previous years varied from 0.26 to 0.45 (Table 2). In terms of N, the ratio of ecological-floristic groups differed little from that in previous years: with some variations, short-growing (70–100%) marine and brackish-water-marine (up to 55 and 57%), predominantly warm-water (up to 45%) representatives of Rhodophyta and Chlorophyta (up to 50 and 40%), related to oligo- and mesosaprobies (up to 50 and 43%) predominated (Table 3). Compared to 2010 and 2020, by 2022 the BM community has significantly decreased. However, the ratio of ecological-floristic groups by BM remains stable in these years and at the same time differs sharply from what was recorded in the previous period. Short-vegetation (up to 91%) brackish-water (up to 82%) cosmopolitan (up to 82%)

³ Previously, 45 species of macrophytes were indicated (Belich, 2002), now the number of species has been adjusted in accordance with modern nomenclature and taxonomic changes (AlgaeBase).

⁴ Complete nomenclature combinations are given below (Table 1).

Table 1. List of species and biomass (g/m²) of macrophyte algae in seasonal summer communities of PSL coastal marine waters of hydrobotanical station in Gurzuf (1991–2022). Dash indicates absence of species in samples, m – less than 0.01 g in sample, error of mean (\pm S) is given for cases when variation coefficient $v < 100\%$.

Species	Period of study (sample collection date)						
	1991 (28.08)	1992 (01.08)	1997 (27.08)	1998 (22.07)	2010 (12.07)	2020 (25.07)	2022 (03.08)
CHLOROPHYTA							
<i>Cladophopsis membranacea</i> (Bang ex C. Agardh) Børgesen, 1905	–	–	–	–	–	–	66.5
<i>Chaetomorpha aerea</i> (Dillwyn) Kütz., 1849	1.13	115.93	7.50	2.50	–	6.50	8.4
<i>Cladophora albida</i> (Nees) Kütz., 1843 [<i>Cladophora albida</i> (Huds.) Kütz.]	94.07	189.33	2.00	175.10	9.8	20.70	139.20
<i>Cladophora sericea</i> (Huds.) Kütz., 1843	422.50	240.87	m	–	1.0	23.40	13.3
<i>Cladophora vadorum</i> (Aresch.) Kütz., 1849	–	469.80	–	–	–	–	–
<i>Rhizoclonium riparium</i> (Roth) Harv., 1849 [<i>Rhizoclonium implexum</i> (Dillwyn) Kütz.]	–	–	–	–	m	m	9.50
<i>Ullothrix implexa</i> (Kütz.) Kütz., 1849	–	–	–	–	–	–	5.5
<i>Ulva intestinalis</i> L., 1753 [<i>Enteromorpha intestinalis</i> (L.) Link nom. illeg.?]]	136.15 \pm 41.10	161.4	128.60 \pm 118.16	114.60	698.5 \pm 611.33	672.55 \pm 308.09	235.90
<i>Ulva kyllinii</i> (Bliding) H.S. Hayden, Blomster, Maggs, P.C. Silva, Stanhope & Waaland, 2003 [<i>Enteromorpha kyllinii</i> Bliding]	–	–	–	–	–	20.20	10.5
<i>Ulva rigida</i> C. Agardh, 1823	–	5.00	–	3.20	–	46.60	–
<i>Ulvella viridis</i> (Reinke) R. Nielsen, O'Kelly & B. Wyvor, 2013 [<i>Entocladia viridis</i> Reinke]	–	–	–	–	m	–	–
OCHROPHYTA							
<i>Dictyota fasciola</i> (Roth) J.V. Lamour., 1809 [<i>Dilophus fasciola</i> (Roth) M. Howe]	50.20	57.00	274.50	243.60	–	3.00	M
<i>Ectocarpus siliculosus</i> (Dillwyn) Lyngb., 1819 [<i>Ectocarpus confervoides</i> (Roth) Le Jolis]	–	–	–	m	m	–	–

Species	Period of study (sample collection date)						
	1991 (28.08)	1992 (01.08)	1997 (27.08)	1998 (22.07)	2010 (12.07)	2020 (25.07)	2022 (03.08)
<i>Ericaria bosporica</i> (Sauv.) D. Serio et G. Furnari, 2021 [<i>Cystoseira bosporica</i> Sauv.]	–	–	9.20	3.00	–	1.5	–
<i>Feldmannia irregularis</i> (Kütz.) Hamel, 1939 [<i>Ectocarpus arabicus</i> Fig. et De Not.]	–	–	m	–	–	–	–
<i>Padina pavonica</i> (L.) Thivy, 1960 [<i>Padina pavonia</i> (L.) Gaill. nom. illeg. ?]	24.53	–	–	–	–	m	0.6
<i>Scytosiphon lomentaria</i> (Lyngb.) Link, nom. cons., 1833 [<i>Scytosiphon lomentaria</i> (Lyngb.) J. Agardh]	–	–	–	2.00	7.5	0.5	–
<i>Sphaecelaria cirrosa</i> (Roth) C. Agardh, 1824	m	0.27	m	m	–	m	m
RHODOPHYTA							
<i>Bonnemaisonia hamifera</i> Har., 1891	–	–	–	–	–	m	m
<i>Callithamnion corymbosum</i> (Sm.) Lyngb., 1819	–	–	–	41.50	–	–	1.8
<i>Carradoriella denudata</i> (Dillwyn) Savoie et G.W. Saunders, 2019 [<i>Polysiphonia denudata</i> (Dillwyn) Kütz., nom. illeg. ?]	0.36	148.67	8.00	149.50	7.4	–	–
<i>Ceramium ciliatum</i> (J. Ellis) Ducluz., 1806	138.98	143.33	536.30	594.50	123.0	5.50	4.6
<i>Ceramium diaphanum</i> (Lightf.) Roth, 1806	–	–	–	–	114.0	–	1.6
<i>Ceramium siliquosum</i> var. <i>elegans</i> (Roth) G. Furnari, 1999 [<i>Ceramium elegans</i> Ducl.]	–	–	–	–	–	m	–
<i>Ceramium virgatum</i> Roth, 1797 [<i>Ceramium pedicellatum</i> (Duby) J. Agardh nom. illeg. ?; <i>Ceramium rubrum</i> (Huds.) C. Agardh nom. illeg. ?]	1.43	–	–	53.60	4.0	–	17.9

Species	Period of study (sample collection date)						
	1991 (28.08)	1992 (01.08)	1997 (27.08)	1998 (22.07)	2010 (12.07)	2020 (25.07)	2022 (03.08)
<i>Chondria capillaris</i> (Huds.) M.J. Wynne, 1991 [<i>Chondria tenuissima</i> (Gooden. et Woodw.) C. Agardh]	17.50	1.00	–	1.60	–	–	–
<i>Colaconema daviesii</i> (Dillwyn) Stegenga, 1985 [<i>Acrochaetium daviesii</i> (Dillwyn) Nägeli]	–	–	–	–	m	–	–
<i>Laurencia coronopus</i> J. Agardh, 1852	–	–	23.40	–	–	2.5	–
<i>Laurencia pyramidalis</i> Bory ex Kütz., 1849 [<i>Laurencia obtusa</i> var. <i>pyramidalis</i> Bory ex J. Agardh].	–	–	–	–	–	–	3.6
<i>Lophosiphonia obscura</i> (C. Agardh) Falkenb., 1897	3.50	3.67	383.00	3.00	27.2	–	6.1
<i>Jania virgata</i> (Zanardini) Mont., 1846 [<i>Coralina granifera</i> J. Ellis et Soland.]	31.43	66.0	–	15.5	–	–	–
<i>Nemalion elminthoides</i> (Velley) Batters, 1902	–	–	–	–	–	18.20	–
<i>Osmundea pinnatifida</i> (Huds.) Stackh., 1809 [<i>Laurencia pinnatifida</i> (S.G. Gmel.) J.V. Lamour. nom. illeg. ?]	–	–	–	1.00	–	–	–
<i>Palisada perforata</i> (Bory) K.W. Nam, 2007 [<i>Laurencia papillosa</i> (Forsk.) Grev. nom. illeg. ?]	2.00	3.33	–	126.50	–	–	–
<i>Palisada thuyoides</i> (Kütz.) Cassano, Senties, Gil-Rodríguez et M.T. Fujii, 2009 [<i>Laurencia paniculata</i> J. Agardh]	–	–	157.50	–	–	–	–
<i>Pneophyllum confervicola</i> (Kütz.) Y.M. Chamb., 1983 [<i>Melobesia minutula</i> Foslie]	m	m	m	–	m	–	m
<i>Pterothamnion plumula</i> (J. Ellis) Nägeli, 1855 [<i>Antithamnion plumula</i> (J. Ellis) Thur.]	–	–	–	–	–	0.5	m
<i>Rhodochorton purpureum</i> (Lightf.) Rosenv., 1900	–	–	–	–	–	m	–
<i>Vertebrata subulifera</i> (C. Agardh) Kuntze, 1891 [<i>Polysiphonia subulifera</i> (C. Agardh) Harv.]	–	–	–	–	–	m	–

Table 2. Jaccard similarity index (K_j) between seasonal summer communities of macrophyte algae PSL of the coastal marine waters of the hydrobotanical station in Gurzuf (1991–2022).

Year	K_j						
	1991	1992	1997	1998	2010	2020	2022
1991	1	0.76	0.53	0.57	0.38	0.30	0.45
1992		1	0.53	0.38	0.26	0.30	0.35
1997			1	0.39	0.33	0.31	0.36
1998				1	0.33	0.31	0.31
2010					1	0.21	0.36
2020						1	0.43
2022							1

representatives of Chlorophyta (up to 96%), mainly related to polysaprobies (up to 82%), dominate by a large margin (Table 4). This situation is due to the massive (up to 70–80% of the total BM) development of *U. intestinalis*. This is one of the most eurybiontic representatives of the macroalgal flora, widespread in the seas across the globe and withstanding strong freshening and an extremely high level of eutrophication of the ocean.

The analysis of the distribution of NS in ecological-floristic groups in the PSL of the hydrobotanical station produced the following results. Throughout the observation period 1991–2022, Rhodophyta were most important in terms of NS in summer, but since 2010, a slight increase in the role of Chlorophyta has been observed in absolute and proportional terms (Table 3, Fig. 2A). The saprobiological groups by N, are dominated by oligosaprobies (49%), but in total, exactly the same amount is accounted for by meso- and polysaprobies (Table 3). Describing the impact of eutrophication on the algal flora of Novorossiysk Bay, A.A. Kalugina-Gutnik considered such a ratio to be evidence of significant pollution of the water area (Kalugina-Gutnik, 1975). In the PSL station, the ratio of saprobiological groups by NS does not show a clear trend during the observation period, but in 2022, a sharp increase in the proportion of polysaprobies is observed, which reached a quarter of the total NS (Fig. 2C). Such a distribution by saprobiological groups suggests that the level of seawater eutrophication in the water area was initially elevated (i.e., in 1991–1992), and by now it has become even higher.

In total, about half of the total NS is accounted for by the warm-water assemblage, although in recent years its proportion has shown a significant decrease: from 60% to 40–45%. Importantly, this occurred mainly due to those representatives of the cosmopolitan and cold-water phytogeographic groups that simultaneously belong to the poly- and mesosaprobies (Table 3).

In terms of halobity more than half of the total NS is attributed to the marine group, although there has been a steady increase in the number of brackish-water marine species since 1998. By 2022, this had doubled to account for half of the total NS (Table 3).

Long-term observations show that BM of different systematic and ecological groups demonstrate the trends in environmental transformation much more informatively than NS (Belich et al., 2019; Sadogursky, 2014, 2017). In the long-term observation series, there were periods of increase and decrease in BM of seasonal summer communities. The maximum BM values were recorded in polydominant communities in 1992 and in the late 1990s (Table 4). At the beginning of the decade, BM was mainly formed by short-vegetation mesosaprobic cold-water brackish-water-marine representatives of Chlorophyta. By the end of this decade, a turning point was observed: during a twofold increase in the proportion of perennials, the leading positions (with a share of at least 60%) were taken over by oligosaprobic warm-water marine representatives of Rhodophyta. During this period, oligosaprobic *C. ciliatum* and *D. fasciola* became dominant in the community, which is typical for summer vegetation of PSL in coastal waters near the SCC, not subject to intense eutrophication (Belich et al., 2018; Sadogursky, 2009, 2014). Since 2010, a decrease in the total BM of vegetation has been noted; by 2022, its values had decreased to a third of the former maximum values. Although Rhodophyta remain the most widely represented group in N, their BM in communities has decreased to less than a tenth

Table 3. The number of macrophyte species in ecological and floristic groups in seasonal summer communities of the PSL coastal marine waters of the hydrobotanical station of Gurzuf (1991–2022).

Ecological-floristic group	Number of species, units / %							Total in flora
	1991	1992	1997	1998	2010	2020	2022	
Chlorophyta	4 26.67	6 40	4 28.57	4 22.22	5 35.71	7 35.00	8 40.00	14 25.45
Ochrophyta	3 20.00	2 13.33	4 28.57	5 27.78	2 14.29	5 25.00	3 15.00	10 18.18
Rhodophyta	8 53.33	7 46.67	6 42.86	9 50.00	7 50.00	8 40.00	9 45.00	31 56.36
Seasonal summer	3 20.00	2 13.33	3 21.43	2 11.11	1 7.14	5 25.00	4 20.00	7 12.73
Seasonal winter	0 0	0 0	0 0	2 11.11	2 14.28	1 5.00	0 0	5 9.09
Annual	9 60.00	9 60.00	7 50.00	8 44.44	11 78.57	8 40.00	12 60.00	26 47.27
Perennial	3 20.00	4 26.67	4 28.57	6 33.33	0 0	5 25.00	3 15.00	15 27.27
No data	0 0	0 0	0 0	0 0	0 0	1 5.00	1 5.00	2 3.64
Oligosaprobies	9 60.00	8 53.33	9 64.29	9 50.00	5 35.71	10 50.00	8 40.00	27 49.09
Mesosaprobies	4 26.67	6 40.00	4 28.57	6 33.33	6 42.86	8 40.00	6 30.00	20 36.36

Ecological-floristic group	Number of species, units / %										Total in flora
	Period of study										
	1991	1992	1997	1998	2010	2020	2022				
Polysaprobies	2 13.33	1 6.67	1 7.14	3 16.67	3 21.43	1 5.00	5 25.00	7 12.73			
No data	0	0	0	0	0	1	1	1			
Warm-water	9 60.00	9 60.00	8 57.14	11 61.11	4 28.58	9 45.00	8 40.00	26 47.27			
Cold-water	4 26.67	5 33.33	4 28.57	4 22.22	5 35.71	7 35.00	7 35.00	21 38.18			
Cosmopolitan	2 13.33	1 6.67	1 7.14	3 16.67	5 35.71	3 15.00	3 15.00	6 10.91			
Endemic	0	0	1 7.14	0	0	1 5.00	0	1 5.00			
No data	0	0	0	0	0	0	0	1 1.82			
Marine	9 60.00	9 60.00	8 57.14	10 55.56	5 35.71	11 55.00	9 45.00	32 58.18			
Brackish-marine	5 33.33	5 33.33	5 35.71	7 38.89	8 57.14	8 40.00	10 50.00	21 38.18			
Brackish	1 6.67	1 6.67	1 7.14	1 5.56	1 7.14	1 5.00	1 5.00	2 3.64			
Total	15 100	15 100	14 100	18 100	14 100	20 100	20 100	55 100			

Table 4. Biomass of macrophytes in ecological and floristic groups in seasonal summer communities of the PSL coastal marine waters of the hydrobotanical station of Gurzuf (1991–2022).

Ecological-floristic group	Biomass, g/m ² / %									
	1991	1992	1997	1998	2010	2020	2022			
Chlorophyta	653.85	1182.33	138.1	295.4	709.30	789.95	508.80			
	70.78	73.64	9.03	19.30	71.47	96.14	93.36			
Ochrophyta	74.73	57.27	283.7	248.6	7.50	5.00	0.6			
	8.09	3.57	18.54	16.24	0.76	0.61	0.11			
Rhodophyta	195.20	366.00	1108.2	986.7	275.60	26.70	35.6			
	21.13	22.79	72.43	64.46	27.77	3.25	6.53			
Seasonal summer	213.71	200.33	810.8	838.1	123.00	26.70	71.7			
	23.13	12.48	52.99	54.75	12.39	3.25	13.16			
Seasonal winter	0	0	0	2	7.5	0.5	0			
	0	0	0	0.13	0.76	0.06	0			
Annual	676.64	1330.67	529.10	541.4	861.9	743.85	469.7			
	73.25	82.88	34.58	35.37	86.85	90.53	86.18			
Perennial	33.43	74.6	190.1	149.2	0	50.60	3.6			
	3.62	4.64	12.43	9.75	0	6.16	0.66			
No data	0	0	0	0	0	M	M			
	0	0	0	0	0	0	0			
Oligosaprobies	265.77	386.86	1008.4	988.2	130.50	37.20	83.7			
	28.77	24.10	65.90	64.56	13.15	4.53	15.36			
Mesosaprobies	520.43	1057.34	393.00	332.8	45.40	91.70	168.1			
	56.34	65.85	25.69	21.74	4.57	11.16	30.84			

Ecological-floristic group	Biomass, g/m ² / %									
	Period of study									
	1991	1992	1997	1998	2010	2020	2022			
Polysaprobies	137.58	161.40	128.60	209.7	816.50	672.55	282.7			
	14.89	10.05	8.41	13.70	82.28	81.85	51.87			
No data	0	0	0	0	0	20.20	10.5			
	0	0	0	0	0	2.46	1.93			
Warm-water	269.63	543.93	1376.00	1184.4	271.6	81.30	89.6			
	29.19	33.88	89.93	77.38	27.37	9.89	16.44			
Cold-water	516.57	900.27	2.00	178.1	18.3	65.30	168.5			
	55.92	56.07	0.13	11.64	1.84	7.95	30.92			
Cosmopolitar	137.58	161.4	128.60	168.2	702.5	672.55	283.3			
	14.89	10.05	8.41	10.99	70.79	81.85	51.98			
Endemic	0	0	23.40	0	0	2.5	0			
	0	0	1.53	0	0	0.30	0			
No data	0	0	0	0	0	M	3.6			
	0	0	0	0	0	0	0.66			
Marine	268.14	279.6	1383.90	991.9	150.2	97.5	91.9			
	29.03	17.41	90.45	64.80	15.14	11.87	16.86			
Brackish-marine	519.49	1164.6	17.5	424.2	142.70	51.60	197.2			
	56.23	72.53	1.14	27.71	14.38	6.28	36.18			
Brackish	136.15	161.4	128.60	114.6	698.50	672.55	255.9			
	14.74	10.05	8.41	7.49	70.38	81.85	46.96			
		1605.60								
Total	923.78	1605.60	1530.00	1530.7	992.40	821.65	545.00			
	100	100	100	100	100	100	100			

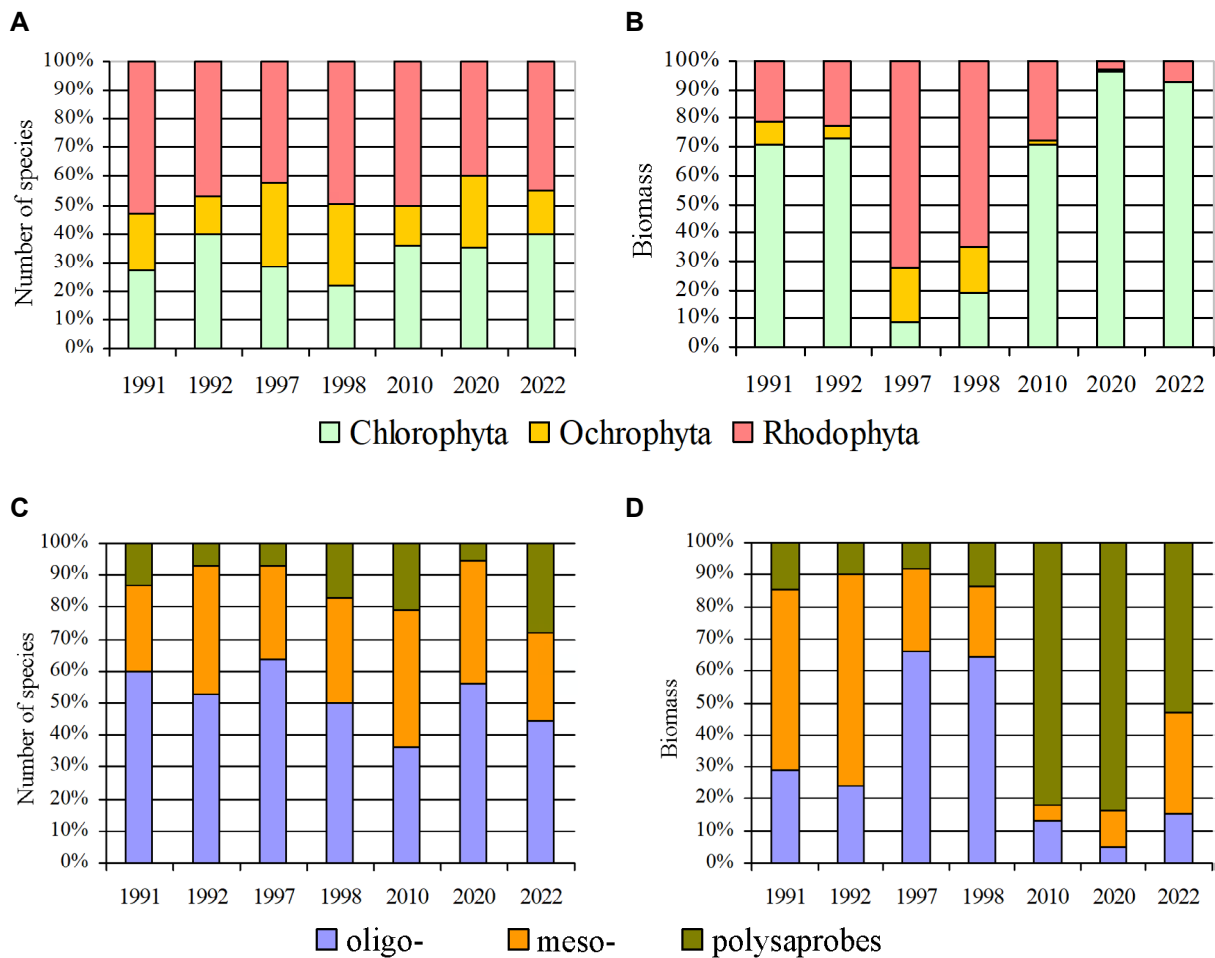


Fig. 2. The ratio of systematic and saprobiological groups of macrophytobenthos in seasonal summer communities of the pseudolittoral of the coastal-marine waters of the hydrobotanical station in Gurzuf (1991–2022): systematic – by the number of species (**A**) and by biomass (**B**); saprobiological – by the number of species (**C**) and by biomass (**D**).

of its former value. Dominance again passes to short-vegetation Chlorophyta, which form mono- and oligodominant communities, but from now on they are dominated by polysaprobic brackish-water cosmopolitans (70–80% BM) (Table 4, Fig. 2B, D).

The nature of the structural and functional organization of the macrophytobenthos of the PSL at the hydrobotanical station indicates that in the early 1990s the water area adjacent to the STP at Gurzuf was characterized by an increased level of eutrophication in the summer season. By the end of the decade, the level of eutrophication had obviously decreased, as a result of which the composition of the flora and the nature of the vegetation cover during this period corresponded as much as possible to those in the natural and slightly transformed water areas of the South Coast of Crimea. Unfortunately, how long it will last and when the next changes will begin, cannot at present be judged with certainty. However, it is obvious that by the end of the 2010s the level of eutrophication had increased so much that the situation had worsened even compared to the early 1990s. From that time until now, the structural and functional organization of the communities of the PSL at the hydrobotanical station indicates a consistently high eutrophication and, probably, local desalination of coastal waters in the summer season.

If the change in the ratio of ecological-floristic groups by NS allowed only some assumptions to be made, then the dynamics of the ratio of ecological-floristic groups by BM gives confidence in the correctness of determining the nature and direction of transformation of the conditions of the aquatic environment.

The source of eutrophication is easy to determine. Considering the location of the station directly in the area of the short shallow emergency collector of the STP, it is logical to assume that the STP discharges are the cause of local intensive eutrophication and desalination. A more difficult task is to assess the dynamics of their influx and, accordingly, changes in the intensity of eutrophication of the coastal marine waters in 1991–2022, as well as to establish a connection with the scale of changes in the vegetation cover of the PSL station. There is no dynamic information, especially for a single collector, in the public domain. On the South Coast of Crimea, the main volume of wastewater is formed by the household activities of the population and tourist facilities, i.e. it is directly linked to the number of holidaymakers. The main influx of tourists also occurs in the summer season (we will consider the number of local population and the intensity of economic activity during the research period and in other seasons of the year to be relatively constant). Statistics show that by 1995 the tourist flow to Crimea (a significant part of which is always concentrated on the Southern Coast of Crimea, including Gurzuf) had decreased to less than a third of its levels at the beginning of the decade (Tourism in Crimea⁵; Federal Service Administration⁶). The load on the infrastructure and the volume of wastewater decreased accordingly, which undoubtedly reduced the trophic level of coastal sea waters near the South Coast of Crimea. The most noticeable reduction should have occurred near the local sources of intense eutrophication, one of which is the Gurzuf STP collector. Obviously, this is what happened. By 1997–1998, the PSL communities of the hydrobotanical station adapted to the decrease in water trophicity, as a result of which their structural and functional organization became the same as in most natural water areas of the region (Belich et al., 2018; Sadogursky, 2009, 2014). A number of researchers note that this period was marked by a period of general recovery of ecosystems off the coast of Crimea and in the Black Sea as a whole (Milchakova, 2003; Minicheva et al., 2008; Zaika et al., 2004). In the 2000s, reverse processes began. By 2009, compared to 1995, the tourist influx had doubled, and therefore so had the volume of wastewater (Tourism in Crimea; Federal Service Administration). It is noteworthy that during the thirty years under discussion, the degree of damage to the Gurzuf STP steadily increased, reaching 98% (Pupyrev, 2015). At the same time, such strong structural and functional changes have occurred in the PSL macrophytobenthos communities that, if the current level of eutrophication is maintained (and even more so if it increases), their degradation is possible. The first signs of this should be considered the development of mono- and oligodominant communities of polysaprobic brackish-water cosmopolitans with low BM in the summer season. As the dynamics of the structural and functional organization of macrophytobenthos observed in the 1990s shows, the situation is reversible. But restoration (probably within 2–3 years) is possible only if the volumes of untreated wastewater entering the coastal waters are reduced.

It would be wrong to assume that mono- and oligodominant communities of meso- and polysaprobic Chlorophyta are not at all typical for the southern coastal PSL. However, they most often develop and are recorded for a relatively short time in the spring (which was noted above in the brief description of seasonal changes), much less often in the autumn, i.e. during transitional periods when some seasonal species (and communities) complete their vegetation, while others have not yet fully developed. Their continuous existence from spring to autumn is clearly associated with excessive eutrophication, since at the same time polydominant communities (unpublished data of the authors), typical of the southern coastal PSL, developed in the adjacent waters (Belich, 2001; Belich et al., 2018; Pogrebnyak and Maslov, 1976). This conclusion is supported by the results of a number of similar studies carried out in other eutrophic coastal areas (Fort et al., 2020; Korpinen et al., 2007, etc.).

In total, 55 species of macrophytes were recorded in the PSL station for the period 1991–2022 (including all seasons of 1991 and 1992): Chlorophyta – 14 (25.45%), Ochrophyta – 10 (18.18%), Rhodophyta – 31 (56.36%) (Table 1). The phylum Rhodophyta is the most widely represented: 3 classes, 10 orders, 11 families, 23 genera. Chlorophyta and Ochrophyta are represented less and equally: one class each, four orders, six families and eight genera. The most numerous genera are *Cladophora* Kütz., *Ulva* L., and *Ceramium* Roth. It should be noted that in the flora of the South Coast of Crimea, and the Black Sea as a whole, there are no species that are found exclusively in the PSL, but there are the most

⁵ Tourism in Crimea. Wikipedia, 2023. Web page. URL: https://ru.wikipedia.org/wiki/%D0%A2%D1%83%D1%80%D0%B8%D0%B7%D0%BC_%D0%B2_%D0%9A%D1%80%D1%8B%D0%BC%D1%83 (accessed: 22.05.2023).

⁶ Office of the Federal State Statistics Service for the Republic of Crimea and the City of Sevastopol (Krymstat). Web page. URL: <https://82.rosstat.gov.ru/> (accessed: 22.05.2023).

characteristic ones that are consistently present in it and form the core of the macroflora. In the case under discussion, these are: *U. intestinalis*, *C. albida*, *C. sericea*, *Ch. aerea*, *L. obscura*, *C. ciliatum*, *D. fasciola*, *Sphacelaria cirrosa*, and *Pneophyllum confervicola*. Due to seasonal fluctuations of BM, some of them periodically enter or are temporarily excluded from the number of dominants, which determines the cyclic change of seasonal PSL communities. At the same time, there are rare species or, to some extent, unusual for the biotope and the region as a whole. In 2000, *Ulva kylinii* was noted for the first time on the South Coast of Crimea and specifically in PSL. Nowadays, the species is recorded more and more often and is already one of the dominants of communities (Table 1) (Belich et al., 2020; Sadogursky et al., 2019a). In 2022, *Laurencia pyramidalis*⁷ was recorded in the PSL of the station. This species was known from the adjacent water area to the west (now within the boundaries of the Mys Martyan Nature Reserve) based on collections from the early 20th century (Chernov, 1929), after which it disappeared from collections for many years, and most recently it was again recorded in the PSL and the shallowest areas of the sublittoral of the South Coast of Crimea, where it is rare and occurs in small numbers (Sadogursky et al., 2019b). This is probably one of the classic examples of "pulsating" elements of the regional flora (Golubev, 2004), while some Black Sea macroalgae have pulsation periods (the reasons for which are not clear) that last for decades (Sadogurskaya et al., 2017). Unlike others, *Bonnemaisonia hamifera* is an alien element of Asian-Pacific origin for the local flora. It is an invasive species that colonized the South Coast of Crimea in 2017 (Sadogursky et al., 2023). In the sublittoral, its mass development changes the structure and appearance of plant communities, which allowed it to be classified as a transformer (Richardson et al., 2000). In PSL, the species occurs only in the form of individual threads, but they are very numerous and in are present all samples without exception.

Further research within the boundaries of the station and in adjacent waters will allow us to clarify information about the dynamics and current state of macrophytobenthos near the Southern Coast of Crimea.

Conclusions

As a result of stationary hydrobotanical observations in the water area subject to local eutrophication, 55 species of macrophyte algae were recorded in the PSL flora for the period 1991–2022 in different seasons: Chlorophyta – 14 (25.45%), Ochrophyta – 10 (18.18%), Rhodophyta – 31 (56.36%). Nine species, constantly present in the PSL flora, form its core. During the monitoring it was established that the summer flora of the PSL hydrobotanical station includes 39 species of macroalgae, which in different years formed plant communities of different composition and structure. It was shown that their structural and functional organization is determined by the level of eutrophication, which depends on the volume and quality of wastewater entering the coastal-marine waters of the surveyed area. By now, due to the increase in recreational load against a background of extreme wear of STP, mono- and oligodominant plant communities formed by polysaprobic brackish-water cosmopolitan representatives of Chlorophyta have developed, which is typical for highly trophic waters. If the level of eutrophication is maintained, and especially if it increases, degradation of macroscopic vegetation of PSL is possible. At the same time, reduction in volumes and high-quality purification of wastewater can contribute to the restoration of communities that correspond in composition and structure to natural and slightly transformed water areas. In this regard, for the surveyed area and for the South Coast of Crimea as a whole, key interventions, in the complex of measures aimed at improving the state of coastal-marine ecosystems, are reconstruction of existing and creation of new modern STP facilities.

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⁷ The species was identified according to E. Taşkin and A. Sukatar (2013).

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