

Monitoring and assessment of artificial reef implementation for biocenosis recovery in the Tyligul estuary

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ABSTRACT

The article is devoted to the issue of organization and possible improvement of the system of monitoring the state of marine and estuarine water areas and their changes due to anthropogenic activity on the example of the Tyligul estuary, the application of methods for reducing the level of eutrophication of the reservoir by installing artificial reefs. One of the main tasks in conducting ecological monitoring of marine coastal ecosystems, along with the assessment and forecast of their state, is the bioremediation of disturbed biocenoses. This applies primarily to biotic communities susceptible to the influence of the anthropogenic factor. Benthic communities are especially in need of ecological reconstruction in order to optimize the development process and their stability, as they are the most vulnerable to pollution of coastal waters.

Keywords: reef ball, artificial reef, ecosystem restoration, marine biocenoses, biodiversity.

INTRODUCTION

The marine environment plays a key role in human life, providing a variety of ecosystem services and valuable resources. However, no part of the oceans today remains untouched [1]. A significant proportion of humanity lives in coastal areas, where intensive anthropogenic activities are gradually changing marine landscapes. This leads to both direct and indirect negative impacts on marine organisms. The increase in the number of artificial structures in marine ecosystems, associated with commercial and residential needs, gives rise to a phenomenon known as “ocean sprawl”. This term describes a situation where the marine environment is increasingly filled with engineered structures such as artificial reefs, breakwaters, sea walls, piers, oil platforms and offshore renewable energy facilities [2]. Such changes often cause a variety of consequences for adjacent ecosystems [3].

A key step in the restoration of mollusc reefs in limited substrate systems is the reintroduction of solid substrates to appropriate locations as

bases for larval settlement [4]. Stone chips or mollusc shell bags (a by-product of aquaculture) are commonly used restoration substrates [5]. These materials were chosen because their complex structure is thought to act as an attractive substrate for larval settlement and also protect new individuals from predators [6]. Reducing predation during restoration is a common goal in sites without limited larval supply to improve juvenile survival. This has led to the development of restoration-specific substrates that create greater habitat heterogeneity and reduce predation (e.g., BESE elements; [7]). However, in sites with low larval supply, alternative methods may be needed to improve larval settlement on these restored reefs [8].

An artificial reef (hereinafter referred to as “AR”) can be defined as a structure of natural or human origin, purposefully deployed on the seabed to influence physical, biological or socio-economic processes associated with living marine resources [6]. A defined AR can be used for a variety of purposes, the main purpose of which is the conservation of the biological environment

and the improvement of fisheries, which also extends to ecosystem restoration, as well as socio-economic development [7]. Specific purposes of an AR can include aquaculture/mariculture, biomass enhancement, biodiversity enrichment, fish product production, ecosystem management, coastal erosion prevention, recreational activities (e.g., scuba diving, ecotourism, fishing), and research [7]. These engineered structures are usually constructed to resemble natural reefs as much as possible, with the ultimate goal of creating similar effects. There are also other structures that act as RRs that (a) accidentally entered the marine environment (e.g. shipwrecks, lost containers), (b) were repurposed (e.g. sunken ships for recreational activities), or (c) perform other functions (e.g. offshore oil and gas platforms) [9].

Reef balls have already been successfully installed in 62 countries around the world, which confirms their effectiveness and reliability of use. This innovation is planned to be implemented for the first time in the Black Sea. These structures are made of cement according to a special patented recipe using microsilica (silicate dust). This composition provides a pH level similar to that of seawater, ensuring compatibility with the marine environment and increasing the attractiveness of the structures for colonizing organisms [10].

Reef balls are specially engineered artificial reef modules created to replicate the structural complexity of natural marine habitats. Constructed from environmentally friendly, non-toxic materials, these spherical units provide safe havens for numerous marine species, helping to restore biodiversity and enhance the ecological health of underwater environments [11].

Primarily, reef balls serve as stable foundations for coral growth—an essential component of ocean ecosystems. Coral reefs support immense biological diversity, offering breeding, feeding, and sheltering grounds for fish, crustaceans, and other marine organisms. However, these habitats are increasingly endangered by climate change, overexploitation, and pollution [12]. By providing durable, secure substrates for coral attachment, reef balls offer struggling reefs a chance to recover and expand even under adverse conditions.

Sustainability lies at the core of their design: the materials used are chosen to avoid releasing harmful substances and to integrate seamlessly into marine ecosystems. Unlike standard concrete structures, reef balls are chemically inert, ensuring that water quality and surrounding habitats remain

undisturbed. According to recommendations from organizations such as the Natural Oyster Restoration Alliance (NORA) and the Reef Ball Foundation, deploying artificial reefs plays a vital role in conserving and rehabilitating marine ecosystems, particularly in areas exposed to intense anthropogenic pressure.

Introducing reef balls into estuarine zones can create favorable habitats for filter-feeding mollusks and other aquatic life. These actions not only promote biodiversity but also help improve overall water quality and ecological balance within the estuary [11]. Given the positive experience of using recommended technologies in different regions of the world, it is important to implement them in accordance with the specific needs and characteristics of the estuary. For this, it is necessary to conduct detailed studies and develop a strategy that takes into account local conditions, climatic features and soil cover characteristics [12]. In addition, it is important to ensure an effective monitoring plan to assess the results and impact of the implementation of artificial reefs on the estuary ecosystem.

For the effective implementation of these solutions in estuary areas, it is important to provide the necessary resources, technical expertise and provide appropriate infrastructure for the production and installation of reef balls. In addition, a monitoring system should be properly configured to track the results and impact of these structures on the ecosystem of the estuaries of the northern Black Sea region over a long period [13].

The results of experiments indicate the high efficiency of using artificial reefs to increase fish productivity in the coastal waters of the Black Sea and the estuaries located there. These water areas have a shortage of hard substrates suitable for fish spawning, where in natural conditions one can often observe fierce competition for the substrate [14]. Design and placement of artificial reefs-biopositive structures in marine and estuarine water areas leads to an increase in the surface of the artificial substrate on which phytofouling is formed, which in turn leads to an increase in the production potential of the ecosystem [15].

When constructing a reef, it is recommended to use cement and silica, with numerous internal cavities to increase the surface area of the substrate. A rough surface is most suitable for attaching hydrobionts and creating favorable conditions for them [16]. The aim of this study is to determine the impact of installing reef balls

on the increase in the population of estuarine zoobenthos, in particular mussels, and their possible impact on the level of eutrophication of the Tiligul estuary.

MATERIAL AND METHODS

To create artificial reefs, a section of the seabed was selected that combines optimal physical and biological characteristics that allow for the most efficient use of water space during the formation of a reef community and the process of biological water filtration. The most suitable depth for the formation of a multilayer phytocenotic structure as the primary stage of a mature reef environment was found to be areas at a depth of 5–7 m with sandy soils. When developing the structure, physical parameters were taken into account, in particular the mass (W), volume (V) and surface (S) of the reef, which significantly affect the biomass of its fouling [1]. As control areas, we selected areas of the bottom where the direct influence of the reef on the distribution of aquatic organisms is not observed. The colonization of a solid substrate by aquatic organisms illustrates the process of ecological succession, where each previous step creates conditions for the next stage of reef colonization. Initially, within a few days, bacteria and motile unicellular benthic diatoms of the genus *Navicula avicula* (*N. pennata*, *N. directa*) and *Nitzschia* sp. appear on the substrate. After this, immobile diatoms appear in the growth, in particular *Cocconeis scutellum*, as well as colonial forms of diatoms *Achnanthes brevipes*, *Synedra tabuta*, *Licmophora* sp. [2].

The formation of a bacterial film begins almost immediately after the shells are immersed in the sea. The rod-shaped bacteria settle on the substrate and firmly attach themselves within 2–3 hours. In parallel with them, diatoms begin to settle: despite the fact that their number at the very beginning of the formation of the mucous film is much smaller than the number of bacteria. Within a few days, the number of diatoms increases dramatically, both due to the settlement of new cells and the reproduction of already settled ones, especially when the reef is built during the spring or autumn peak of their population. It is known that algae release metabolic products into the environment, which serve as a source of nutrients for bacteria. In addition, living algae cells and valves remaining after their death serve as a substrate for

the attachment of bacteria. In turn, bacteria release carbon dioxide, nitrates, phosphates and other substances necessary for the growth of algae.

The development of a reef community is a series of successive changes in its biological organization and the growth of species diversity, in which interactions between aquatic organisms become balanced, and the structure is close to complementary. With the growth of species diversity in the community, the amount of biological information increases, which contributes to the stability of the ecosystem. During succession, the biomass and production of the community increase and stable interspecific relationships between aquatic organisms of different trophic levels are established. Against this background, the rhythms and cycles of development of community species with different ecological strategies occur [3].

Water, bottom and deep soil samples, as well as algae were taken from different areas of the coastal water area of the Tiligulsky estuary: on the channel connecting the Tiligulsky estuary with the Black Sea, near the bridge at the entrance to the village of Koblevo, Berezansky district, Mykolaiv region, in the coastal water area in the village of Koblevo, in the village of Leninka and in the coastal water area near the village of Ukrainka.

Monitoring studies were conducted in different seasons of the year. Samples were taken in sterile vials for further morphological and biochemical studies [4]. Figure 1 shows the location of sampling sites for studying changes in the species composition of the substrate that settled on the installed reef balls.

Sampling points 1–2 correspond to distances from the shore of 75 and 55 m, respectively, and depths of 4.5–5 m. The distance between these two points was approximately 25.5 m. Points 3 and 4 were located closer to the shore at distances of 45–50 m, approximately 10–15 m south of points 1 and 2, and at the same latitude relative to each other as points 1 and 2. The distance between points 3 and 4 was 4–5 m. Points 5–7 corresponded to the installed reef balls. The distance between points 5 and 6 is 8 m, the sampling depth was 5 m. Also, at point 7, which was located at a distance of 62 m from points 5 and 6, the sampling depth was 10 m.

Many researchers on the fouling of the SR indicate that among invertebrates there are practically no species that selectively settle on rocky or plant substrates. It was previously noted, however, that in the Tiligul estuary, barnacles and polychaetes



Figure 1. Locations of sampling control points

mainly colonize the thalli of cystosira, and mussels and mussels prefer to settle on the wider thalli of *Phyllophora* [5]. The reason for such selectivity in the substrate is probably related to the different sensitivity of aquatic organisms to the action of metabolites secreted by red algae, which can inhibit their growth. It is known, for example, that allochemicals secreted by red coralline algae prevent the development of kelp seedlings and the growth of other aquatic organisms [6].

The methods of attachment of epibionts to the substrate of artificial reefs are extremely diverse: shell valves, calcareous houses, limbs, tubes and mucus threads, etc. During the period when the water temperature in early spring exceeded +10 °C and mussel spawning was active, they were among the first to colonize artificial reefs, often displacing barnacles, settling after their death on calcareous houses. The mussels, which often inhabited certain areas of the reef, were also an obstacle to the fouling of the substrate by mollusks.

RESULTS

Figure 2 shows the condition of the reef balls installed in the Tyligul estuary, immediately after

installation and after two years of research. Table 1 shows the results of the studies conducted on the height, width, length of mollusks that settled on reef balls, as well as their genotype and phenotype. A total of three samples were examined. The mass of the samples ranged from 32.626 to 175.344 kg. The dimensions of the reef ball studied were 10 × 10 cm and were estimated using the frame method.

Total mussel biomass in artificial reef plots was significantly affected by time after deployment ($P < 0.001$, Table 1) and by the interaction between treatment and time after deployment ($P = 0.001$), while treatment did not affect total fish biomass. Pairwise comparisons of reef type for each monitoring event (time after deployment) showed that total mussel biomass was significantly higher in layered pie plots compared to reef ball plots at one year ($P = 0.006$) and 1.5 years (0.044), but not at two and 2.5 years. Table 2 presents the modeling approaches to identify the random model coefficients for each case of observed mussel population growth on the studied reef balls.

Mussel biomass was significantly affected by the interaction between treatment and time after deployment ($P < 0.001$, Table 2). Pairwise comparisons of reef type for each monitoring event

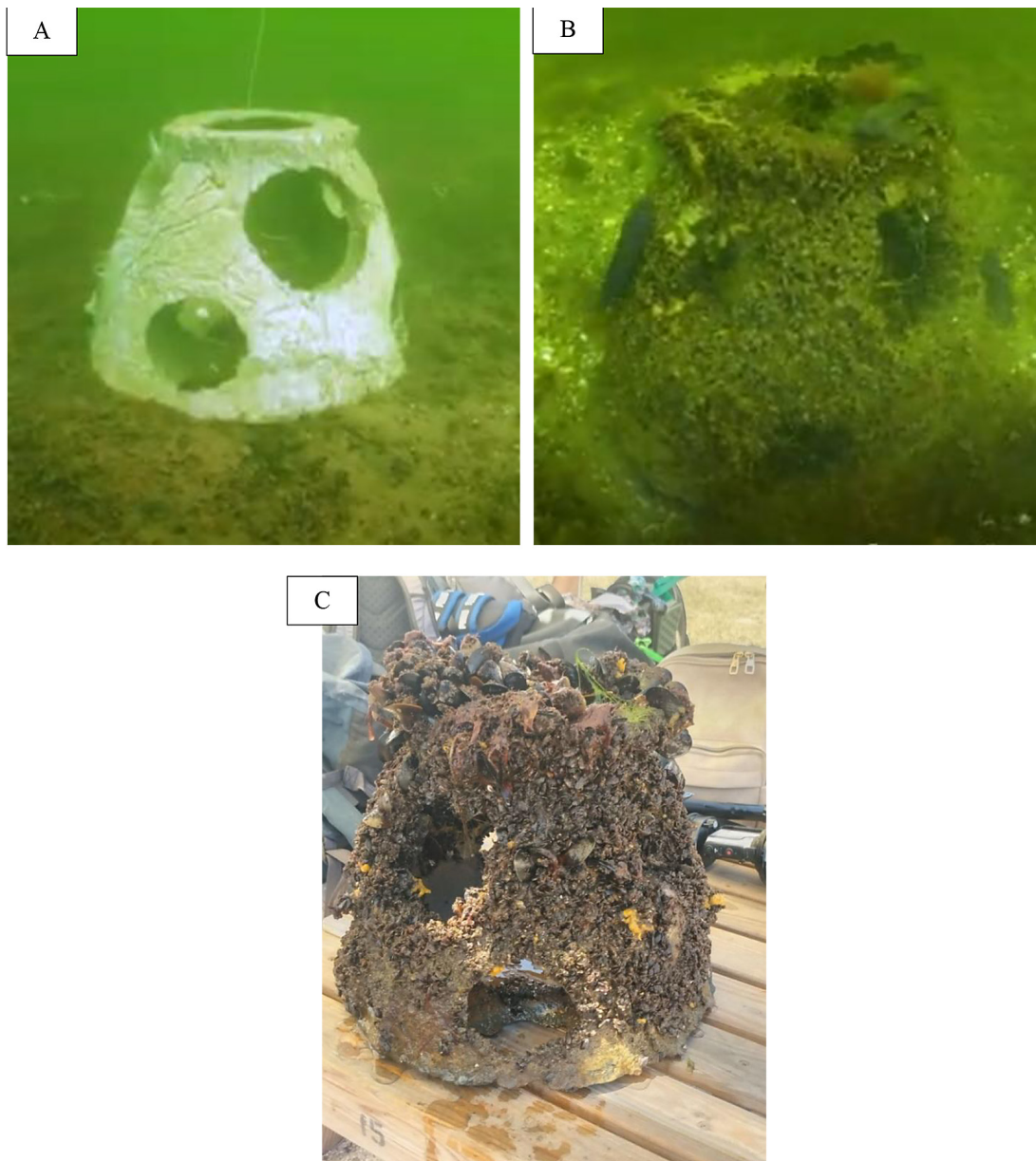


Figure 2. Dynamics of fouling of artificial reefs by zoobenthos representatives during 2024–2025: (a) beginning of the study, immediately after installation; (b, c) level of fouling of reefs by zoobenthos

showed that layered pies had significantly higher mussel biomass than reef balls after one year ($P < 0.001$). This difference decreased over successive monitoring periods and was no longer significant after 1.5 years.

The relative contribution of mussels to total biomass decreased over the course of the study. One year after deployment, the average biomass of the studied molluscs was 33% of the total biomass in reef ball plots and 22% in reef ball plots. After 2.5 years, the relative contribution decreased to 12% in reef ball plots.

At the beginning of summer, mussels reached a size of 4–5 mm and their biomass was 70% of

the biomass of all epibionts that settled on the reef. The biomass of macroepiphytes per cystosome in different seasons varied from tens to hundreds of grams per kilogram of shale. Moreover, the number of macrozoepiphyton on the reef compared to the surrounding environment increased by 6–7 times, and the biomass increased only by 2 times due to the high density, which limited the growth of individual individuals in the population. Although up to 30 or more invertebrate taxa were sometimes found on artificial reefs, the number of mass species usually did not exceed a dozen species. Moreover, the size of most animals was less than 10 mm [7].

Table 1. Results of the study of zoobenthos settled on reef balls

No.	L length of the mollusk shell	F phenotype	G genotype	H the height of the mollusk shell	B width of two sinks when they are closed
04.07.2025, Tiligul Reef with reefball 10*10 4 samples, m = 32.626 sample 1					
1	40.3	1	2	24	16.6
2	46.8	1	2	26.5	16.2
3	43	1	2	25.3	13.9
4	41.8	1	3	23.6	15
04.07.2025 ,Reef with reefball 10*10 24 samples, m = 175.344 sample 2					
1	32	3	2	18.3	11.2
2	41.8	1	1	24.3	14.8
3	45.3	1	2	24.7	15.9
4	43.6	1	3	25.3	15.7
5	41.8	1	1	23.3	14.4
6	43.2	1	1	26.1	16.7
7	40.6	1	1	27.5	15.6
8	48.1	2	3	27.2	18.6
9	47.7	1	1	24.9	18
10	44.8	1	1	25.9	18.3
11	48.9	1	1	28.2	18.4
12	48.3	1	1	28.5	18.7
13	48.3	1	1	27	17.3
14	48.1	1	1	26.7	18.3
15	50	1	1	27.5	18.1
16	50.4	1	3	26.8	18.9
17	51.8	1	1	28.3	19.6
18	52.2	1	1	28	19.7
19	53.8	2	3	30.5	20.3
20	55.2	3	1	29.9	21.4
21	53.1	1	2	30.7	17.4
22	54.8	3	1	32.6	20.2
23	58.4	2	1	30.3	21.8
24	53.5	3	3	30.7	19.9
04.07.2025 Reef with reefball 10*10 14 samples m=97.316 sample 3					
1	26.6	1	3	16.4	9.6
2	35.2	1	2	19.9	12.4
3	36.5	1	1	21.8	13.5
4	42.4	3	2	25.4	16.1
5	40.8	3	1	23.1	14.6
6	45.1	1	1	26.2	17.4
7	47.1	1	3	27.8	17.9
8	48.3	1	1	28	18.4
9	50.6	2	2	28.4	21
10	50.9	1	3	27.6	17.9
11	52	1	1	29.1	19.9
12	51.6	1	1	29.3	19.4
13	53.4	1	3	28.1	19.8
14	59.9	1	1	31.9	22

Table 2. Modeling approach, fixed and random coefficients of the best-fitting model, and repeatability for each response variable

Response variable	Modeling approach	Data transformation	Fixed factors best fit model	Model best fit random factors	Replication
Total biomass of mussels (graph g ⁻¹)	LMM *	Cube root	Time before deployment + time after deployment	Reef ID + location	10 examinations at 3 locations over 3 monitoring periods and 3 examinations at 3 locations over 1 monitoring period = 99 examinations per case processed
Mussel biomass (graph g ⁻¹)	LMM	Cube root		I Reef ID + location	
Total number of mollusks (n _{sites} ⁻¹)	GLMM **	–		Reef ID	
Territorial abundance of mussels (n sites ⁻¹)	GLMM	–		Reef ID	
Territorial behavior (hour of chasing ⁻¹)	GLMM	–	Biomass growth	Reef ID + location	6–11 videos in 3 locations = 26 videos with reef balls and 25 videos with layer cakes
Grazing intensity (g·h ⁻¹)	LMM		Biomass growth		
Benthic cover (% per main group)	Multidimensional GLM***	–	Biomass growth + time after deployment	–	2–3 modules at 3 locations over 4 monitoring periods = 28 reef ball surveys and 36 bottom sediment surveys
The number of coral inhabitants (n-module ⁻¹)	GLMM	–	Biomass growth + time after deployment	Artificial reef module identifier + arrangement	
Survival of coral inhabitants (n-module ⁻¹)	LMM	–	Time after deployment	Artificial reef module identifier	
Size of coral inhabitant (mm ²)	LMM	Cube root	Biomass growth + time after deployment	Coral ID + arrangement	16–48 corals on bottom reefs and 19–38 corals on reef balls during 4 monitoring events
Growth of a coral inhabitant (mm ² ·pik ⁻¹)	LMM	Cube root	Monitoring interval	Coral ID + arrangement	16–50 corals on bottom reefs and 19–38 corals on reef balls during 3 monitoring intervals

Note: *LMM – linear mixed model, **GLMM – main linear mixed model, ***GLM – generalized linear model.

CONCLUSIONS

The potential for reef balls to attract territorial mussels and the subsequent relative increase in territorial behavior of these mollusks is therefore quite high. The biomass of mollusks on artificial reefs also appeared to be high enough to effectively control macroalgae, and the higher grazing intensity documented on reef balls resulted in small but significant differences in benthic community development.

Sedimentation was a likely factor explaining the negative growth rates, and highlights the importance of proper site selection when considering the deployment of artificial reefs. Despite their small size, the experimental reefs used in this study provided additional habitat for fish, coral recruits, and other marine organisms. We therefore expect that larger artificial reefs, if properly designed and managed, could potentially provide

additional value in terms of habitat, biodiversity, and ecosystem services. Therefore, future comparative studies will be conducted that include larger artificial reefs, natural reefs and sandbanks to determine the net benefit of artificial reefs to the wider ecosystem of the Tiligul Estuary. In addition, new artificial reef designs should be investigated that combine the advantages of reef balls (holes) and other types of artificial structures (high and diverse cover availability) to better support mussel populations.

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