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Article

Changes in zooplankton communities in Kazan city waterbodies after remediation activities

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Abstract. In 2019–2020, remediation activities in the Komsomolsky pond and Lake Maryino were carried out in the Kazan city (Volga River, Russia). During these works, bottom sediments were extracted using the Geotube® technology, submerged macrophytes were removed, and the coastal zone was developed. Water aerators were additionally installed in Lake Maryino. In both waterbodies, a decrease in their trophic status was observed after the activities performed. The zooplankton diversity in the Komsomolsky pond increased from 30 to 48 species, rotifers and cladocerans prevailed. In Lake Maryino, the number of species increased from 41 to 52, rotifers prevailed. After the activities were completed, frequent changes in the dominant zooplankton species and dominating of a single species were observed during the first year. In subsequent years, two or three species dominated. The lowest abundance and biomass were registered during the remediation period; these indicators have increased in subsequent years. During the remediation period and immediately after it, the greatest variability of zooplankton abundance and biomass throughout the vegetation period was noted. Over time, the fluctuation range has decreased, and the communities became more stable. No obligate predators were found in zooplankton trophic chains of Lake Maryino; in the Komsomolsky pond, they were registered singly, without making a significant contribution to the energy transformation. Cladocerans and rotifers contributed the most to the energy flows. After the remediation activities, the production of zooplankton communities increased.

Keywords: lake, remediation, community, eutrophication, bioindication, food webs, water quality, pollution

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Научная статья

Изменение зоопланктона водоемов г. Казани после проведения мероприятий по экореабилитации

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Аннотация. Мероприятия по экореабилитации водоемов Комсомольское и Марьино были проведены в г. Казани (Россия) в 2019–2020 гг. В ходе работ из водных объектов были извлечены донные отложения при помощи технологии «Геотьюб», удалены погруженные макрофиты, благоустроена прибрежная зона. В оз. Марьино дополнительно были установлены аэраторы воды. В обоих случаях после проведенных мероприятий наблюдалось снижение трофического статуса водоемов. Число выявленных видов зоопланктона в пруду Комсомольском увеличилось с 30 до 48, преобладали коловратки и ветвистоусые ракообразные. В оз. Марьино число видов увеличилось с 41 до 52, преобладали коловратки. В первый год после завершения мероприятий наблюдалась частая смена доминирующих видов зоопланктона, монодоминирование. В последующие годы доминировали два–три вида. Наименьшие значения численности и биомассы наблюдались в период проведения работ по экореабилитации, в последующие годы эти показатели увеличились. В период проведения мероприятий по экореабилитации и непосредственно после их завершения наблюдалась наибольшая изменчивость численности и биомассы зоопланктона на протяжении вегетационного периода и наибольшая вариабельность биомассы. По прошествии времени размах колебаний снизился, сообщества стали более стабильными. В трофических цепях зоопланктона оз. Марьино отсутствуют облигатные хищники, а в пруду Комсомольском они встречаются единично, не внося существенного вклада в трансформацию энергии. Основные потоки энергии проходят через звенья ветвистоусых и коловраток. После проведенных работ увеличилась продукция сообществ зоопланктона.

Ключевые слова: озеро, восстановление, сообщество, эвтрофирование, биоиндикация, трофические сети, качество воды, загрязнение

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Introduction

Waterbodies located in urbanized areas experience the anthropogenic load, which leads to water quality deterioration, disruption of the structure of aquatic communities, and a decrease in the recreational value. Urban development in some cases is accompanied by the development of new territories, backfilling of waterbodies, or, conversely, filling the newly dug pits with water, so they become small waterbodies (Mingazova et al., 2014). Small lakes have a small volume of water, so they are highly susceptible to external influences: in particular, pollutants coming from storm water, emergency wastewater, surface runoff; this preconditions an unpredictable mixing regime and a rapid response to changing environmental conditions (Mansfield et al, 2014). In artificial waterbodies, the water composition is determined primarily by anthropogenic factors (Mingazova et al., 2008).

Waterbodies of urban territories are important elements of landscapes, they create a mosaic of habitats and contribute to the conservation of biodiversity of aquatic and semi-aquatic organisms in the transformed urban environment (Bolduc et al., 2016; Celewicz-Goodyn and Kuczyńska-Kippen, 2017; Cereghino et al., 2008a). Waterbodies and streams are places of attraction for local residents, who use them for recreation and fishing (Cereghino et al., 2008b; Kuczyńska-Kippen and Joniak, 2016; Pinel-Alloul and Mimouni, 2013; Stefanidis and Papastergiadou, 2010). Due to the intensive anthropogenic impact on natural areas, restoring polluted, heavily transformed waterbodies and including them in the composition of created recreational zones call for urgent action. In recent years, much attention in Russia has been paid to develop a comfortable urban environment, and state-funded programs are being implemented. The integral elements of these territories are landscaped green areas, embankments, and waterbodies. However, the analysis of a number of already implemented projects shows that the environmental features of the territories are rarely taken into account, as well as the impact of remediation on natural objects. Often, the measures taken lead to a deterioration in the ecological state of natural areas, increasing the load. Unfortunately, only single successful examples of restoration of polluted or disappeared waterbodies exist (Derevenskaya and Gallyamova, 2021; Derevenskaya and Urazaeva, 2020; Gerasimov and Shabanova, 2018). Moreover, the ecosystem successions in these waterbodies have not been sufficiently studied. In this regard, research of zooplankton community succession is relevant in restored lakes.

Remediation activities were carried out on two small shallow waterbodies, Komsomolsky pond and Lake Maryino, located in Kazan (Republic of Tatarstan, Russia). The waterbody "Komsomolsky pond" is of artificial origin, it is a pit filled with groundwater. A constant water level is maintained by artificially feeding groundwater (in summer). The pond is small and shallow (Table 1).

A beach was organized on the north-eastern side of the pond, which was very popular place of recreation for local residents. Gradually, the waterbody silted up, the depth decreased, and the water quality worsened. In recent years, swimming in the pond was prohibited due to unsatisfactory sanitary and microbiological indicators. At numerous requests from local residents, the project was developed to perform the remediation activities and to improve its coastal zone. During the project implementation, the pond depth was increased and the bottom sediments were partially removed using small dredgers. Geotube® technology was used to remove the silt. According to this technology, the pumped-out pulp is placed in special containers made of dense fabric that allows water to pass through, but does not allow suspended particles to do this. After the water drained, the extracted bottom sediments were taken away and disposed. Sand was brought to the coastal zone, the beach area was organized, and the adjacent territory was improved. Remediation were carried out in June–August 2019, after which the water level in the pond was raised again.

Lake Maryino is located on the site of a former swamp massif, which has now been almost completely drained, then numerous residential multi-storey buildings were built here. Lake Maryino is small, it is fed both by groundwater and surface runoff (Table 1). A fairly large layer of organic matter had accumulated at the lake bottom. The organic matter decomposition led to a deficiency of dissolved oxygen, to formation of hydrogen sulfide, so the surface of the lake was covered with a thick layer of filamentous algae in summer. An increased content of biogenic elements was noted in the bottom layers. The lake is surrounded by multi-storey buildings, it is the central element of the Maryino ecopark

Table 1. Morphometric characteristics of the studied waterbodies.

Water body	Area, ha	Maximum depth, m	Average depth, m	Length, m	Width, m
Komsomolsky pond	1.76	3.7	0.8	313.0	67.0
Lake Maryino	0.9	1.6	0.5	184.1	64.2

in the area with extremely insufficient landscaping. In order to improve the aesthetic properties of the waterbody and to create a natural landscape, the Lake Maryino remediation project was developed and implemented. Part of the bottom sediments were removed using Geotube® technology, excess higher aquatic plants were removed as well, an aeration system was installed, and the coastal park area was improved. The work was carried out in April–August 2020.

Therefore, a similar set of restoration measures was applied for two small waterbodies in the city of Kazan. As remediation measures were completed, a new stage of succession of aquatic communities began. When the state of the aquatic ecosystem has at least aesthetic qualities restored, this allows us to consider the measures taken were successful. In order to assess the ongoing ecosystem changes, it is necessary to consider representatives of different trophic levels. Zooplankton communities are organized biological systems closely related to other components of ecosystems. Therefore, any impact on the lake ecosystem entails a change in the species composition, quantitative characteristics, ratios of taxonomic groups and other indicators of the structural organization of zooplankton. All these make zooplankton community state an objective indicator of water quality as a habitat. In addition, the zooplankton community comprises the representatives of different trophic levels, which allows one to track changes in the trophic structure during the period of restoration measures and after they are completed (Anton-Pardo et al, 2013). Therefore, the zooplankton community was an object to assess the changes occurring in waterbodies.

The study aims to assess the changes in zooplankton communities during the period of restoration activities and after their completion by the example of two small waterbodies in the city of Kazan (Komsomolsky pond and Lake Maryino).

Materials and methods

The study covers three periods, differing in the load intensity on the waterbodies:

Period before the measures were applied. The studies were conducted in August 2007 and June 2014 on Komsomolsky pond and during the vegetation period (from May to September) 2019 on Lake Maryino. The anthropogenic impact on waterbodies was mainly due to their recreational use; polluted surface runoff might have also possible effect; the load from accumulated bottom sediments was quite significant.

The period of remediation activities. Activities were carried out on Komsomolsky pond in June–August 2020, on Maryino Lake, in April–August 2021. The removal of bottom sediments had a significant impact on all components of the ecosystem: mechanical impact from the dredge operation, bottom sediment mixing, and releasing the accumulated pollutants and biogenic elements from bottom sediments into the water.

Post-activity period. The studies were conducted during the growing season: in 2020–2022 at Komsomolsky pond and in 2021–2022 at Lake Maryino.

The lake studies comprised measuring the physical and chemical parameters of water and zooplankton sampling. Water temperature and dissolved oxygen content were measured using a Mark 302e oxygen meter, electrical conductivity, by a DIST HI 98312 conductometer (Hanna, Romania), pH, by portable conductometer pHep+ HI 98108 (Hanna, Romania). Hydrochemical analysis was performed in accredited laboratories by generally accepted methods. Water quality was assessed by comparing obtained physicochemical indicators with maximum permissible concentrations for fishery waterbodies (MPC_{fw}) and according to the ecological and sanitary classification of surface water quality (Romanenko et al., 1990).

Zooplankton samples were collected in the littoral zone of the lakes by filtering 50 L of water through an Apstein plankton net (mesh size of 100 μm). The sampling was performed every 10–14 days during the growing season (from May to October). The abundance and biomass of zooplankton were calculated for each sampling site. The weight of zooplankton organisms was calculated using power length-to-mass equations (Metodologicheskie..., 1982). The community structure and species diversity of zooplankton were assessed using the Shannon index (H) in terms of abundance and biomass (Shannon and Weaver, 1949). The saprobity index (S) was calculated according to Pantle and Buck as modified by Sladečhek (Sladečhek, 1973) to assess water quality. Similarity index was calculated to assess the similarity of the zooplankton species composition in different study periods (Sørensen, 1948).

In order to identify the trophic structure of zooplankton, all zooplankton species were assigned to relevant trophic link in accordance to their food spectra as reported in (Gutelmakher et al., 1988; Ivanova, 1999; Krylov, 1989; Kutikova, 1970; Monakov, 1998). After that, probable trophic chains in the zooplankton communities were developed in regard to the study period and studied waterbody; their dynamics was analyzed. The trophic groups of zooplankton were: herbivorous rotifers, herbivorous cladocerans and copepods (representatives of the families Sididae, Daphniida, Chydoridae, Bosminidae, naupliar and copepodite stages of Cyclopoida), rotifers (genus *Asplanchna*), omnivores (copepods, except naupliar and copepodite stages of Cyclopoida), predatory crustaceans (*Leptodora kindtii* (Focke, 1844), *Polyphemus pediculus* (Linnaeus, 1761)). Herbivorous rotifers and herbivorous crustaceans belonged to the same trophic level, but they were classified into different groups. This was because the size range of consumed food particles differed significantly; in addition, they were eaten by different predators. A separate group included rotifers of the genus *Asplanchna,* which were omnivorous, consuming both phytoplankton and small rotifers.

Production of the zooplankton community was calculated using the physiology-based approach to assess the change in ecosystem productivity after remediation. The generally accepted equation was applied (Metodologicheskie..., 1982):

$$P = R \times k_2/(1-k_2),$$

where P is production, cal/(m^3 × day); R, energy for metabolic exchange, cal/(m^3 × day); k_2, the efficiency coefficient of using assimilated food energy for production.

The metabolic costs were calculated as:

$$Q = a \times w^{a/b},$$

where Q is the rate of oxygen consumption at 20 °C, mL O_2/(ind. × h); w, average body weight (wet weight, g); a and a/b, the average values of the constants (Metodologicheskie..., 1982).

The average rate of oxygen consumption was found by multiplying Q by 24 (hours), average body weight of a zooplankton specimen, by dividing the biomass by the population size. The transformation coefficient was set as 4.86 cal/mL O_2. When the water temperature at sampling deviated from 20 °C, a correction coefficient was introduced:

$$q = 2.3^{0.1(t-20)},$$

where t is the actual water temperature, °C.

The production and metabolic costs were initially calculated for zooplankton species that formed communities, then for the trophic groups in regard of their species composition. The production of the entire community and specific trophic groups and the metabolic costs for the growing season were calculated using the trapezoid method.

The data were subject to statistics. The average values of the abundance and biomass of zooplankton and biotic indices, errors of the mean, standard deviations, and significance were calculated. The stability of communities was assessed by the coefficient of variation (*CV)* in terms of zooplankton abundance and biomass in regard to the study periods.

Results

In the Komsomolsky pond, in July and August 2007 and in June 2014, water oxygen saturation was high, ranging as 10.7–17.3 mg/dm^3 in the surface water layer and 7.1–3.6 mg/dm^3 in the near-bottom layer. The water pH was neutral, hydrocarbonate-calcium type, calcium cations and sulfate anions were dominant. The pond was replenished with groundwater with a high sulfate content; this has caused increasing of the maximal allowable concentration (MAC) of sulfates by 6.7 times comparing the MPC (maximal permissible concentration)[1]. The electrical conductivity was 1209–1430 μS/cm. The sum of ions varied from 953 to 1402 mg/dm^3. Therefore, in Komsomolsky pond, the water was weakly mineralized (GOST R 54316–2011). The water was "very hard" (12.20–15.30 mg-eq./dm^3)[2]. Ammonium ions' content exceeded the MPC_{fw} in 3.3 times. Concentrations of other nitrogen compounds and phosphates were low and did not exceed permissible limits. The content of easily oxidizable organic matter (based on BOD_5) was high (2.7–6.2 mg O_2/dm^3). High content of petroleum products (pollutant) was also detected in the water (up to 1.9 MPC_{fw}). Therefore, before the remediation was performed in the Komsomolsky pond, the water was contaminated with compounds of biogenic elements, organic substances, and petroleum products, which may be a consequence of recreational use, as well as the influx of contaminated surface runoff.

During the remediation activities at the Komsomolsky pond, oxygen content in the water decreased below the permissible standards, which might be due to the influx of organic matter from the bottom sediments and its subsequent oxidation. After the activities have been completed, the oxygen content has increased again (Fig. 1**A**). High electrical conductivity and water mineralization were due to the influx of groundwater. During the activities, groundwater was not directed into the pond, which caused a decrease in electrical conductivity (Fig. 1**B**).

In Lake Maryino, the mineral composition of the lake water was relatively stable in 2005, 2007, 2012, and 2018. Hydrocarbonates were dominant anions, the cations were either sodium or sodium/calcium. Water was "moderately hard". Water conductivity ranged from 460 to 670 μS/cm. Water mineralization was relatively high, varying within 500–613 mg/dm^3. In Lake Maryino, as well as in the Komsomolsky pond, there was excess in ammonium ions (sixfold in regard to MPC_{fw}) and in easily oxidizable organic substances (5.2 times, in regard to BOD_5). Concentrations of some heavy metals were also elevated: copper levels exceeded MPC by 7.8 times, zinc, by 8.4 times, and manganese, by 1.6 times. The quality of the water in the lake could be described as "slightly polluted." The water had a deficiency of oxygen, its concentration in the summer dropped down to 3.55 mg/dm^3, hydrogen sulfide was present. The water had an alkaline reaction, the pH values increased up to 9.4. High pH values were a consequence of the active photosynthesis of filamentous algae, which developed actively and in large quantities in the lake (Table 2).

During the remediation activities (2020), the oxygen content dropped down to 4 mg/dm^3, probably, due to the decomposition of organic matter that entered the water from disturbed bottom sediments. After the works have been completed, aerators were installed in the lake; this increased the oxygen content in the water, and the electrical conductivity of the water decreased (Table 2).

Structure of the zooplankton community in the Komsomolsky pond

In 2007 and 2014, 25 zooplankton species were found; however, regard must be paid to random samplings. During the remediation period (2019), 30 species were identified; in subsequent years, the species number increased up to 34 species in 2020, 48 species in 2021, and 46 species in 2022. Rotifers predominated as a taxonomic group before and after the remediation activities, accounting for 41–56% of the total species number. Cladocera dominated during the period of the activities (47%).

The species composition of zooplankton had the greatest similarity in 2020–2022 after the restoration measures were completed (Fig. 2).

[1] Order of the Ministry of Agriculture of Russia dated 13.12.2016 No. 552 "On the approval of water quality standards for water bodies of fishery importance, including standards for maximum permissible concentrations of harmful substances in the waters of water bodies".

[2] GOST R 54316–2011. Natural mineral drinking waters.

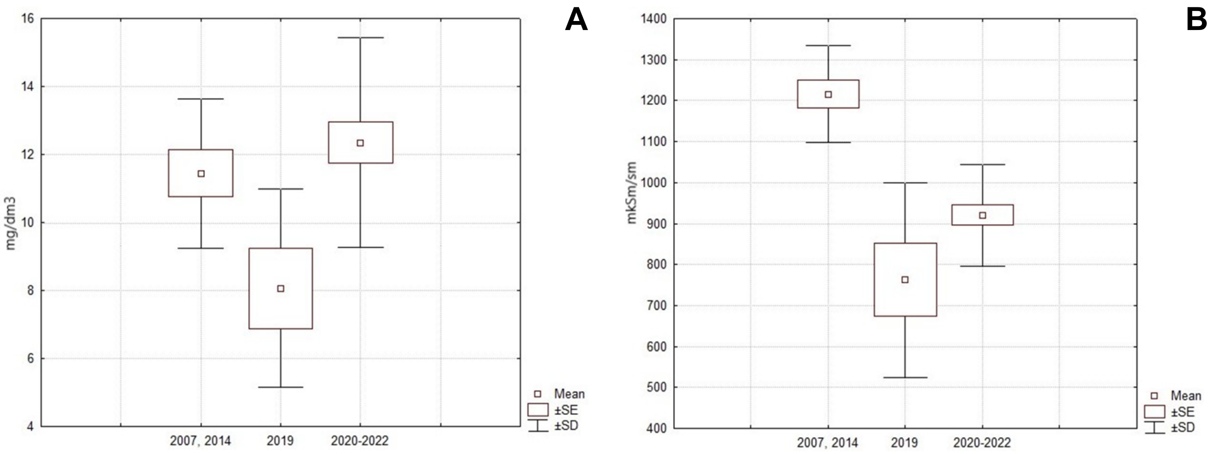

Fig. 1. Average concentration of dissolved oxygen (mg/dm^3) (**A**) and electrical conductivity (μS/cm) (**B**) in Komsomolsky pond in different periods of the study.

Table 2. Physicochemical parameters of water in Lake Maryino during different periods of study. M ± m – mean value and error of the mean, min – max – maximum and minimum values.

Parameter		Year			
		2019	2020	2021	2022
Temperature, °C	M ± m	15.2 ± 1.3	19.5 ± 1.3	21.7 ± 1.6	18.7 ± 1.8
	min–max	8.7–19.6	13.0–27.5	8.9–28.0	11.9–25.9
Oxygen, mg/dm^3	M ± m	7.3 ± 1.3	9.1 ± 1.0	11.0 ± 0.9	9.6 ± 1.1
	min–max	3.5–10.6	4.5–14.5	6.9–15.8	6.0–16.1
Electrical conductivity, microsiemens/cm	M ± m	668 ± 30	657 ± 9	600 ± 12	626 ± 16
	min–max	610–840	610–720	540–690	560–700
pH, units	M ± m	7.3 ± 0.3	7.4 ± 0.1	7.4 ± 0.2	7.6 ± 0.2
	min–max	6.8–9.4	7.0–7.8	6.9–8.6	7.2–8.2

The average number of species per sample is another indicator characterizing the changes in zooplankton species richness. This indicator has an advantage: it does not depend on the number of samples taken. In the Komsomolsky pond, the lowest values of this indicator were registered before the start of the activities and during their implementation (Fig. 3).

In 2007 and 2014, the dominant species (in terms of abundance) were rotifers *Asplanchna girodi* de Guerne, 1888, *Brachionus angularis* Gosse, 1851, *Keratella cochlearis* (Gosse, 1851), and cladoceran *Bosmina longirostris* (O.F. Muller, 1785); in terms of biomass, copepods *Thermocyclops oithonoides* (Sars, 1863), *Eudiaptomus gracilis* (Sars, 1863) and their juvenile stages, rotifers *Asplanchna priodonta* Gosse, 1850 and *A. girodi.* During remediation, a permanent complex of dominant species was not formed. Regard must be paid to omnivorous rotifer *A. girodi,* which dominated both by abundance and biomass during the growing season more often than other species, herbivorous copepods *E. gracilis* was also dominating by biomass for frequently than others. In the subsequent period, the number of dominant species increased significantly. *A. priodonta*, *A. girodi*, *Keratella quadrata* (Mùller, 1786), *Filinia longiseta* (Ehrenberg, 1834), *Synchaeta stylata* Wierzejskii, 1893, as well as naupliar and copepodite stages of cyclops were dominants by abundance. Facultative predator *A. priodonta*, copepods *E. gracilis*, *Mesocyclops leuckarti* (Claus, 1857), naupliar and copepodite stages of cyclops dominated by biomass.

The zooplankton abundance and biomass experienced significant changes during the study periods. The average zooplankton abundance decreased from 273.56 ± 60.70 thous. ind./m^3 to 217.59 ± 91.49 thousand ind./m^3 during the remediation period, biomass, from 2.18 ± 1.13 g/m^3 to 0.82 ± 0.28 g/m^3 (Table 3). Rotifers prevailed both by abundance and biomass in 2007 and 2014, cladocerans, in 2019. In 2020, zooplankton abundance and biomass were low: 58.67 ± 15.47 thous. ind./m^3 and 0.48 ± 0.27 g/m^3, respectively (Fig. 4). This was probably due to the load effects of the remediation

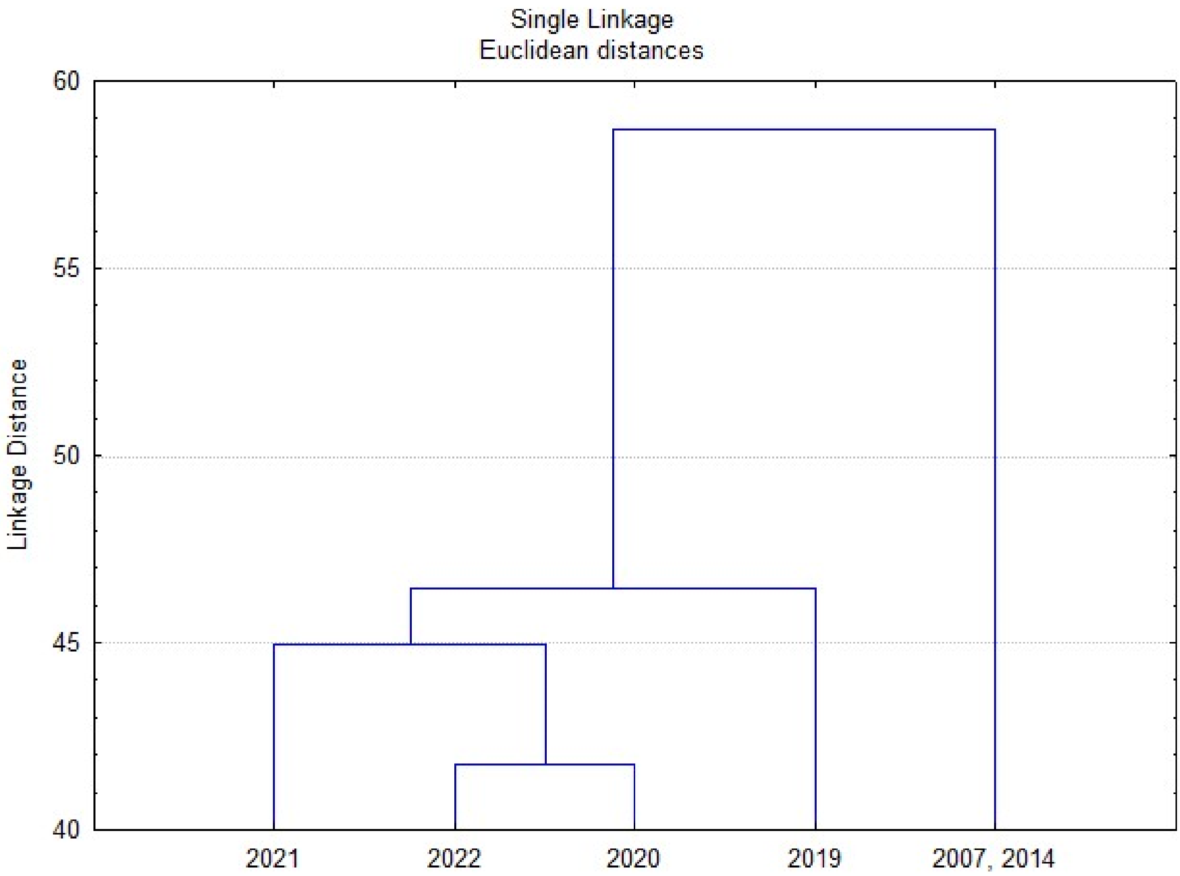

Fig. 2. Dendrogram of similarity of zooplankton species composition in Komsomolsky pond in 2007–2022.

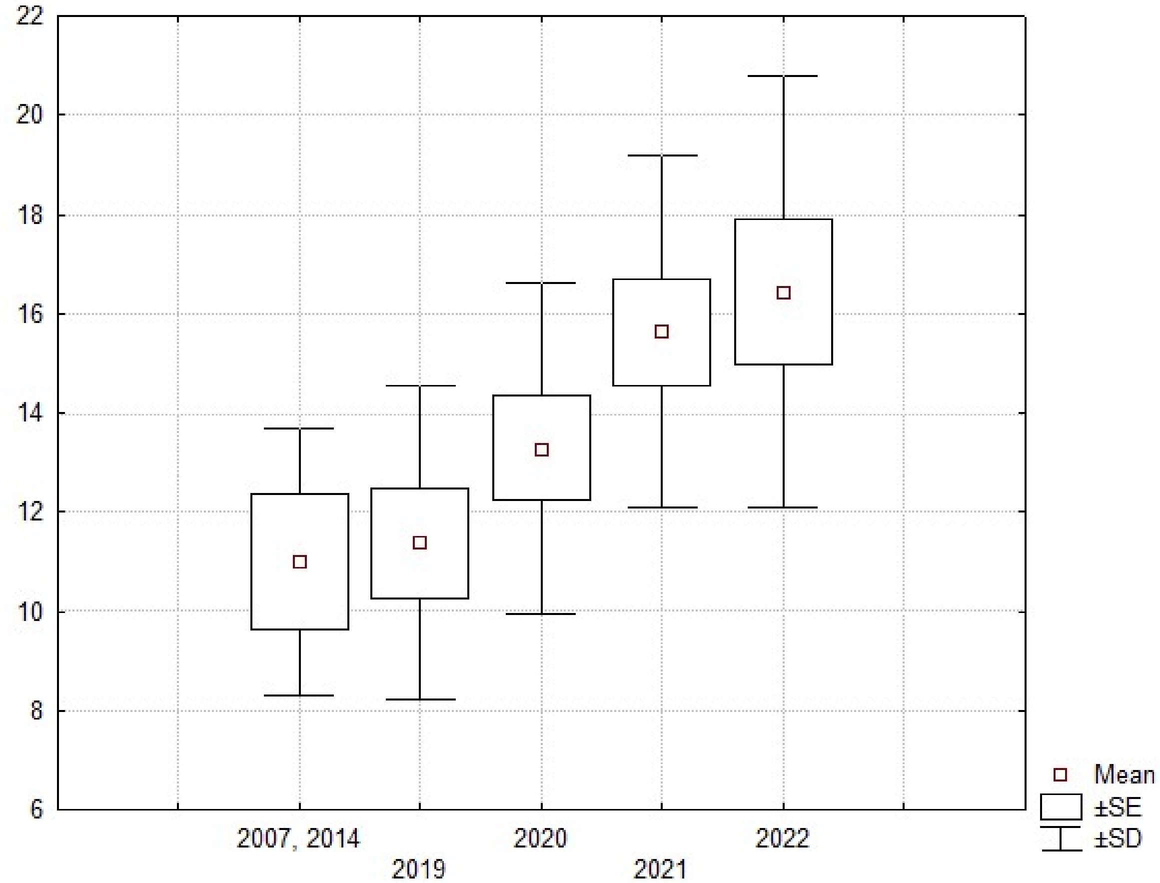

Fig. 3. Average number of species in a zooplankton sample of Komsomolsky pond in 2007–2022.

measures. In subsequent years, the quantitative indicators increased significantly, indicating a gradual recovery of the zooplankton community. During the remediation period, Cladocera and Copepoda made the greatest contribution to the total abundance and biomass of zooplankton, but as the works have been finished, rotifers dominated.

The biological system structure is affected by environmental factors. The smaller the range of fluctuations of a system indicator in response to external changes, the more stable the system is. In relatively simple systems, the fluctuation range of structural and functional indicators increases compared to more complex ones. This range of quantitative indicators may be used to characterize the degree of complexity of the community structure and the stability of the entire system (Alimov et al., 2013). The ratio of the minimum to maximum biomass during the growing season (*B*min/max), or biomass variability was previously proposed as such an indicator (Alimov et al., 2013). In the Komsomolsky pond, the greatest variability of zooplankton biomass was observed in the first year after the remediation measures were completed (Table 4). In subsequent years, the range of biomass fluctuations during the growing season decreased, which indicated an increase in the stability of the system.

The variation coefficient (CV) was calculated to assess the variability of zooplankton abundance and biomass. In the Komsomolsky pond, the greatest variability of zooplankton abundance was noted during the period of the activities, of biomass, immediately after their completion (Table 4); this reflected the process of zooplankton recovery after the impact.

The Shannon index was used to assess the complexity of the zooplankton community structure. In Komsomolsky pond, the lowest average index was registered before and during the activities, both in

Table 3. Average values of abundance and biomass of zooplankton in Komsomolsky pond in 2007–2022.

Taxonomic group	Year				
	2007, 2014	2019	2020	2021	2022
			Abundance, thous. ind./m^3		
Rotifera	199.32 ± 54.91	44.38 ± 18.13	31.12 ± 9.15	55.84 ± 15.03	72.14 ± 30.30
Cladocera	19.52 ± 18.71	105.91 ± 98.22	14.78 ± 7.18	31.05 ± 16.77	10.64 ± 6.43
Copepoda	54.72 ± 19.04	67.31 ± 24.09	12.76 ± 3.37	64.76 ± 22.53	52.59 ± 19.16
Total	273.56 ± 60.70	217.59 ± 91.49	58.67 ± 15.47	151.66 ± 39.66	135.37 ± 46.85
			Biomass, g/m^3		
Rotifera	1.71 ± 1.15	0.18 ± 0.11	0.12 ± 0.07	0.60 ± 0.22	0.45 ± 0.17
Cladocera	0.05 ± 0.05	0.33 ± 0.28	0.32 ± 0.27	0.33 ± 0.19	0.09 ± 0.04
Copepoda	0.41 ± 0.13	0.32 ± 0.10	0.04 ± 0.01	0.53 ± 0.41	0.22 ± 0.08
Total	2.18 ± 1.13	0.82 ± 0.28	0.48 ± 0.27	1.47 ± 0.59	0.75 ± 0.20

Table 4. Biomass variability (Bmin/max) and the variation coefficient of zooplankton abundance (CV_N) and biomass (CV_B) in Lake Maryino.

Parameter	Year			
	2019	2020	2021	2022
B min/max	0.036	0.005	0.010	0.022
CV_N, %	119	83	87	104
CV_B, %	97	178	132	81

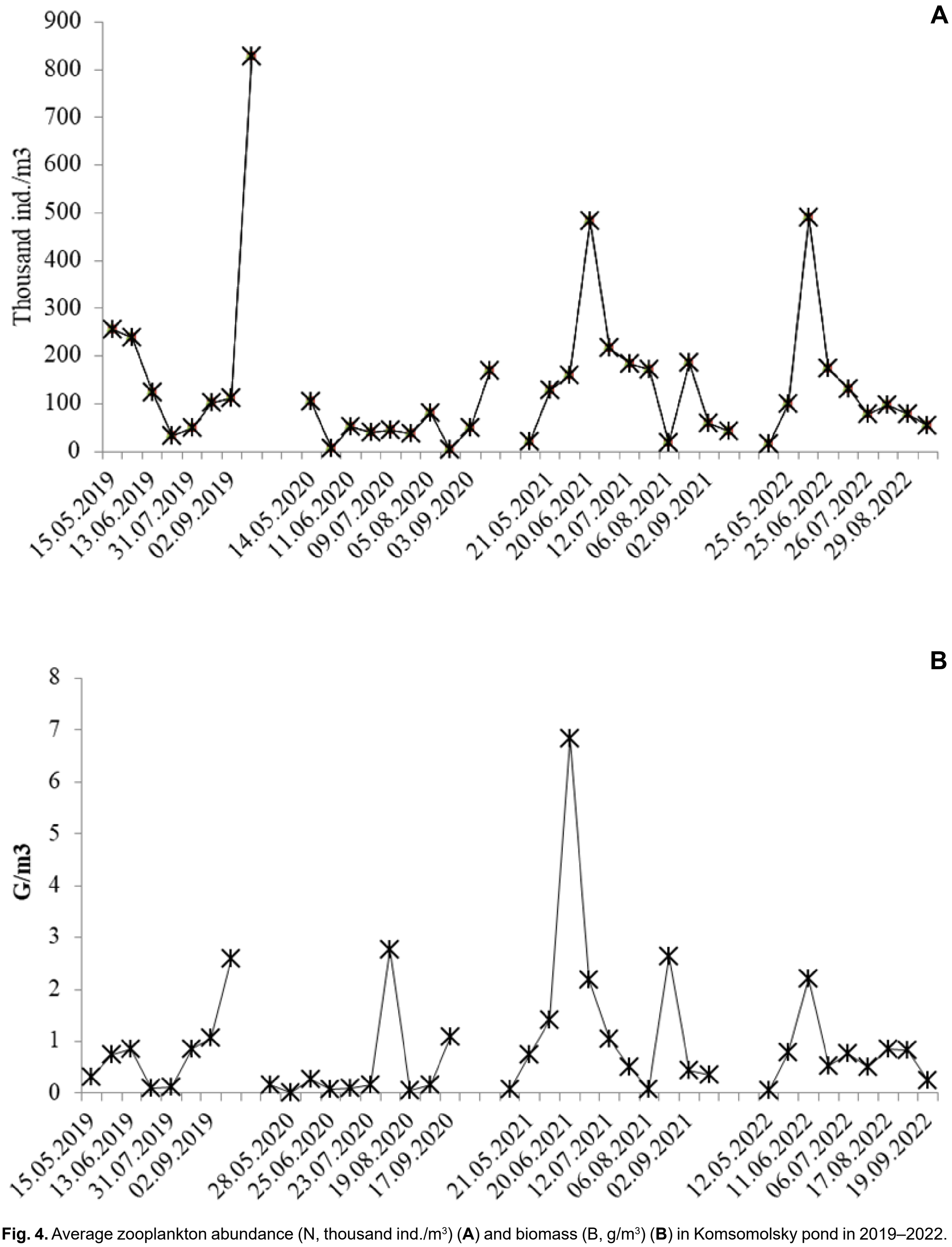

Fig. 4. Average zooplankton abundance (N, thousand ind./m^3) (**A**) and biomass (B, g/m^3) (**B**) in Komsomolsky pond in 2019–2022.

terms of abundance (H_N) and biomass (H_B) (Fig. 5). After remediation was completed, the Shannon index increased. The average Shannon index corresponded to eutrophic waterbodies (Andronikova, 1996).

The saprobity index, characterizing the degree of organic pollution of the lake, varied from 1.76 ± 0.04 in 2014 to 1.63 ± 0.04 in 2022, which corresponded to the β-mesosaprobic zone (water quality class III).

Zooplankton communities include representatives of different systematic groups, and zooplankton organisms may belong to several trophic levels. Most species of rotifers and cladocerans consume food of plant origin, detritus, and bacteria. Many copepods are facultative predators, consuming both animal and plant food. Among planktonic organisms, there are also obligate predators (Monakov, 1998). Various types of anthropogenic impact change the structure of communities, including the trophic structure, which leads to simplification of trophic webs and changes in the entire ecosystem (Reimers, 1994). Therefore, one can indirectly conclude on the processes occurring in a reservoir by observing the changes occurring in the trophic webs of zooplankton communities under conditions of various impacts or in their absence.

In the Komsomolsky pond, the main energy flows passed through cladocerans, but the role of rotifers increased in 2022 (Fig. 6). The production of facultative predatory crustaceans was small; the production of rotifers of the genus *Asplanchna*, feeding on both animal and plant food, was much higher. They utilized the biomass formed by small rotifers, protozoa and algae. Obligate predators *L. kindtii* were encountered singularly, and were not observed in the first year after remediation was completed. The total zooplankton production increased significantly the following year, after the implementation of the remediation program, but decreased again a year later.

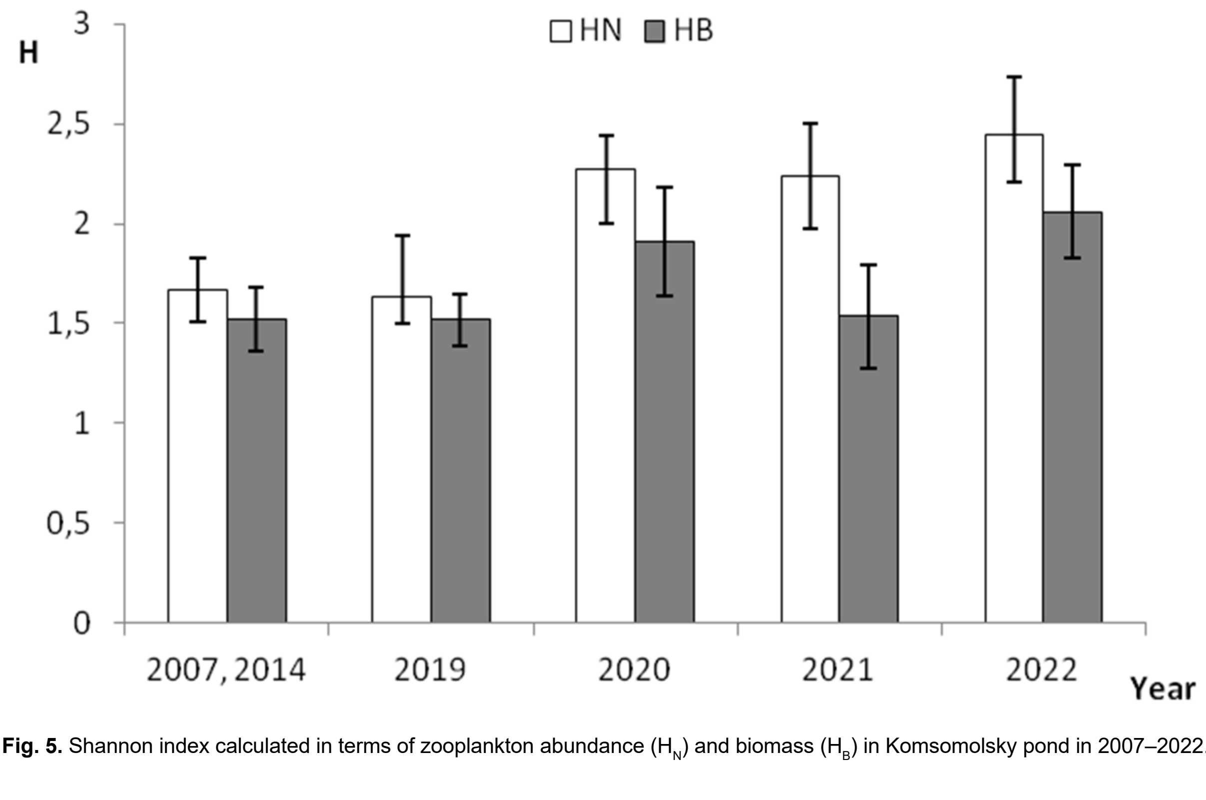

Fig. 5. Shannon index calculated in terms of zooplankton abundance (H_N) and biomass (H_B) in Komsomolsky pond in 2007–2022.

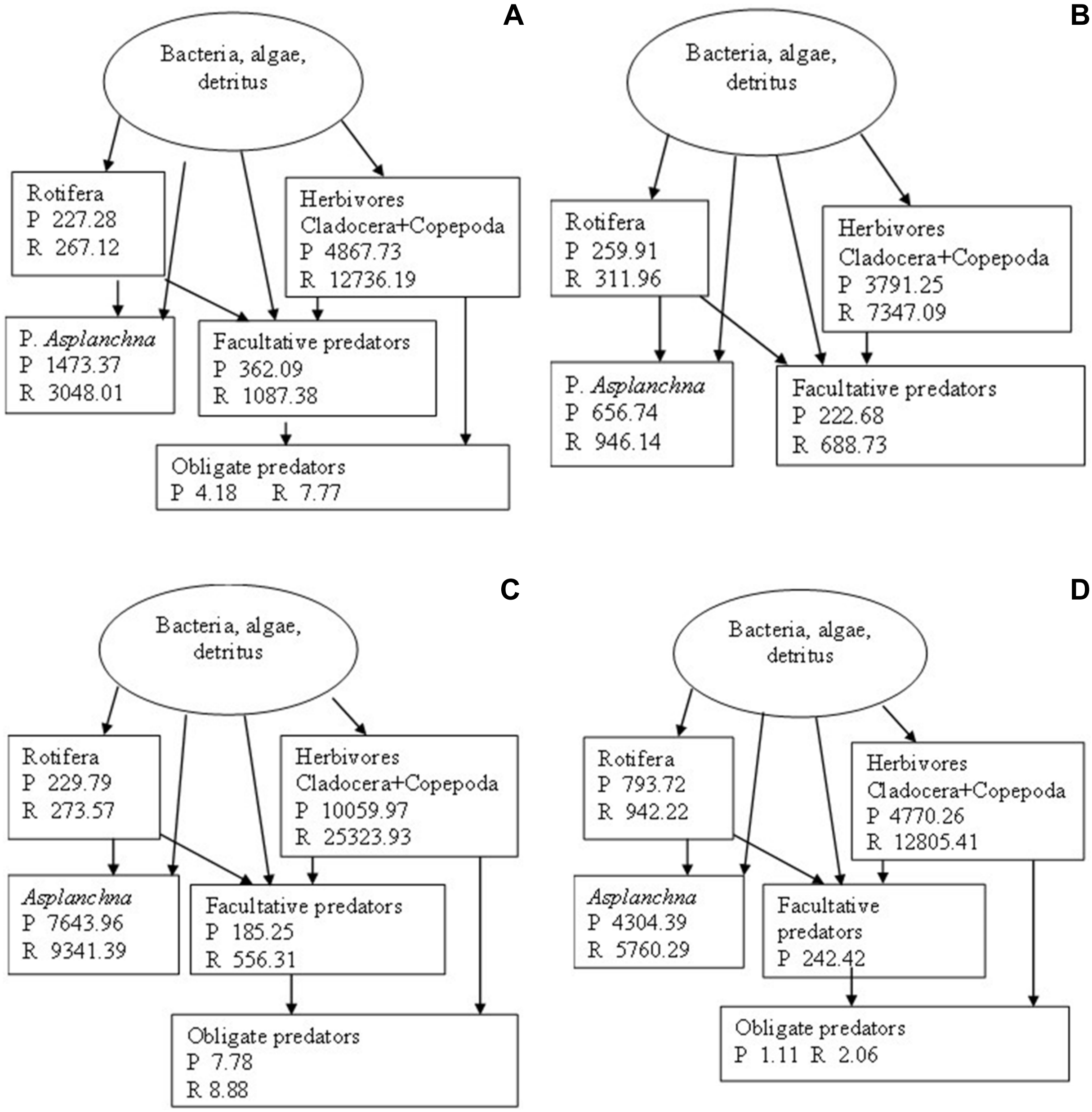

Fig. 6. Schemes of food webs in the communities of planktonic rotifers and crustaceans of Komsomolsky pond: **A** – in 2019, **B** – in 2020, **C** – in 2021, **D** – in 2022. P – production during the growing season (cal/m^3), R – metabolic costs during the growing season (cal/m^3).

Structure of zooplankton community in Lake Maryino

In Lake Maryino, 41 species of zooplankton were found in 2019 before the start of remediation activities; after remediation was completed, the species number has increased, and rotifers predominated (Table 5).

Before the start of the activities, the average number of species per sample was 14.4 ± 1.2, and a year after their completion, 17.1 ± 1.3 (Fig. 7).

After remediation was completed, the composition of the newly formed zooplankton community was similar that existed here previously. The similarity index was 63–69% (Fig. 8).

Before the remediation activities began, naupliar and copepodite stages of Cyclopidae dominated, 1 or 2 more species periodically joined the group of dominants. During the work, *B. longirostris* and *Ceriodaphnia pulchella* G.O. Sars, 1862 entered the dominant species complex in addition to nauplii and copepodites. After the activities were completed, juvenile stages of Cyclopidae, *C. pulchella*, and *K. quadrata* also dominated. Shannon index decreased during the remediation period, indicating a simplification of the community structure. In the following two years, Shannon index increased (Fig. 9), although the differences were not always statistically significant.

Before the works have started, low zooplankton abundance (46 ± 12 thous. ind./m^3) and biomass (0.004 ± 0.001 g/m^3) were registered in Lake Maryino (Fig. 10), cladocerans predominated. During the remediation period, the quantitative indicators increased; average abundance was 327.8 ± 145.1 thous. ind./m^3, biomass, 3.64 ± 2.59 g/m^3.

The maximum values of zooplankton abundance and biomass were recorded on July 25, 2020 and reached 1,472 thous. ind./m^3 and 26.6 g/m^3, respectively (Fig. 11). The only one species, *B. longirostris,* had the largest contribution (84% of the total abundance, 91% of the total biomass). In subsequent years, summer peaks in the abundance and biomass of zooplankton were significantly lower, and cladoceran *C. pulchella* dominated in the zooplankton community.

The coefficients of variation of both abundance and biomass were the highest during the period of remediation activities (Table 6). In subsequent years, they have decreased, so the system became more stable.

The saprobity index varied as 1.56 ± 0.03 in 2019 to 1.54 ± 0.02 in 2022, i.e., the waterbody corresponded to the β-mesosaprobic zone.

The main energy flows passed through cladocerans in the trophic webs of both Lake Maryino and the Komsomolsky pond (Fig. 12). Facultative predatory crustaceans transformed almost twice as much energy as the rotifers of the genus *Asplanchna*. The production and metabolic costs of facultative predating crustaceans in Lake Maryino were significantly higher than that in the Komsomolsky pond. This might be due to the high degree of overgrowing of Lake Maryino with higher aquatic plants and significantly lower development of phytoplankton community compared to the Komsomolsky pond. Obligate predators were absent in Lake Maryino. During the remediation period and subsequent years, the amount of energy transformed by zooplankton increased.

Table 5. Number of zooplankton species (n) in Lake Maryino in 2019–2022.

Taxonomic group	Year							
	2019		2020		2021		2022	
	n	%	n	%	n	%	n	%
Rotifera	17	42	27	55	21	50	27	52
Cladocera	14	34	16	33	14	33	18	35
Copepoda	10	24	6	12	7	17	7	13
Total	41	100	49	100	42	100	52	100

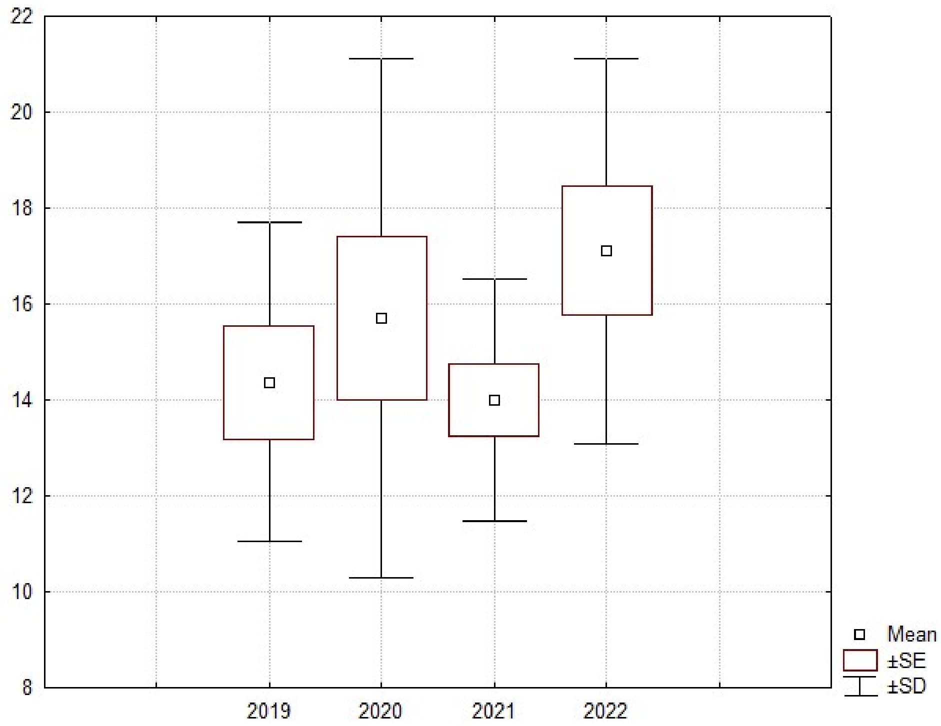

Fig. 7. Average number of zooplankton species per sample in the Lake Maryino in different periods of study.

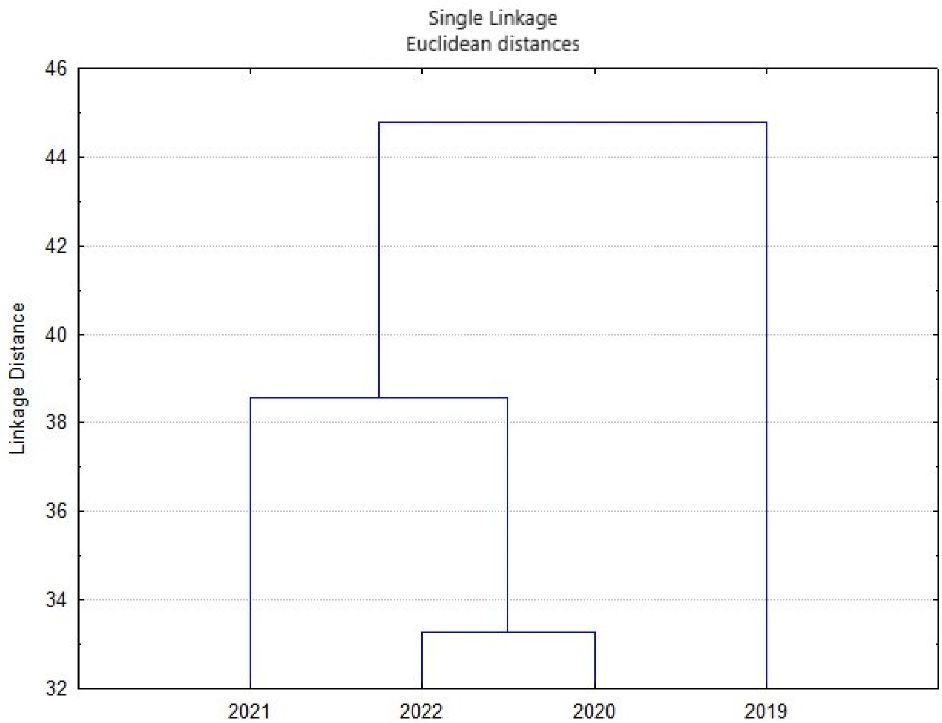

Fig. 8. Dendrogram of similarity of species composition of zooplankton of Lake Maryino in 2019–2022.

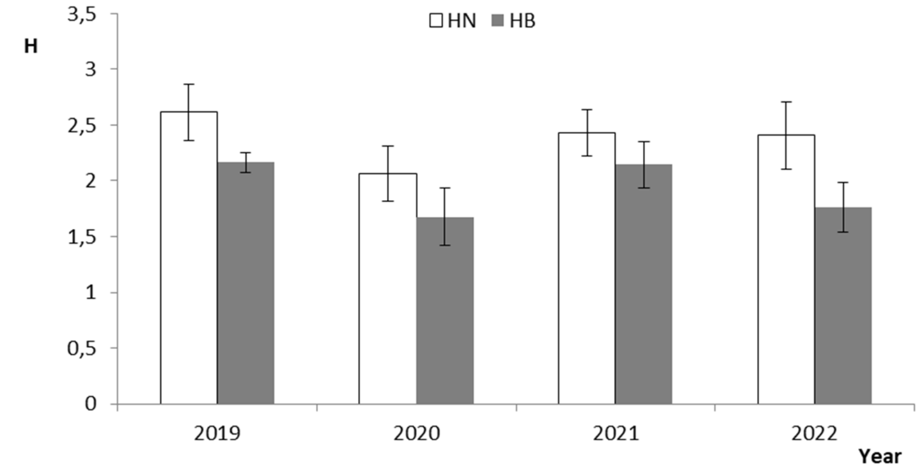

Fig. 9. Shannon index calculated in terms of zooplankton abundance (H_N) and biomass (H_B) in Lake Maryino in different years.

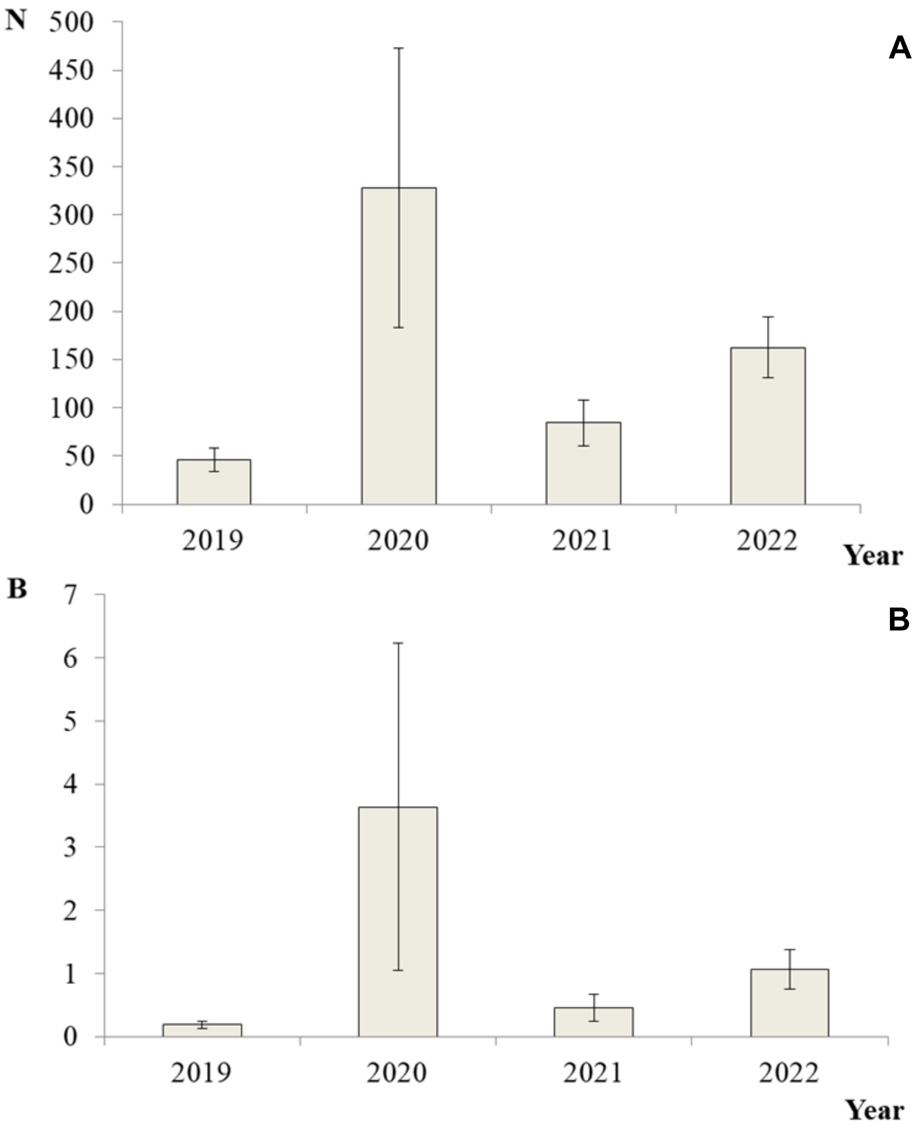

Fig. 10. Average zooplankton abundance (N, thous. ind./m^3) **(A)** and biomass (B, g/m^3) **(B)** in Lake Maryino in different years.

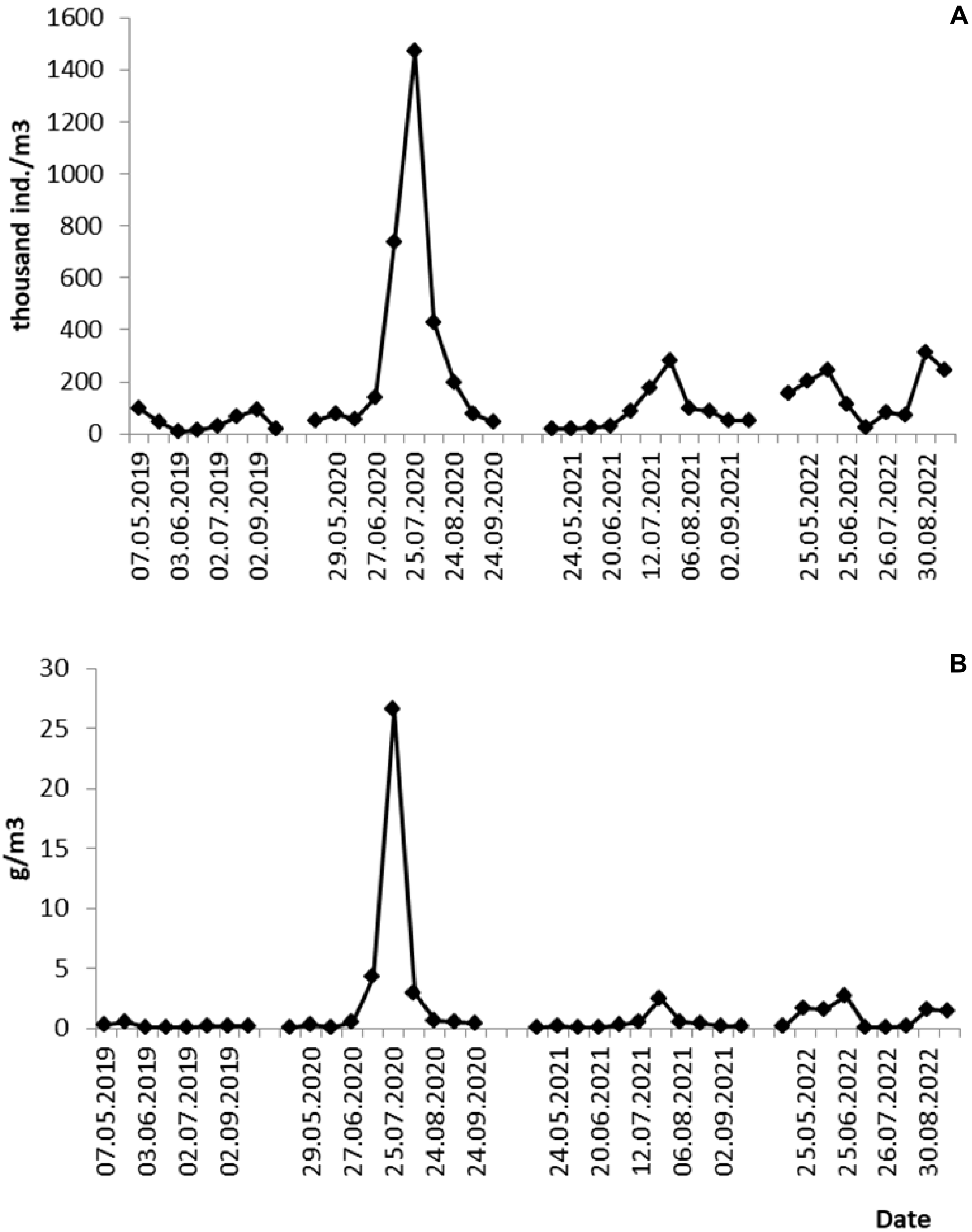

Fig. 11. Dynamics of zooplankton abundance (N, thous. ind./m^3) **(A)** and biomass (B, g/m^3) **(B)** in Lake Maryino in 2019–2022.

Table 6. Biomass variability (Bmin/max) and the variation coefficient of zooplankton abundance (CV_N) and biomass (CV_B) in Lake Maryino.

Parameter	Year			
	2019	2020	2021	2022
B min/max	0.08	0.003	0.016	0.036
CV_N, %	75	140	95	59
CV_B, %	88	225	155	88

Discussion

Various types of anthropogenic impact and the resulting eutrophication, pollution or acidification of waterbodies usually lead to a simplification of the structure of ecosystems in general and zooplankton communities in particular (Derevenskaya, 2017; Lazareva, 1994). A decrease in the trophic status of a waterbody is usually accompanied by increasing the biodiversity and the number of trophic links and by developing more complex community structure. There are few examples of forming more complex ecosystem due to anthropogenic impact: these are biomanipulation and remediation of waterbodies. If a decrease in the trophic status of a waterbody occurs during remediation, the ecosystem returns back to earlier stages of development.

According to general ecological principles, the biosphere strives to restore ecological balance, ecosystems, to achieve terminal or stable climax states. Theoretically, a climax community maintains itself indefinitely, all its internal components are balanced with each other, being in equilibrium with the physical environment (Odum, 1986). However, if anthropogenic environmental changes exceed system self-restoring ability, such a system cannot restore to the original state, as stated by the irreversibility law for the interaction "man-biosphere" (Reimers, 1994). In accordance with this law, remediation of waterbodies occurs. The anthropogenic impact, exerted on the aquatic ecosystem during remediation, changes the direction of the processes, and the ecosystem acquires other structural and functional characteristics. The latter usually correspond to earlier developmental stages of the system. When implementing waterbody restoration projects, it is necessary both to lower the trophic status or reduce the amount of pollutants entering waterbodies and to achieve ecosystem stability in the new conditions.

According to our research in the city of Kazan, where remediation activities were carried out, trophic status of the waterbodies has decreased. Remediation caused significant changes in the aquatic ecosystems, which affected the diversity of zooplankton communities, so its species richness has increased. In addition, the species composition was restored to the previous state, but not in full. Restoration of zooplankton communities in remediated waterbodies occurs due to the influx of dormant stages of organisms from the catchment area, the introduction of waterfowl, and the release from bottom sediments. In the first year after remediation, a frequent change of dominant species alongside with dominating of a single species were observed. In subsequent years, complexes of dominant species were formed, two or three species dominate for a quite long time, or one species was an absolute dominant again. Quantitative indicators of zooplankton increased slightly or did not change. Both abundance and biomass varied largely throughout the growing season and from year to year; high variability of biomass was registered during remediation and in the first year after it was completed. A year later, the structure of communities became more complex, so they became more stable. After remediation, the energy flow transformed by zooplankton communities increased. The saprobic status of lakes after remediation had almost no change. The further community development depends on the magnitude of anthropogenic load, so monitoring the current state of waterbodies is necessary, as additional measures may be required.

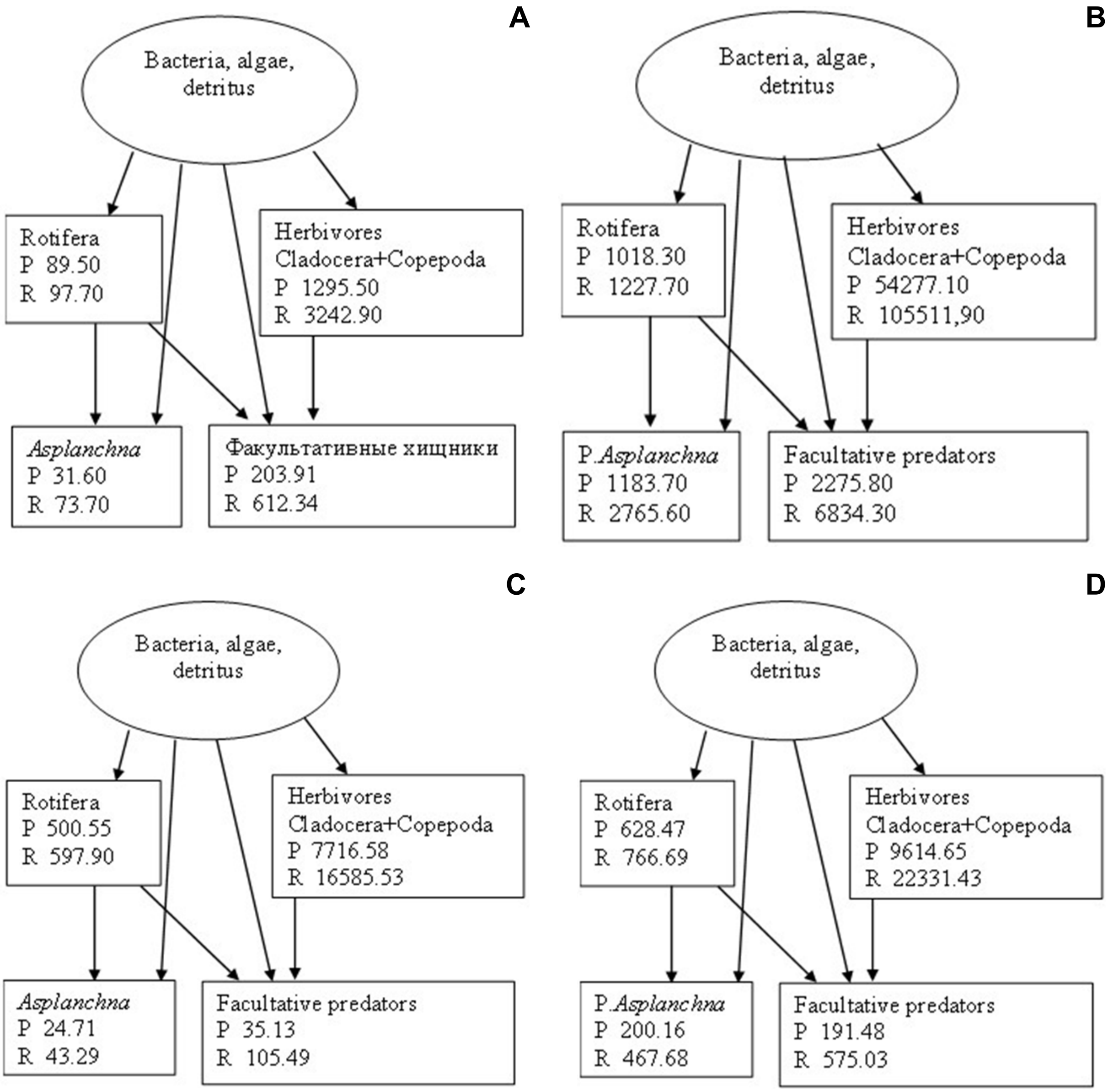

Fig. 12. Schemes of food webs in communities of planktonic rotifers and crustaceans of Lake Maryino: **A** – in 2019, **B** – in 2020, **C** – in 2021, **D** – in 2022. P – production during the growing season (cal/m^3); R – metabolic costs during the growing season (cal/m^3).

Conclusion

1. After remediation work, the number of zooplankton species in the Komsomolsky pond increased from 30 to 48. *A. girodi*, *A. priodonta*, *F. longiseta*, *K. quadrata* dominated by abundance, *A. girodi*, *A. priodonta*, *E. gracilis*, *M. leuckarti*, by biomass. In Lake Maryino, the number of species increased from 41 to 52 during the same period, rotifers dominated. Here, *K. quadrata*, *C. pulchella*, *B. longirostris* dominated by abundance, *C. pulchella*, by biomass.

2. The lowest zooplankton abundance and biomass were observed during the remediation period; in subsequent years, both parameters were increasing gradually. There were some fluctuations from year to year. During the remediation activities and immediately after they were completed, the greatest variability in abundance and biomass during the growing season was observed. Gradually, the range of fluctuations decreased, and the communities became more stable.

3. After remediation, the zooplankton diversity increased and the water in both the Komsomolsky pond and Lake Maryino waterbodies belonged to the β-mesosaprobic type.

4. No obligate predators were found in the zooplankton trophic chains in Lake Maryino; in the Komsomolsky pond, they were found singly, making an insignificant contribution to the transformation of energy. The main energy flows passed through cladocerans and rotifers. After remediation, production of zooplankton communities increased.

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