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Article

Epilithic biofilms of the Eastern Caspian (Aktau region, Kazakhstan) under conditions of falling sea level

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Abstract
Communities of microorganisms that form biofilms on the rocky shores of the Middle Caspian are capable of maintaining the integrity of the coastal landscape in the conditions of sea retreat associated with the ongoing drop in sea level since 1995. Algal-bacterial biofilms developing on rocky substrates of the East Caspian coast within the City of Aktau were studied in autumn (October 2022) and spring (April 2023) seasons. Communities in biotopes with different structure were investigated. It has been established that the most stable and diverse communities with a pronounced vertical structure live in the areas with high sheer cliffs on capes. On flat areas of the coast, which have undergone recent shallowing and are protected from surfing waves by ridges of large stones, less diverse cenoses, demonstrating clear spatial organization. In the shallow open areas of the shore, which are subject to intense wave action, live communities of two types were observed. Both cenoses contained a relatively small number of species, but differed in structure and potential for protecting the coast from erosion. The first of them live in biotopes outside the impact of urban domestic sewage, and are able to protect coastal marl from destruction due to the development of stable, rapidly regenerating complex structural elements. The latter were noted in the conditions of along-shore spreading of untreated domestic wastewater from new city developments located close to the coast. Such biofilms were no longer able to protect marls from being destroyed by waves, and took the form of constantly renewed patches with minimum diversity of components and unstable spatial organization.

Key words: Caspian Sea, biofilms, algal-bacterial communities, epilithon, stability of cenoses, coastal degradation, diatoms, cyanoprokariotes.

Introduction

This paper is focused on field investigation and laboratory analysis of algal-bacterial biofilms developing on rocky substrates of the East Caspian coast within the City of Aktau made in October 2022 and April 2023.

The level of the Caspian Sea has been decreasing since 1995 (Ginzburg et al., 2021; Kostianoy et al., 2022; Lavrova et al., 2022). The phenomena associated with the retreat of water from shallow coastal areas have become especially noticeable in the last years, when the annual sea level drops reached 20 to 30 cm (Lavrova et al., 2022) so that coastal bottom landscapes were exposed to drying (Figure 1). The action of waves at the seasonal scale was also modulated. Previously located at depths of 2-2.5 m, these landscapes let the rolling waves pass over them, not being exposed during periods of offshore winds. Now that they are situated at depths of only 15-30 cm, their surfaces are directly affected by non-periodic surge events (Figure 1). During offshore surges, the bottom is exposed and subjected to a complex effect of drying. During onshore surges, especially during strong winds and storms, soils at such shallow depths suffer from the effect of rolling waves.

The region of the city of Aktau (Kazakhstan), located on the eastern coast of the Middle Caspian, is often significantly affected by strong winds and northwestern waves (Rahimi et al., 2022; Kruglova, Myslenkov, 2023). According to recent research, an average wave height in the coastal region of Aktau is of 0.6 m, but maximum waves above 4.5 m have been documented (Kruglova, Myslenkov, 2023). The shores within the city of Aktau are composed of layered marls alternating the layers of soft sandstone and gray prehistoric clay. These soils, not being protected from the direct impact of a rolling wave in the area of newly formed shallow waters, can easily be destroyed by surf, especially in autumn and winter, when storms occur more often (Kruglova, Myslenkov, 2023).

Figure 1. A view of the impact of the wind waves on the newly dry bottom at the shoreline in the center of Aktau on 20 October 2022. Photo by Andrey Kostianoy.

The biofilms, i.e., the thin (often no more than a millimeter thick) film communities of microorganisms protect coastal soil and mitigate the aggressive impact of waves causing erosion of the coast. The main structuring role in such cenoses is played by cyanobacteria and diatoms (Schuster et al., 2019). Due to their special spatial organization, such communities are able to withstand both strong insolation and wave impacts, retain water, and can quickly restore their structure in case of mechanical damage. Having found abundant biofilm developments on the rocky shore of Aktau in autumn (October) of 2022 (Figure 2), we investiated them, noting a number of interesting details.

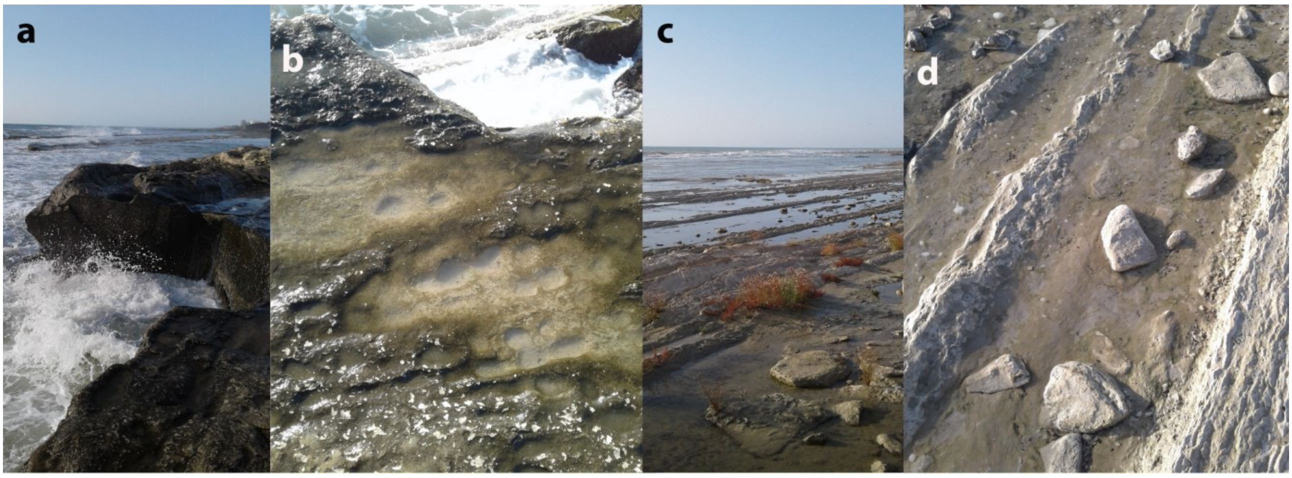

Figure 2. Examples of biotops at the newly dry coast of the Caspian Sea in the City of Aktau: a, b - sheer cliffs irrigated by surf; c, d - folded marl forming flat areas of the pseudolittoral. Photos by Philipp Sapozhnikov.

The biofilms were then re-examined in the same coastal area in spring in April 2023. As a result, we were able to note a number of structural features of these algal-bacterial communities corresponding to high (cape) and flat (lagoonal and open) parts of the coastal areas. Attention was also paid to the severe erosion of the folded coast at the site, where the landfalls of many seeps of untreated sewage from the new cottage quarters, which were significantly closer to the sea, were clearly visible. Here, biofilms could no longer protect the marl surface from the aggressive mechanical impact of the environment.

Data and Methods

The material for this work was biofilm samples collected in the periods of October 16-21, 2022 and April 17-22, 2023. The scheme of sampling in the autumn season, at 6 points in different biotopic locations, is shown in Figure 3. In particular, the following types of biotops were covered by the sampling campaigns: the surfaces of sheer black rocks on the cape (1), the furrows and leaching cauldrons located on them (2), extended puddles of sea water in the upper part of the pseudolittoral from wavy marl (3), narrow channels between low sandstone ridges in its middle part (4), the surface of the marl on the lower pseudolittoral (5) and on the middle part - in the area of seepage of domestic sewage (6).

According to satellite altimetry data, between the autumn and the spring surveys, the Caspian sea level decreased in the Aktau region by 12 cm (Hydroweb, 2023). Chains of stones appeared from the water, outlining the contours of new habitats from the seaward side as shallow lagoons with depths of 15-30 cm, protected by these stone blocks from the direct impact of rolling waves.

In the spring period, 7 samples were taken (Figure 3) from a wider range of locations: (1) the exposed clay layer, between flat boulders on the upper pseudolittoral, in the lagoon; (2) areas located further on the edge of the channel among the stones, and also on the upper part of the surge strip; (3) the flat sandstone in a winding lagoon, on the middle pseudolittoral; (4) an open sea surf area with the influence of sewage, where storm waves during the winter cut off all the low ridges of marl, leaving a cracked and almost flat sandstone bottom; (5) the long puddles on the upper pseudolittoral (i.e., the area of influence of surge winds during the period of water surge); (6) cauldrons and washout furrows on the high cliffs of the cape, and (7) the sheer black wall of the cape.

Samples were taken by scraping off microepiliton fragments from the surface of a rocky substrate in various coastal biotopes, within the pseudolittoral. Scraping was performed with a sharp edge of a transparent plastic (PET) scraper, in the form of several strips 1–1.5 cm wide, up to 10–15 cm long. The microfouling strips thus obtained were placed in a 50 ml transparent PET bottles, where they were filled with Caspian sea water from the same habitat to half the volume of the container. The vial was screwed with a cap so that the air penetrated inside. All samples were taken in duplicate: one of them was left alive, and the second was fixed with an ethanol solution at the sampling site. Live samples were stored in diffuse natural light at a temperature of 10-12 ^{0}C. For the period of transportation to the laboratory of Shirshov Institute of

Oceanology, located in Moscow, the caps of vials with living material were tightly screwed for temporary sealing. The transportation time was 6 to 8 hours. Then the samples were depressurized (to this end, the lids of the vials were slightly unscrewed to allow the air to penetrate) and again placed in a refrigerator, where they were exposed under constant illumination and a temperature of 10 ^{0}C.

Analysis of living material was performed in the first two days after transfer to the laboratory of Shirshov Institute of Oceanology. Primary attention was paid to the spatial organization of biofilms and regularly repeating elements of their structure, and then to the taxonomic composition of microorganisms that formed these structural compositions. The analysis was carried out by light and scanning electron microscopy. When studying living material, Leica DMLS, Leica DM2500, and Carl Zeiss Primo Star light microscopes were used at x200, x400, and x1000 magnifications. Structural features of biofilms were photographed at various magnifications using Leica, Blackview, and Canon digital cameras. A detailed study of the organization of structural elements was carried out using high-resolution digital images.

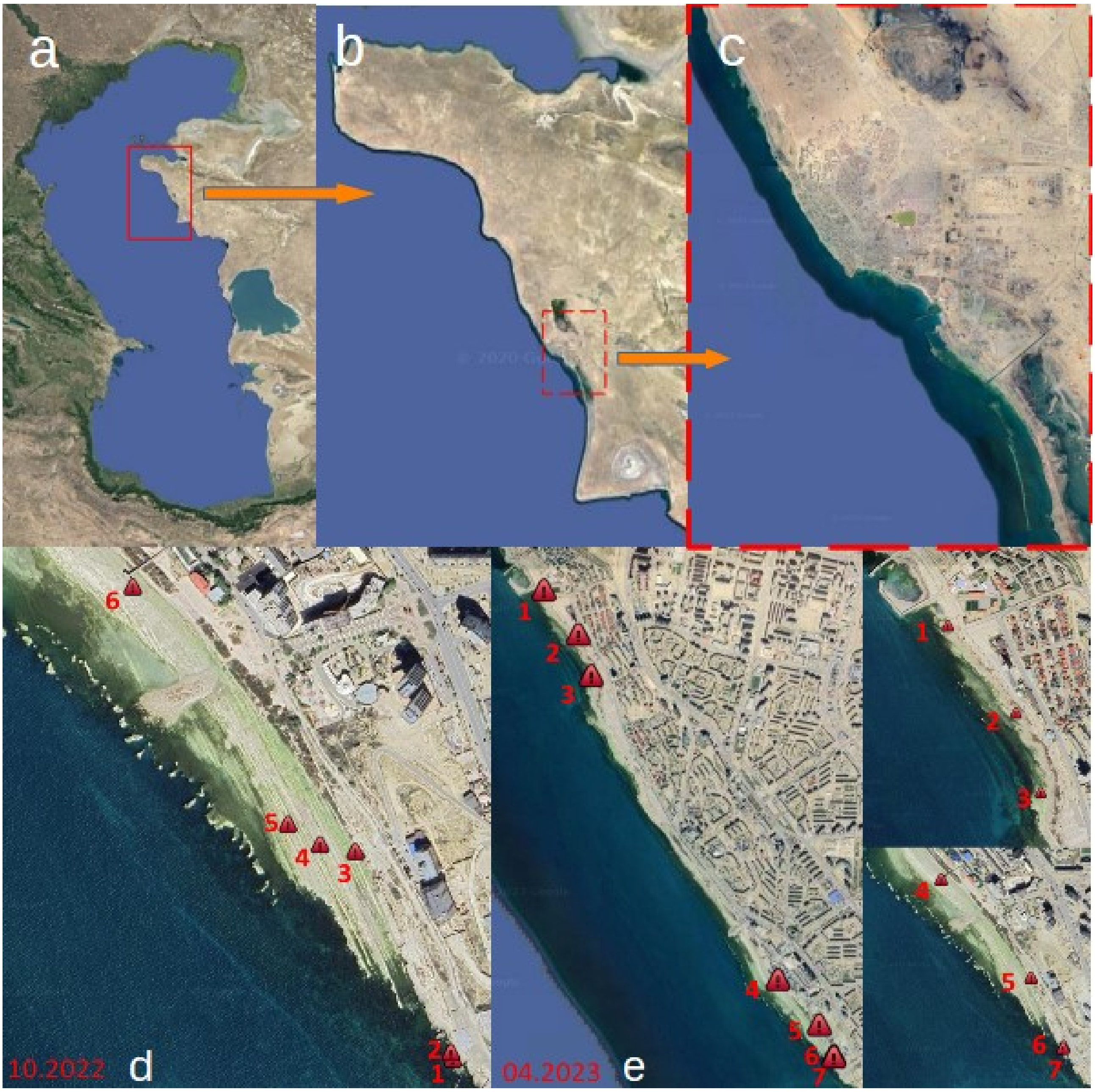

Figure 3. Map of microepiliton sampling points in various coastal locations in the city of Aktau: a - map of the Caspian Sea with a highlighted area of the coast of the Mangystau region, b - section of the coast of the Mangystau region with a highlighted area of the city of Aktau, c - coast in the area of the city of Aktau and its immediate suburbs, d - locations of sampling in October 2022, e - locations of sampling in April 2023.

To study the fixed material and dried fragments of living biofilms, Scanning Electron Microscopy methods were used on JEOL JSM-6380LA and Cambridge Instruments CamScan S2 devices. This was done to reveal the details of the microspatial organization of structural elements that are characterized by relatively high frequency, as well as to clarify the taxonomic identity of diatoms.

The microphytes were identified based on the available literature sources (Witkowski et al., 2000; Krammer, Lange-Bertalot, 2004; Spaulding, Edlund, 2008a,b,c,d; Levkov, 2009; Spaulding, 2011a,b; Komárek, Anagnostidis, 1989, 1998, 2005; Komárek, 2013; Kulikovsky et al., 2016). As to the current taxonomic status of microphytes, we also used periodically updated materials from the World Register of Marine Species (WoRMS Editorial Board, 2023) and AlgaeBase (Guiry, Guiry, 2022) portals.

Results

Passing to the results of this study, we consider separately the biofilms that were formed under biotopic conditions of various types and in different seasons.

In the southeastern part of the studied coastal region, rocks were studied on the cape, which sheerly breaks into the sea and is subject to a strong shock effect of a rolling waves even during a small storm. On their surfaces facing the seaward side, as well as in the cracks and on the tops, a continuous layer of black coating up to 1 mm thick developed. Biofilms of this type were studied in October 2022 at location 1, and in April 2023 at location 7. In autumn, the lower layer of the film, which directly adhered to the surface of the sandstone, was formed by a dense mixture of crusted cyanobacteria colonies. These were representatives of the genera that form mucous, friable at the microscopic level crusts from densely located thick branches, where the cells were arranged in compact assemblages of 2 to 4. The volume and strength of such colonies are based on multi-layered transparent sheaths that cover the packages of cells. In this biofilm layer, the main structuring species were *Gloeocapsa crepidinum, Aphanothece* cf. *saxicola,* and *Placoma vesiculosa*, accompanied by smaller colonies of *Entophysalis granulosa*. This layer served as a kind of cementing base for the filamentous (“hairy”) component of the biofilms. The hairy layer was formed by relatively short, up to 500–600 μm, trichomes of the cyanobacterium *Calothrix parietina*, as well as by three long trichome species (*Calothrix micromeres, C. geitonos*, and *C. incerta*), reaching 1–2 mm in length. *Calothrix* trichomes rose from the layer of mucous colonies in spreading bundles of 3-7 threads. At the same time, long colorless hairs of *C. geitonos*, formed by elongated cells with high oil content, formed the uppermost, fine-fibrous and slippery layer of the biofilm: they were transparent for light, but at the same time they retained moisture among the underlying layers from evaporation under intense insolation. In turn, thick and strong trichomes of *C. micromeres*, dressed in multilayered brown sheaths, served as a structural basis for this layer.

Epiphytic trichomes of *Leibleinia calotrichicola* often and in mass developed on the surface of sheaths of different species of *Calothrix*, braiding them in a spiral. The hairy layer had no gaps between the *Calothrix* trichomes - a layer of thin, sinuous, and abundantly branching *Schizothrix cresswellii* trichomes, also dressed in transparent polymer sheaths, developed closer to their bases and to the mucous layer of cortical colonie. Above it, entwining vertical trichomes like loose “cotton wool”, tubular colonies of the diatom *Berkeleya rutilans* (Figure 4a) developed, also abundantly branching. It should be noted that all these structural elements, accompanying each other, created conditions for retaining water and maintaining the overall elasticity of each of the biofilm layers. At the same time, their general arrangement, as well as the presence of exopolymer covers capable of conducting and partially scattering incoming sunlight, created conditions for the overall transparencyof the entire film as a whole.

In April, the principal component of the lower, cortical layer were abundant loose colonies of *G. crepidinum*, whose cell membranes had rich brown color. In the layer of vertical reinforcing trichomes, *C. geitonos* developed massively (Figure 4b). At the surface, its torn sheaths covered the film.

The bundles of *C. micromeres* trichomes, dressed in dense dark brown sheaths, were arranged in compact groups of 10–15. The trichomes of both *Calothrix* species were short, and their sheaths showed signs of massive shearing, probably due to the impact of long early spring storms. The structure of the films at this stage of their development was depleted, most of the species were at the minor stage of development, and the main structuring function was provided by the first two dominants that survived the winter in the most viable state.

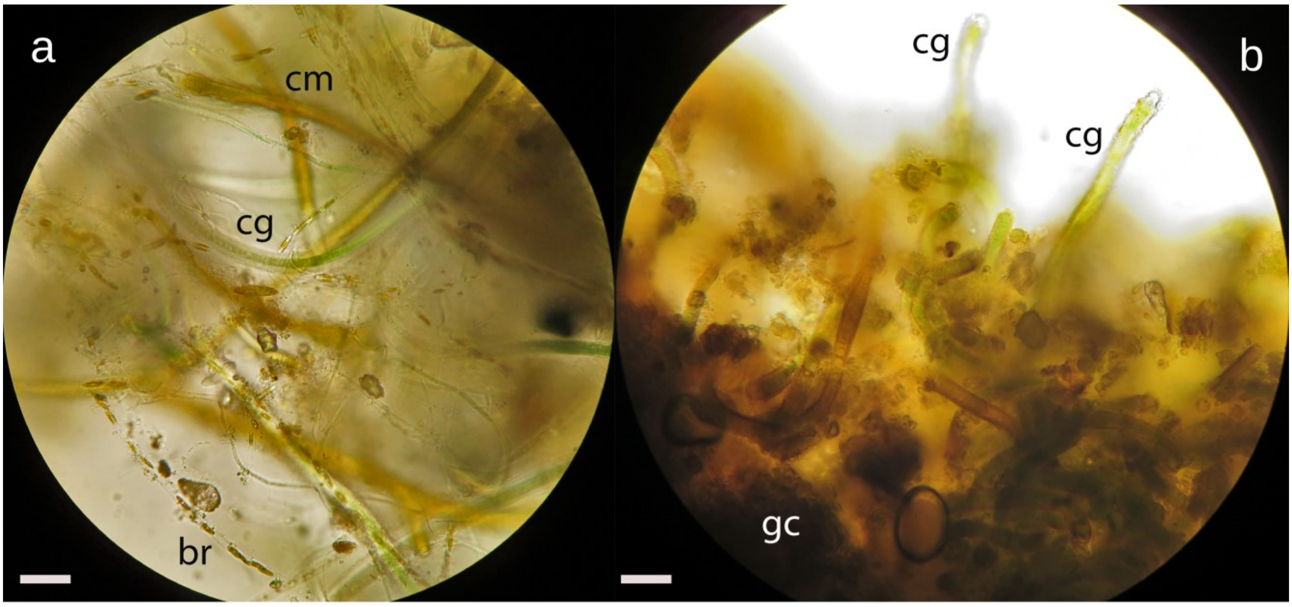

Figure 4. Fragments of a black biofilm formed on rocks in the surf zone: a — October 2022, b — April 2023. Scale bar: 20 µm. Designations: gc - *Gloeocapsa crepidinum*, cg - *Calothrix geitonos*, cm - *Calothrix micromeres*, br - *Berkeleya rutilans*. Photos by Philipp Sapozhnikov.

Sea water accumulated in cauldrons and washout furrows on the surface of the rocks on the same cape. Here, the epilithic communities were studied at locations 2 (October 2022) and 6 (April 2023). In October 2022, the main structuring component of biofilms here were large trichomes of *Lyngbya* cf. *major*. Epiphytes developed on their sheaths: numerous semi-motile diatoms *Halamphora coffeaeformis* and attached *Licmophora* cf. *lyngbiei*, as well as the fine trichome cyanobacteria *Leibleinia* cf. *porphyrosiphonis*. The main volume of the biofilms was formed by abundantly branching tubular colonies of *B. rutilans*, with an insignificant admixture of colonies of *Berkeleya* cf. *sparsa*. The free-floating diatoms *Cylindrotheca closterium* and dinoflagellata *Oxyrrhis marina* also lived in masses here, as well as seedlings of thalli *Ceramium* sp. In April 2023, loose colonies of *G. crepidinum* were the main cortical component of the biofilms in washout furrows. A sparse hairy layer rose from them, formed mainly by *C. geitonos* with long terminal hairs, braided in the lower part by *Schizothrix cresswellii*, and in the upper part by tubular colonies of *B. rutilans*, densely planted with *H. coffeaeformis* in some places (Figure 5). The minor components of these cenosis were *C. micromeres*, *L.* cf. *major* and large mobile species of naviculoid diatoms.

In the upper part of the pseudolittoral, the sea water remained in alongated puddles, accumulating after surges in deep folds of marl. The puddles were flooded both in autumn and in spring. Here we observed beige-reddish-brown biofilms that developed on the surface of the sandstone and had the appearance of thick cheesy flakes. The thickness of such formations reached 3-8 mm.

In October 2022, the films covering marl at the bottom of puddles were woven with thalli of filamentous green algae *Rhizoclunium* sp. with the participation of *Cladophora* sp. (Figure 6a). Among them, palmelle-like colonies of goldish algae (*Chryzophyta*) *Chrysocapsopsis rupicola*, coccoid cyanobacteria *Chroococcus subnudus*, and mobile diatoms *Navicymbula pusilla* developed in mass, as well as in large numbers, forming the inner "felt" of the film, fine trichome cyanobacteria from the genus *Leptolyngbya*. On the surface of the threads of filamentous algae epiphytically attached diatoms *Tabularia waernii* lived, forming extensive and dense colonial settlements, and numerous microcolonies of *Chroococcus quaternarius* in the form of compact drusen (Figure 6b).

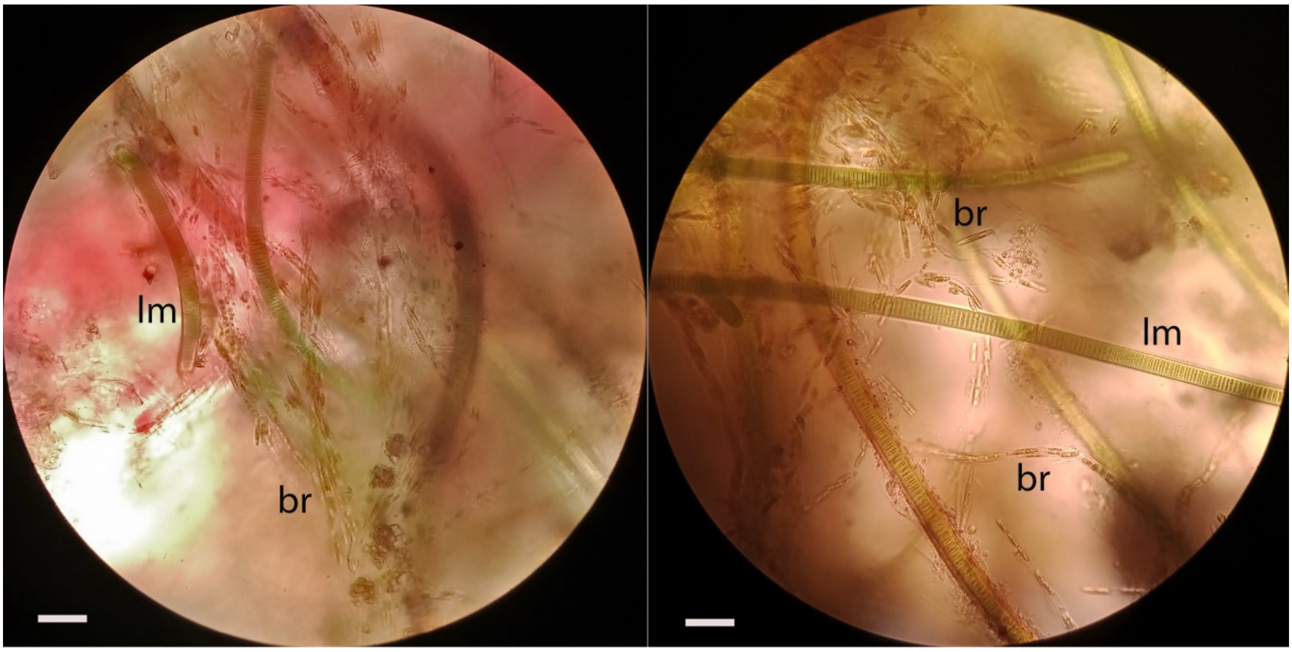

Figure 5. Fragments of biofilms lining the bottom of cauldrons and washout furrows on the tops of sheer cliffs in October 2022. Designations: lm - *Lyngbya* cf. *major*, br - *Berkeleya rutilans*. Scale bar: 20 µm. Photos by Philipp Sapozhnikov.

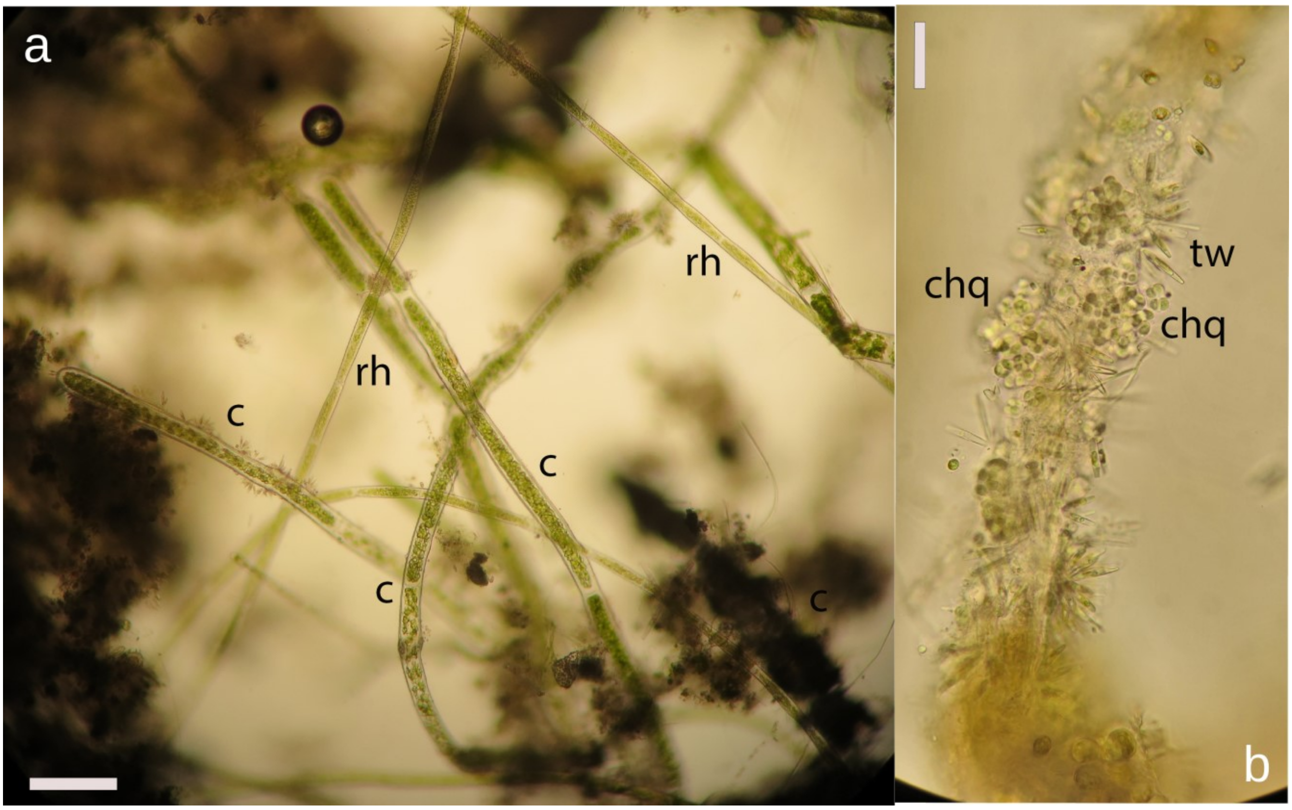

Figure 6. Fragments of biofilms that covered the bottom of puddles in marl folds on the upper pseudolittoral: a — filamentous green algae; b — microfouling (microepiphyton) on the surface of the thallus of *Rhizoclunium* sp. Designations: c – *Cladophora* sp., rh – *Rhizoclunium* sp., tw - *Tabularia waernii*, chq - *Chroococcus quaternarius*. Scale bar: a – 50 µm , b – 20 µm. Photos by Philipp Sapozhnikov.

During the next survey, in the spring of 2023, the basis of the ocher-green-brown flaky mat in the same habitat (location 5, Figure 7a) was formed by mass accumulations of motile cells of the diatoms *Navicymbula pusilla* and *Achnanthidium* sp., in combination with abundant mucous membranes ("cloudy" colonies) of tiny coccoid cyanobacteria (Figure 7b) (presumably *Rhabdoderma lineare*), microcolonies of *Chroococcus limneticus* and tocotrichome cyanobacteria (presumably *Leptolyngbya ochridana*). Compact colonies of *Gomphosphaeria aponina* were often found. The structural basis of the flakes was formed by "cloudy" colonies of cyanobacteria, while *N. pusilla* cells actively moved between them.

In October 2022, the biofilms on the surface of folded sandstone in the middle pseudolittoral zone (location 4) were formed by intertwining mobile (sliding) trichomes of the cyanobacterium *Phormidium* cf. *breve* as well as cluster-like colonies of diatoms *Navicula cincta*. They were accompanied by large accumulation of a fine mineral fraction, organic detritus, large trichomes *Oscillatoria princeps*, and diatoms *Rhopalodia brebissonii*, *Halamphora coffeaeformis,* and *H. borealis*. In turn, on the lower pseudolittoral with the same landscape pattern, intense brown biofilms developed, formed almost exclusively by mobile diatoms. *N. cincta* dominated here, *Nitzschia clausii, H. borealis, Ph.* cf. *breve* and *Phormidium* sp. were developed to a smaller extent. Microscopic examination of living film fragments showed that *N. cincta* cells were in constant motion, forming a network of intersecting flows, kind of mobile fibers containing a large amount of polysaccharides released by diatoms during their movement.

In April 2023, biofilms based on diatoms developed on the surface of the stone bottom exposed during the storm surges, on the open and semi-covered from the sea ("lagoon") areas of the coast, under the protection of flat stone blocks that limited the impact of the surf. In most biotopes, their main structuring elements remained constant: they were semi-motile diatoms *Halamphora coffeaeformis* and *H. hybrida*, which formed thick amorphous fibers based on the transparent polysaccharides mucus they secreted.

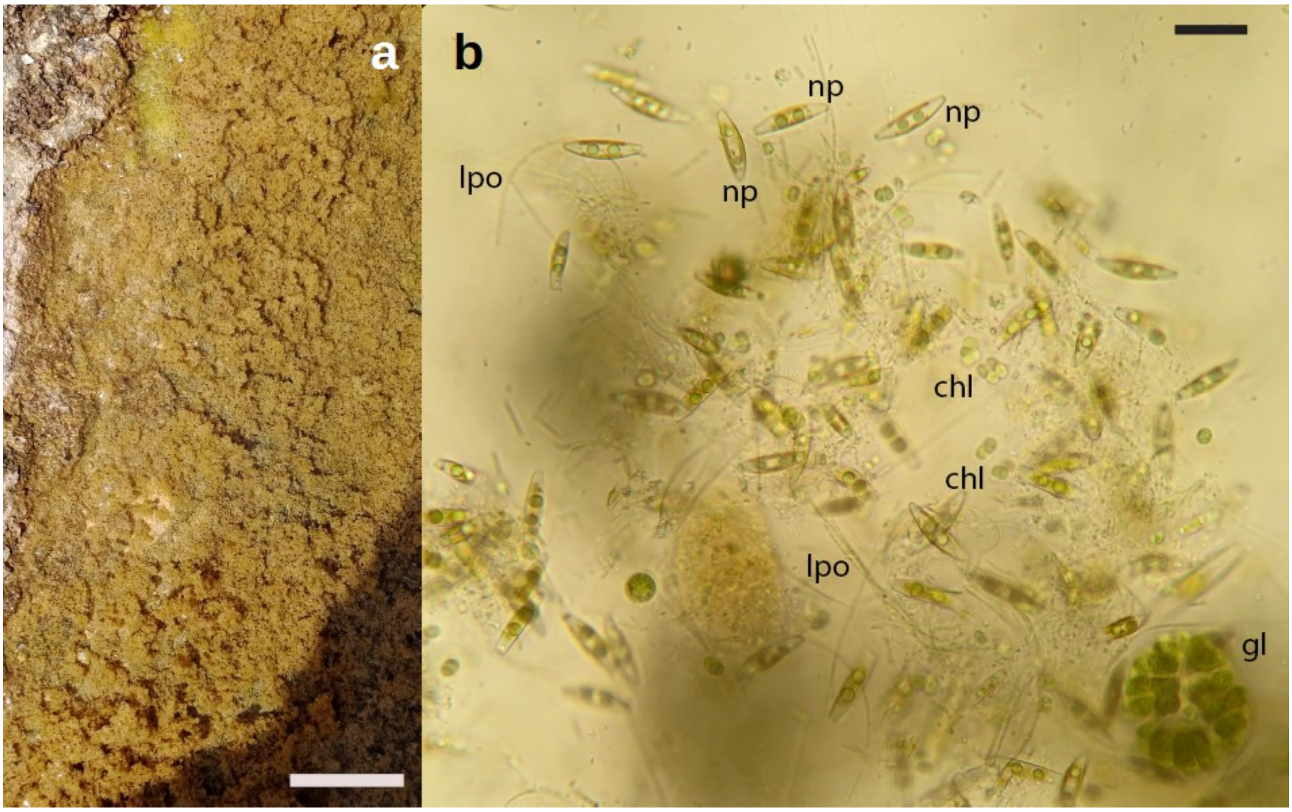

Figure 7. Algal-bacterial mat (a) formed in longitudinal puddles (marl folds) on the upper pseudolittoral by mid-April 2023 (location 5). A fragment of the mat at x400 magnification (b), the structural basis is formed by mucous colonies of the smallest cyanobacteria. Designations: np – *Navicymbula pusilla*, chl – *Chroococcus limneticus*, lpo - *Leptolyngbya ochridana,* gl – *Gomphosphaeria aponina.* Scale bar: a — 5 cm, b — 20 µm. Photos by Philipp Sapozhnikov.

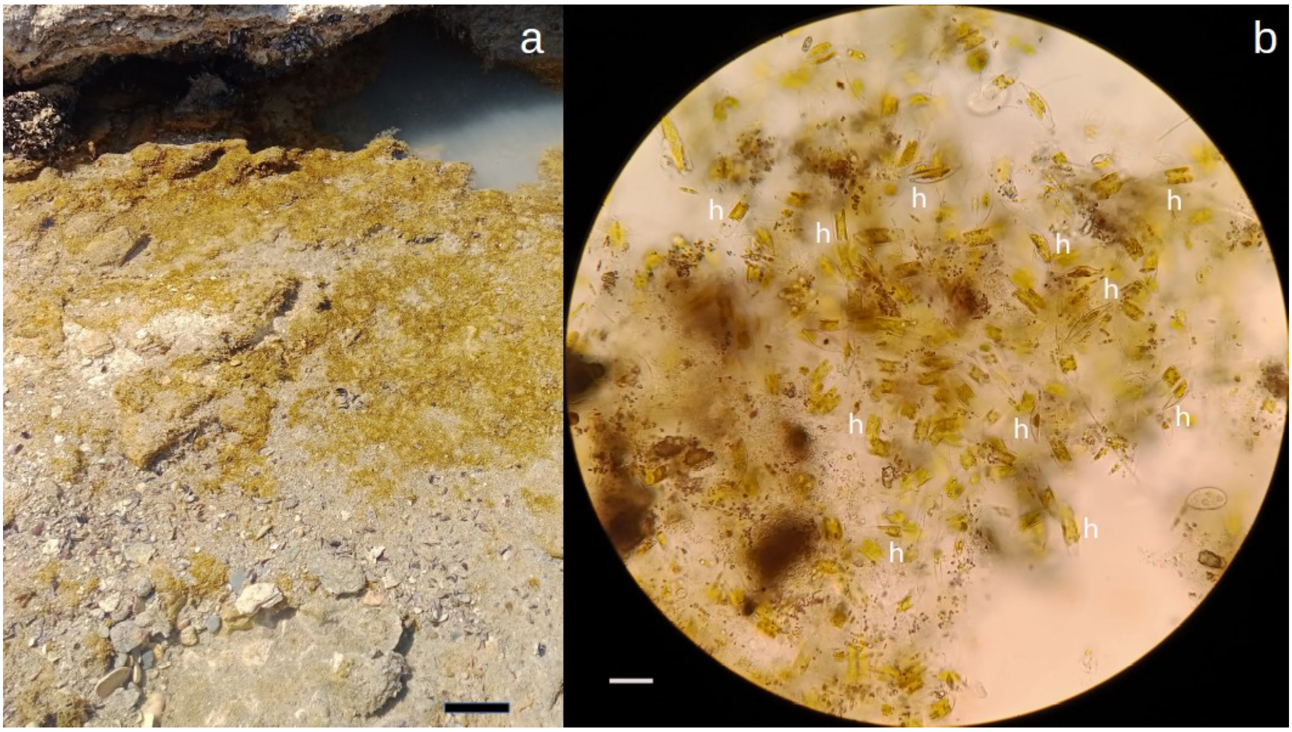

Figure 8. Biofilm on clay soil in the “lagoon” (location 1, April 2023). General view of the community in the pseudolittoral landscape (a) and its fragment when assembled x400 (b). Designations: h — cells of different *Halamphora* species. Scale bar: a - 5 cm, b - 20 µm. Photos by Philipp Sapozhnikov.

On the clay and sandstone bottom in the “lagoons” (location 1), such fibers grew into a reselient network densely covering the soil surface with a layer up to 3-4 mm (Figure 8). As accompanying elements, *Entomoneis paludosa, Nitzschia* sp. as well as trichome species of cyanobacteria were also observed here. For example, the fibers located on a clay surface among stone blocks contained motile trichomes of cyanobacteria *Phormidium breve* and sulfur bacteria *Tiothrix* sp.

On the surface of flat sandstone boulders, in the middle pseudolittoral zone (location 3), a “cheesy” brown fouling developed (Figure 9a) up to 4-5 mm thick. It was based on a dense growth of short *Enteromorpha* thalli, on which diatoms profusely reproduced in epiphytic form. At the same time, only bundles of *Ctenophora pulchella* cells lived in an attached state directly on the thalli. The main part of microfouling here was formed by huge accumulations of two species of semi-motile diatoms: *Halamphora coffeaeformis* and *H. hybrida*. Here, they built colonial settlements in the form of "clouds" or flakes of an indefinite shape based on diatom mucus secreted by cells and braiding *Enteromorpha* filaments serving as a support (Figure 9b, c). Along the outer contour of the “clouds”, *Entomoneis paludosa* and *Nitzschia* sp. were often encountered.

On a vast open area of the rocky shore, where sewage seepage was noted, over the winter, grinding of undulating marl to a relatively more even surface took place. Here, the biofilms had the character of extensive spotsm they were brownish-yellow, with a speckled structure, very thin, almost grown into the surface of the stone (Figure 10a). At the same time, the destruction of the stone surface continued, small plates of sandstone were split off near and within the spots. Here, the cenoses were of a simplified nature: the small species *Halamphora borealis* dominated, forming dense colonial settlements, without the formation of mucous fibers. It was accompanied by massive *H. coffeaeformis*, *H. hybrida* (Figure 10b) and *E. paludosa*, which built short fibers in this biotope without forming a single network. This film was destroyed along with the surface layers of sandstone.

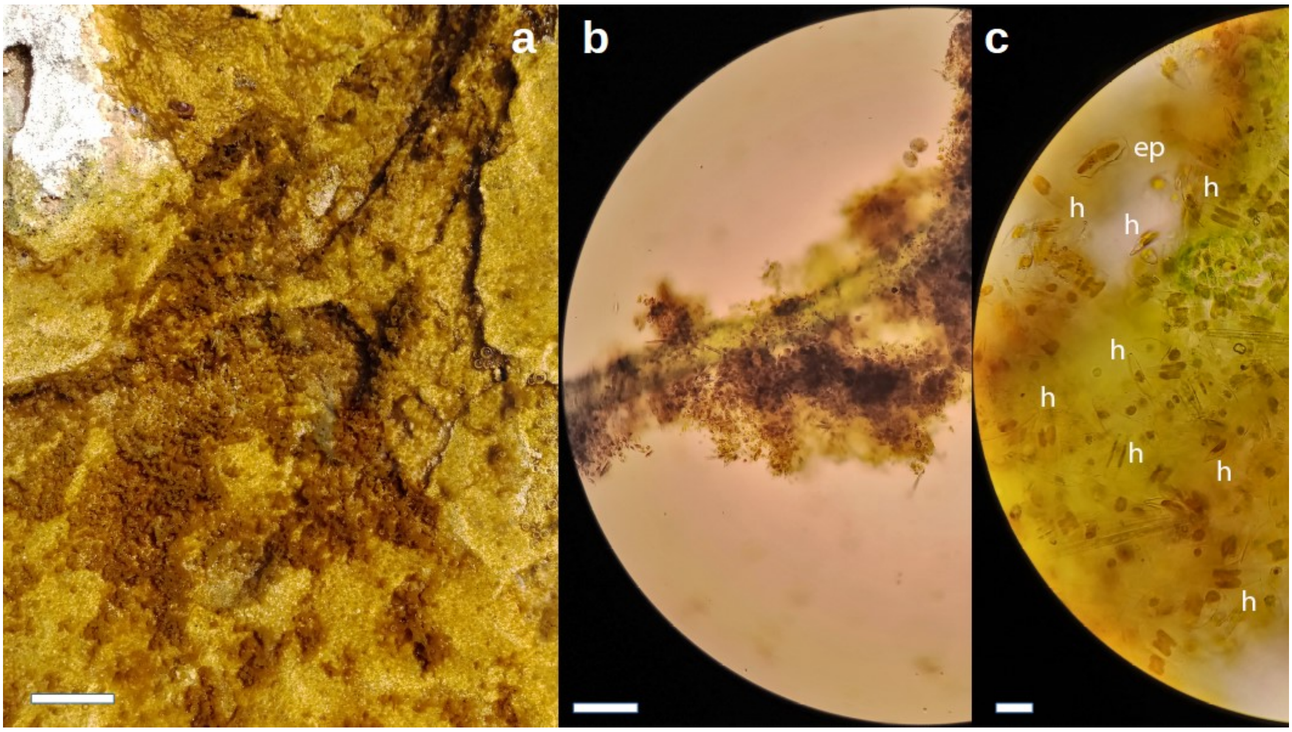

Figure 9. Fragment of cheesy ("moss") biofilm (a) on flat blocks of sandstone, in the middle pseudolittoral zone. Mixed colonial settlements of *Halamphora coffeaeformis* and *H. hybrida* (b, c) growing in the form of "clouds" (flakes) on *Enteromorpha* filaments. Designations: h — cells of various species of *Halamphora*, ep — cell of *Entomoneis paludosa*. Puddles of the upper pseudolittoral, April 2023. Scale bar: a – 5 cm, b – 100 µm, c – 25 µm. Photos by Philipp Sapozhnikov.

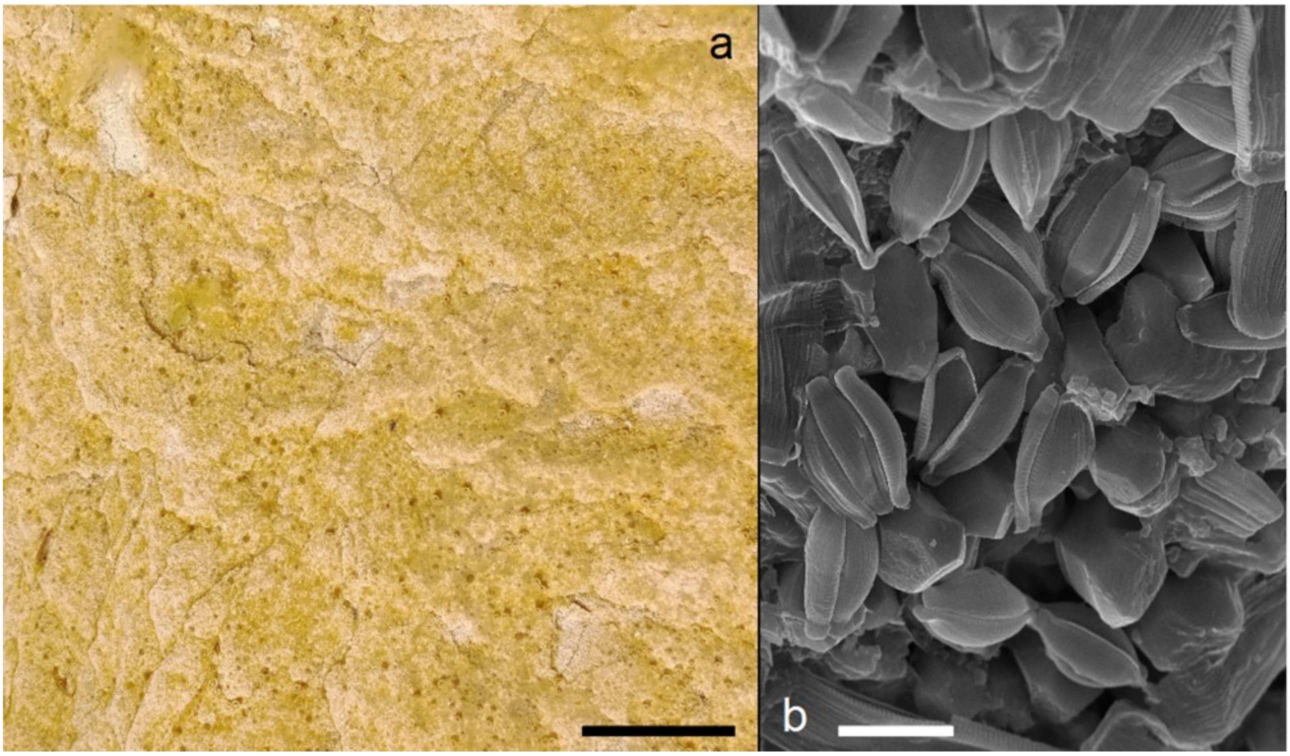

Figure 10. A thin biofilm that has practically grown into the surface of crumbling sandstone in the abrasive section of an open pseudolittoral (a). Fragment of colonial settlment by *Halamphora borealis* (b). Scale bars: a — 5 cm, b — 10 µm. Photos by Philipp Sapozhnikov, Olga Kalinina.

Another type of biofilms was observed in April distributed in the areas of the middle and upper pseudolittoral, where the relief of the stone surface was lowered. Here, algal-bacterial communities developed in wide gutters through which water flowed in the direction of the sea (for example, in location 2). The films had a curly fibrous character and an intense brown color (Figure 11a). Their structural basis was formed by branching thalli of green algae *Enteromorpha* sp. and *Cladophora* sp. Diatom microfoulings abundantly covered the thalli, forming two distinct tiers. The upper one was formed by fan-shaped colonies of needle-shaped cells of seamless diatoms *Ctenophora* sp., *Tabularia tabulata*, and *T. fasciculata*, which lived here in approximately equal abundance and alternately (Figure 11b). The lower layer was formed by compact colonial settlements of small cells of *H. borealis*, which built films of a transparent matrix on the thalli of filaments. The bases of the colonies were entwined with thin fibers formed by *H. hybrida* and *H. coffeaeformis* based on polysaccharides secreted by them. Among the thickets of attached diatoms, cells of the motile *Navicula gregaria* lived in the mass. The fouling structure remained stable regardless of the substrate type.

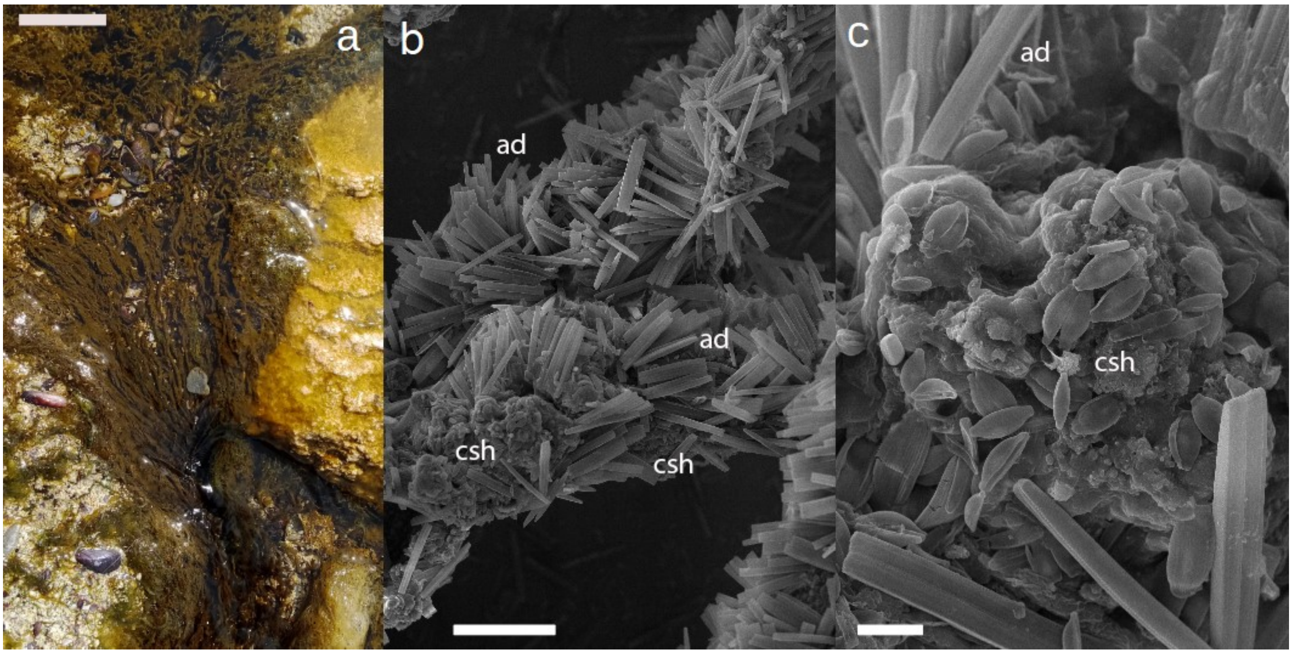

Figure 11. Fibrous brown biofilms that grow in narrow low areas of the landscape of the middle and upper pseudolittoral in presence of water flow. General view of biofilms in a thin layer of water flowing to the sea (a) and fragments of diatom microfouling on the surface of *Enteromorpha* sp. (b, c). Designations: csh - colonial settlements of *Halamphora borealis,* ad – araphid diatoms, e.g. *Tabularia fasciculata.* Scale bar: a - 5 cm, b – 100 µm, c- 10 µm. Photos by Philipp Sapozhnikov, Olga Kalinina.

The only example known to us of a water body that experienced changes of its benthic communities associated with a drop in water level at approximately similar rates was the coastal part of the Large Aral Sea (Zavialov et al., 2012). There, the rocks formed along the banks of the Aral Sea by layers of sandstone were gradually exposed to storm and wind surges on the background of generally falling water level. There, microphyte communities that developed on their surface at a mineralization of 85-113 ppt were formed by colonial forms of diatoms. In the salinity range of 85 to 90 ppt, these were colonies of *Navicula ramosissima*. With a further increase in the total concentration of salts in the water, these colonies were replaced by colonies of *Brachysira styriaca*. It should be noted that the communities in the Middle Caspian were formed at a significantly lower water salinity.

Conclusions

Our observations showed that epilithic cenoses inhabiting the rocky shores in the eastern part of the Middle Caspian are capable of developing and maintaining a stable structure under extreme conditions of pseudolittoral biotopes, which are non-periodically flooded during surge winds and exposed during offshore winds. These communities are manifested as biofilms covering the rock surface. Due to special combinations of structural elements formed by assemblages of microalgae, cyanobacteria and their exopolymers, such films are relatively resistant to temporary drying, strong insolation, and storm waves. They are also able to protect the soil from destruction by the surf. The material collected in different seasons made it possible to divide these cenoses into two groups.

The first of them, covering the surface of steep cliffs on capes as blackish films, have the most stable structure at inter-seasonal scales, thanks to which they protect from destruction by waves not only themselves, but also the marl on which they grow. They have multi-layered, highly reinforced structures that retain a set of elements to restore the organization after prolonged exposure to storm waves.

The second group has become widespread in new biotopic conditions that had formed against the background of a drop in the Caspian Sea level in recent decades on vast areas of a relatively flat stone bottom, previously permanently covered by water and populated by macrophytic algae. The structure of these biofilms differs for autumn and spring. However, their strength and watering regime are based on sets of clearly arranged elements, placed in space in a certain way.

A special feature of the majority of spring biofilms covering the marl surface in the middle and lower pseudolittoral zones are fibers built by diatoms *Halamphora hybrida* and *H. coffeaeformis*. Their cells, multiplying, secrete a transparent exopolymer, based on which thick (up to 100-150 microns) branching fibers containing a large number of cells are built, entangling the stone substrate in a dense network. Due to the mucous structure of the surface of the fibers, as well as the microscopic size of the loops and cells of such a network, it retains water when the bottom is exposed during the offshore surge. The exo-polysaccharides secreted by diatoms into fibers protect them from direct sunlight. Biofilms of this type appear in several variations, and are the least stable in the area where raw sewage seeps, where their structural diversity is reduced to a minimum and a network of fibers is not formed. As a result, biofilms in this area are not able to protect the sandstone from the damaging effects of waves.

In autumn, the functions of reinforcing fibers in the second group of biofilms were performed by other elements. In the middle pseudolittoral zone, these were trichome cyanobacteria interspersed with compact, slimy colonies of the diatom *Navicula cincta*. On the lower dry land, there are exo-polymeric structures formed by the cells of the same diatom, consisting of pseudofibers formed by the mucus secreted by diatoms during movements along the intersecting routes that form a network.

Biofilms in the conditions of the upper pseudolittoral inhabited puddles. They did not form a network of fibers, but manifested a significant ordering of structural elements, high diversity, and the presence of structures protecting from direct sunlight.

All structures mentioned above are described for the first time for the eastern coast of the Caspian Sea. Their important role in maintaining the biodiversity structure of the pseudolittoral zone and its productivity, the food base for gastropod mollusks that feed on biofilms, as well as maintaining the integrity of coastal landscapes in the current extreme hydrological conditions is notable.

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