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Features of the formation of microecotones in aquatic ecosystems

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Abstract. The formation of ecotones in aquatic ecosystems on artificial mechanical barriers placed on fouling glasses has been studied. A positive statistically significant relationship was established between the size of an organism and the width of the ecotone formed by this organism in the series from bacteria to bryozoans and polyps. In relation to microorganisms, a more intensive formation of biofilms and mats was revealed in the marginal areas of biotopes. Larger fouling, such as algae, also more quickly develop the marginal areas of a discrete landscape and serve as a secondary biotope already for phytophilic invertebrates, which are characterized in these artificial biotopes by several times and sometimes by an order of magnitude greater abundance and biomass compared to adjacent standard conditions. The marginal ecotone aggregations also revealed increased polyp size and elevated concentrations of catalase in some molluscs and invertebrate larvae.

1 Introduction

An increase in the discreteness of natural landscapes and biotopes leads to the formation of ecotones and marginal communities of organisms. The study of ecotones, as a rule, is carried out by the fact of their fixation, description and further study of the structure [1-2]. At the same time, the experimental study of ecotones gives an idea of the dynamics of their development, the types of community succession, and the nature of the formation conditions [3-4]. An experimental study of ecotones in the aquatic environment more clearly demonstrates the formation of ecotone communities than in terrestrial ecosystems, since biotopes in the form of hard surfaces grow faster in water. By changing the relief, shape, and angles of solid surfaces of solid substrates, it is possible to study the features of the structure and dynamics of communities of organisms that develop solid surfaces [4-5]. The purpose of this work was to study the features of the formation of ecotone communities in the aquatic environment.

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2 Materials and methods

Studies with natural cenoses were carried out in 2010-2021. in freshwater reservoirs differing in trophic structure and hydrodynamics. Glass constructions were used as artificial biotopes, where furrows and depressions of various diameters were made on a flat surface with abrasive paper, a sandblaster and scalpels. After that, the modified substrates for water fouling were immersed in a vertical and horizontal position in various water bodies: the Miass rivers, the Shershnevskoye and Troitskoye reservoirs, Lake M. Terenkul, and small water bodies without a name [3]. After that, during the growing season, glasses were removed from water bodies, and the abundance and distribution of organisms on the glass were studied [6-7].

For a separate line of experiments, artificial cenoses of marine fouling, as well as monocultures of bacteria, served. The study of the features of the formation of bacterial ecotone aggregations was carried out in a nutrient meat-peptone broth [4, 8]. Cultures of *Staphylococcus aureus*, *Pseudomonas aurogenosa* were used for research. Next, the number of bacteria was counted on a microscope. Aiptasia communities (*Aiptasia sp*.) with algae cultivated in a marine aquarium were used to study marine ecotone aggregations.

The nonparametric Kendall correlation [9] was used to statistically assess the degree of association. Calculations and graphical plots were performed using the KyPlot and PAST packages [10]. Relationships were considered statistically significant at $p>0.05$, unreliable at $p>0.10$.

3 Results and Discussion

When a relief barrier is applied to a relatively even biotope in the form of a scratch on glass, a primary ecotone aggregation consisting of bacteria is formed, which is distinguished by a characteristic linear extent and increased cell density (Figure 1). This pattern was observed in the development of two monocultures in a nutrient medium - *Staphylococcus aureus* and *Pseudomonas aurogenosa*. For both cultures, a more intensive growth in the number of cells along the mechanical barrier was observed. At the last stages of development, during the formation of a monolayer of bacteria immersed in the intercellular matrix, a more intense rate of its coverage was also observed in areas with an uneven glass relief or near such areas. Under conditions of illumination in water from natural reservoirs, unicellular, colonial, and trichome algae *Cyanobacteria* and *Chlorophyta* settled in place of bacteria or simultaneously with them near scratches and furrows on the fouling glasses (Figure 1). The density and frequency of algae cells near scratches was also higher compared to cells located on a flat surface away from scratches and furrows. However, the nature of the arrangement of trichome thalli of algae was different - elongated cells and trichomes were located across scratches and furrows. The location of algal trichomes across the furrows is explained by the physiological tendency of trichomes to bind a discrete substrate, which we also observed in trichomes of multicellular algae [3, 7]. It is known that trichome cyanobacteria bind particles with a size of 1–50 μm, and the strands formed by these trichomes and “filamentous” multicellular eukaryotic algae bind 50–3000 μm [6, 11]. Algae mats capture particles several millimeters in size. Thus, elongated microorganism cells react to uneven disturbances on relatively flat glass in an attempt to "tie" them together. Centric algae colonies, as well as individual cells, formed ecotone aggregations at the edges of fouling glasses (Figure 2). Colonial algae, when colonizing barriers in the form of scratches on an artificial biotope consisting of glass, changed the shape of colonies from centric to more elongated, located along the scratches. At the same time, the ecotone colonies developing along the scratches were characterized by smaller sizes (by a factor of 2–3) and higher density compared to the colonies located at a distance from the scratches (Figure 2). This is explained by different resource strategies for space exploration - colonies near the barriers are provided with organic resources to a greater extent compared to colonies located at a distance. In this connection, colonies in the distance of scratches are characterized by a typical centric structure, and colonies located near scratches tend to form a monolayer similar to bacterial biofilms and algobacterial mats of filamentous algae. Unicellular algae with elongated cells were located along the scratches.

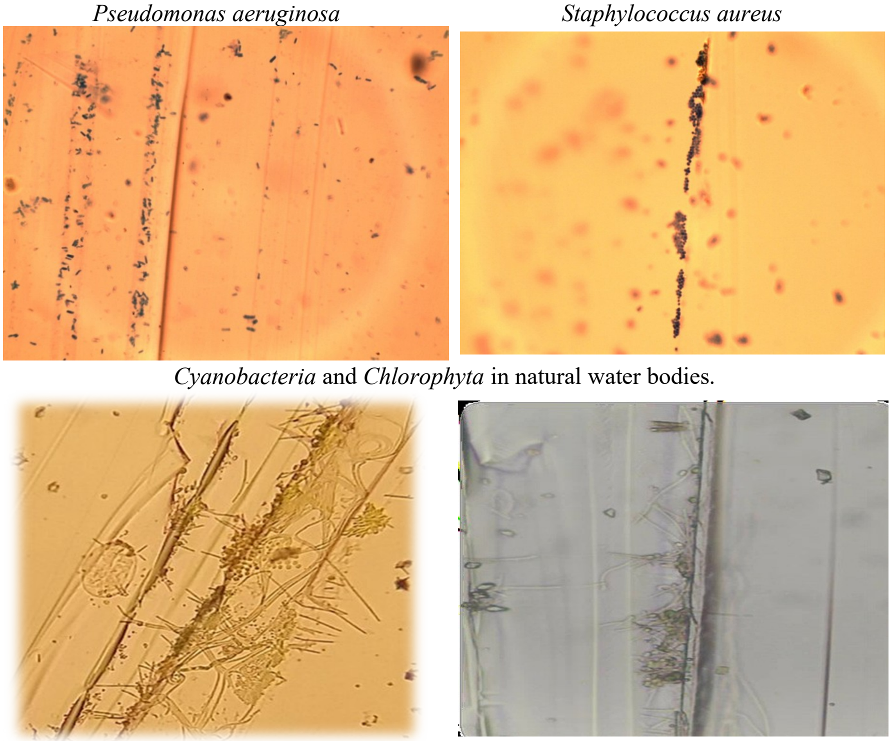

Fig. 1. Settlement of glass with scratches and formation of ecotone aggregations in the culture of Pseudomonas aeruginosa and Staphylococcus aureus and algae Cyanobacteria and Chlorophyta in natural water bodies.

Larger foulings represented by animals on artificial biotopes in the form of glasses with furrows were also characterized by ecotone types of aggregations. Thus, hydras (*Hydridae*) settled along the corners and large furrows in elongated compacted aggregations 1–1.5 cm wide. Bryozoans (*Plumatella repens*) lined up coeloms along large furrows and edges of elongated glass, while on narrow scratches and even glass, coelomes were characterized by a centric shape (Figure 2). Thus, the size of the barrier on the biotope determines the size of the organisms that form the ecotone. The largest fouling (*Aiptasia sp.*) in the development of biotopes with furrows of different diameters gravitated to the largest furrows, being located along their edges (Figure 2). It should be noted that similar larger specimens were also observed by us in terrestrial herbaceous plants growing along the barriers [5]. The largest aiptasia, located at the edges, apparently filter the correspondingly larger water flows that supply them with food. A similar mechanism can also promote dense aggregation of hydras at the glass edges. In the case of hydras and aiptasians, a typical geochemical barrier characteristic of an ecotone is observed.

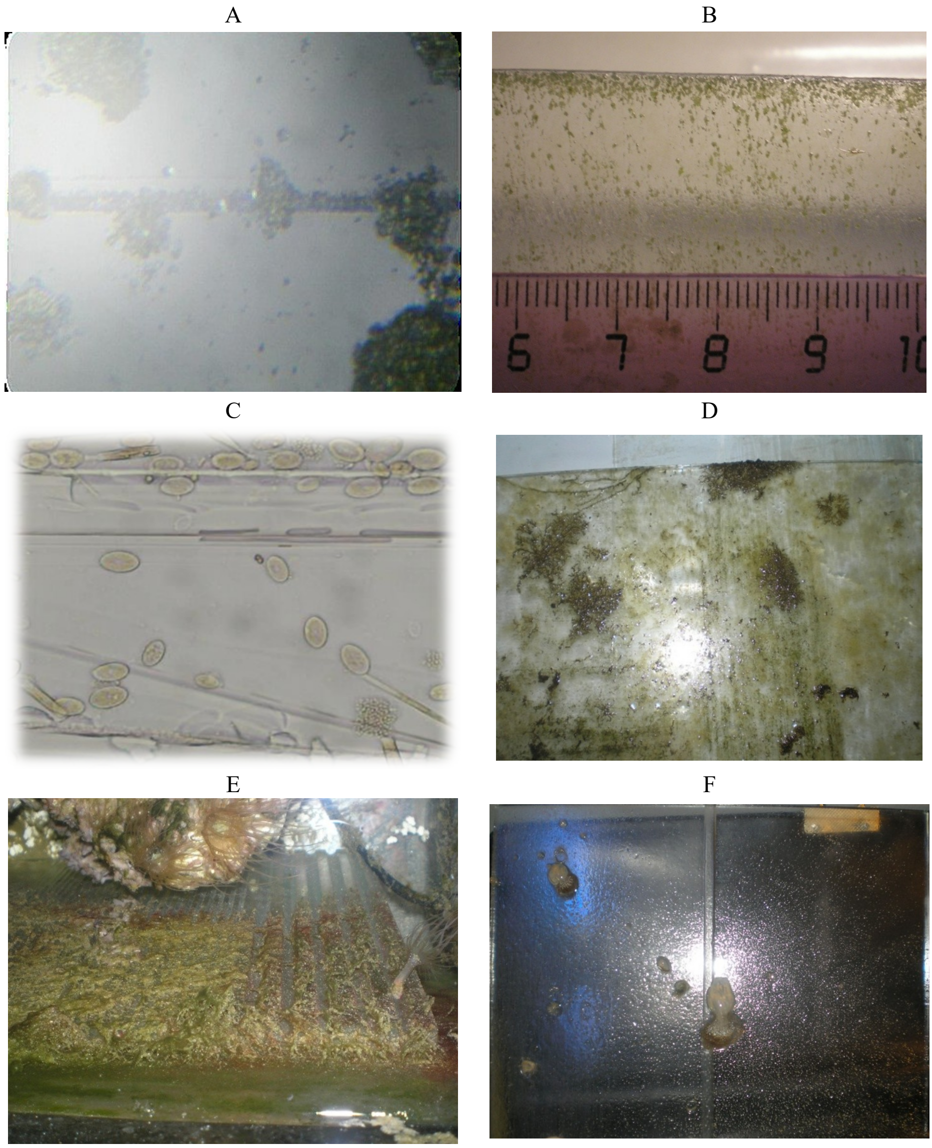

Fig. 2. Features of the physiology and the nature of the location of various foulings on the edges of artificial biotopes in ecotone conditions: A - algae colonies on scratches and on a flat surface, B - ecotone aggregation of algae colonies on the edge of the glass, C - individual cells of algae in ecotone aggregation located along the scratch, D - Bryozoan coelomes on the edge of the glass, furrows of different diameters and smooth glass surface; E, algobacterial mats and aiptasia on furrows of different diameters; F, sizes of aiptasia near the ecotone barrier and smooth glass surface.

For 11 species of hydrobionts, the width of ecotone aggregation was determined. The sizes of organisms varied from a few micrometers to several centimeters and included bacteria (*Staphylococcus aureus, Pseudomonas aurogenosa*), blue-green, green, diatoms, multicellular colonial, filamentous (*Compsopogon coeruleus*) algae, hydras, bryozoans and polyps. The statistical relationship between the size of an organism and the width of the ecotone formed by this organism according to Spearman was p=0.0022 (Figure 3). That is, with an increase in the size of an organism, the width of the ecotone formed by the organism increases accordingly, and the size of the barrier on the biotope also determines the size of the organism forming the ecotone.

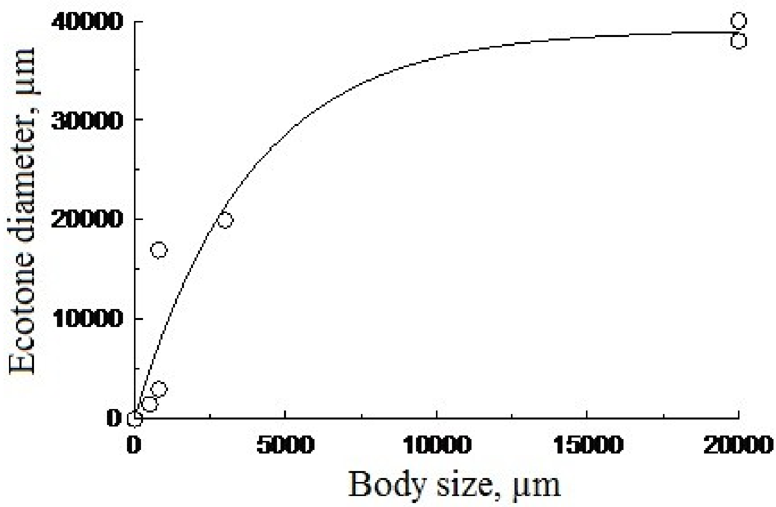

Fig. 3. Dependence of the ecotone diameter increase on the size of the organism formed by this ecotone.

In addition to the increased size of hydrobionts in ecotone aggregations like Aiptasia sp. another physiological feature was observed. In the mollusc *Physa acuta*, the content of catalase under ecotone conditions was 34.3 mkatal/l, and in rarefied aggregations, it was 3–5 mkatal/l [5]. In *Melanoides tuberculata*, the content of catalase under ecotone conditions was 39.8; in rarefied aggregations, it was 5.6 mkatal/l. In chironomids under ecotone conditions, the content of catalase was 20; in rarefied aggregations, it was 14.3 mkatal/l. In chaoborids under ecotone conditions, the content of catalase was 29, in rarefied aggregations it was 10 mkatal/L.

In the ecotone conditions arising on the mechanical barriers of the continuum biotope, a more intensive development of hydrobionts was observed, from microorganisms to large fouling in the form of algae and invertebrates. In the Shershnevskoe Reservoir, the number of oligochaetes under ecotone conditions exceeded the number of oligochaetes on a flat glass surface by an order of magnitude (Table 1). In addition, chironomids, nematodes, and mollusks were present in the marginal areas. The biomass of invertebrates was also 1–2 orders of magnitude higher under ecotone conditions. A similar picture was observed on the Miass River (Table 2). With a similar composition of aquatic organisms, the abundance and especially biomass in ecotone conditions was always higher. At the same time, the biomass of invertebrates in ecotone aggregations was several times and an order of magnitude higher than the number of animals on flat glass. Higher numbers and biomass of invertebrates are due to more intensive growth of filamentous algae on the marginal areas of glasses with a changed relief. In this case, filamentous algae are not only a resource enriched with a nutrient medium, but also a biotope, since some animals that settle in ecotone aggregations belong to zoophytos [3]. Intensive development of mechanical barriers in the form of uneven glass was also observed in typical fouling in the form of bryozoans (Table 3). The area of bryozoan colonies in the cooling system of the Troitskoye Reservoir on glass areas with scratches was always higher than on flat glass.

Table 1. Population of glasses divided into sectors with even and uneven relief in the Shershnevskoye reservoir (furrow diameter 0.2 mm).

Kind	**Smooth surface**		**Surface with scratches**	
	Abundance, ind./m^2	**Biomass, g/m^2**	**Abundance, ind./m^2**	**Biomass, g/m^2**
	Glass 1 (07/15/2010 - 07/24/2010, exposure - 9 days)			
Gastropoda	-	-	10	0.02
Algae: Spirogyra	-	0.50	-	0.80
	Glass 1 (07/16/2010 - 09/16/2010, exposure - 62 days)			
Chironomidae *Oligochaeta* *Nematoda* *Gastropoda*	- 40 - -	- 0.31 - -	50 950 1600 40	0.15 1.44 0.26 5.4
Total invertebrates	40	0.31	2640	7.25
Algae: Spirogyra	-	2	-	27
	Glass 2 (08/15/2010 - 09/16/2010, exposure - 30 days)			
Gastropoda *Oligochaeta*	- 50	- 0.05	20 920	0.76 0.98
Total invertebrates	50	0.05	940	1.74

Table 2. Population of glasses divided into sectors with even and uneven relief in the Miass River (furrow diameter 0.2 mm).

Kind	**Smooth surface**		**Surface with scratches**	
	Abundance, ind./m^2	**Biomass, g/m^2**	**Abundance, ind./m^2**	**Biomass, g/m^2**
	Glass No. 1 (06/15/2010 - 07/03/2010, exposure - 18 days)			
Hirudinea	40	2	50	2.3
Algae: *Spirogyra*	-	3	-	10
	Glass No. 1 (06/15/2010 - 09/18/2010, exposure - 93 days)			
Oligochaeta *Ephemeroptera* *Chironomidae* *Hirudinea*	180 160 470 80	0.2 0.2 0.5 2	160 250 560 70	0.1 3.8 0.6 2
Total invertebrates	890	2.9	1040	6.5
Algae: *Spirogyra*	-	70	-	65
	Glass No. 2 (08/03/2010 - 09/18/2010, exposition - 45 days)			
Chironomidae *Ephemeroptera* *Oligochaeta* *Gastropoda*	310 60 20 10	0.35 0.22 0.02 0.05	490 200 20 20	0.56 2.06 0.01 0.03
Total invertebrates	400	0.64	730	2.66
Algae: *Spirogyra*	-	132	-	455

Table 3. Settling of glass by bryozoans (*Plumatella repens*) divided into sectors with even and uneven relief in the Troitsk Reservoir.

Smooth surface		**Surface with scratches**	
Number of colonies	**Area of colonies, cm^2**	**Number of colonies**	**Area of colonies, cm^2**
Glass No. 1 (06/15/2010 - 07/03/2010, exposure - 18 days)			
1	2	1	4-6
Glass No. 1 (06/15/2010 - 09/18/2010, exposure - 93 days)			
1	1	3	4-6

4 Conclusion

Mechanical barriers on artificial biotopes made of glass for attaching organisms of periphyton and zoophytos are environmental gradients in which ecotone communities and aggregations of various organisms are formed. Bacteria and algae settle first. Biofilms and algobacterial mats, when microorganisms die, become a nutrient medium for larger aquatic organisms settling in the marginal areas of the biotope. Of the multicellular organisms, the marginal areas of the biotope are developed by filamentous algae, which more intensively populate the ecotone environmental conditions. Filamentous algae are already a habitat for phytophilic invertebrates. Large fouling in the form of bryozoans and polyps also differ in large areas and sizes in ecotone conditions, where flows are formed for them, supplying food resources [1, 2, 5].

It should also be noted that a special strategy for the smallest settlers of disturbed biotopes - microorganisms capable of forming verified aggregations in the form of biofilms and mats - is a decrease in the size of cells and centric colonies at the edges of a discrete biotope. Whereas in the distance of the edges of the biotope, an increase in the size of the colonies themselves is observed with a decrease in their density. Trichomes are located across the furrows, connecting discrete biotopes with their thallus. Almost all aquatic organisms, from bacteria and algae to hydras with a diameter of 1.5-2 mm, have multi-row ecotones consisting of several organisms that make up the width of a linear ecotone aggregation. Whereas in the largest bryozoans and polyps with a diameter of more than 1 cm, only single-row ecotone aggregations were recorded. This indicates more favorable conditions for colonization and provision of resources for ecotone conditions of mechanical barriers for smaller aquatic organisms. At the same time, the established positive statistically significant relationship between the size of an organism and the width of the ecotone formed by this organism makes it possible to further rely on experimental approaches in the artificial construction of ecotones and predict the parameters of the structure of ecotone aggregations.

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