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ASSESSMENT OF THE IMPACT OF CLIMATE CHANGES ON ZOOPLAKTON GROUPINGS USING THE EXAMPLE OF LAKE GENEVA

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Modern climate change significantly affects natural ecosystems, especially aquatic ones, changing the temperature, hydrological regime and the level of dissolved oxygen, which leads to transformations in the structure and functioning of hydrobiocenoses. There is a completely justified need for comprehensive research on the current topic: food resources of aquatic areas, in particular, zooplankton as a key element of trophic chains. Considering that negative changes in its groups can destabilize the entire ecosystem, reduce fish productivity and affect ecosystem services, the topic is becoming relevant.

The aim of the study is to assess the impact of modern climate change on zooplankton communities of aquatic ecosystems based on the analysis of changes in biological indicators of Lake Geneva, as well as to identify the main patterns of zooplankton transformation under the influence of climatic factors.

The object of the study is zooplankton of aquatic ecosystems under conditions of modern climate change using the example of Lake Geneva.

The subject of the study is the peculiarities of the impact of climate change on the structure, dynamics and functional characteristics of zooplankton communities, as well as the relationships between abiotic environmental factors and the state of plankton communities.

Analysis and synthesis of scientific literature, comparative and systematic analysis, statistical methods of data processing, as well as generalization of the results obtained.

Based on the analysis of literary sources and statistics, it was established that climate change causes a structural restructuring of zooplankton communities, which is manifested in a change in species composition, a decrease in the size characteristics of organisms, a shift in phenological phases of development and a disruption in the synchronization of trophic chains. A tendency towards the dominance of small forms of zooplankton was revealed, which is accompanied by a decrease in the efficiency of trophicity in aquatic ecosystems. It was substantiated that the cumulative impact of climate change is cumulative and causes a decrease in the efficiency of energy transfer in trophic chains, which may have long-term negative consequences for fish productivity and the overall ecological stability of aquatic ecosystems.

Modern climate change is a determining factor in the transformation of zooplankton communities and aquatic ecosystems in general. The revealed patterns can be used to predict further changes, improve monitoring systems, and develop adaptation measures and sustainable management of aquatic bioresources under global warming.

Key words: reservoir, transformations of climatic parameters, zooplankton, species composition water temperature.

Statement of the problem. The relevance of the topic is due to the fact that modern climate change is one of the most important global factors in the transformation of natural ecosystems, in particular aquatic ones. An increase in air and water temperature, a change in the hydrological regime, increased stratification of water masses, a decrease in the content of dissolved oxygen and changes in the cycle of biogenic elements significantly affect the structure and functioning of hydrobiocenoses. Zooplankton groups are especially sensitive to such changes, which occupy a key place in trophic chains, ensuring the transfer of energy from primary producers to higher trophic levels. Violation of their structure and functioning can lead to destabilization of the entire ecosystem, a decrease in fish productivity and changes in ecosystem services. In this regard, the study of the impact of climate change on zooplankton is extremely relevant.

Analysis of research and publications. In modern science, zooplankton is considered one of the most sensitive to climate change links in aquatic ecosystems. This is explained by the fact that zooplankton has a high reproduction rate, a short life cycle, and correlations between physiological processes and the temperature factor [1]. In the scientific works of most scientists, it is noted that zooplankton in water bodies is an important element of the trophic chain, because it connects primary producers, namely phytoplankton, with higher-order consumers, in particular marine mammals and commercially valuable fish species. At the same time, zooplankton is an important component of the "biological carbon pump", because it provides vertical transport of organic matter to the abyssal layers of aquatic ecosystems through the mechanisms of gravitational sedimentation of fecal masses and active vertical migration. Modern scientific data indicate that climate transformation leads to changes in the biogeography, structure and functional characteristics of zooplankton [2].

A very pronounced consequence of the global temperature increase is the meridional shift of zooplankton distribution areas towards the poles. In particular, scientific studies conducted in the North Atlantic have recorded an expansion of the habitats of thermophilic species to the north by a distance of about 1000 km. At the same time, a rather striking example is the replacement of the copepod species *Calanus finmarchicus* with the warmer species *Calanus helgolandicus.* Such substitution is a rather unfavorable consequence for aquatic ecosystems, as *Calanus finmarchicus* has a higher lipid content and higher energy value compared to *Calanus helgolandicus. Calanus finmarchicus* is accordingly an important nutritional element for the survival of cod larvae and other commercially valuable fish species [3].

At the same time, a number of scientific studies confirm that temperature fluctuations affect not only the distribution areas, but also have an impact on the dominant groups of zooplankton. Studies conducted in the Mediterranean Sea and the Atlantic Ocean have shown that climate change has a significant and diverse impact on the following groups of zooplankton: *Calanus finmarchicus; Calanus helgolandicus; Temora stylifera; Euphausia superba; Salpa thompsoni* [4].

It should be noted that according to the analysis of scientific research, it was found that in addition to horizontal shifts of zooplankton, vertical shifts of zooplankton groups are also characteristic. In particular, an increase in the temperature stratification of water masses limits their vertical mixing, which causes a decrease in nutrients in the euphotic zone and leads to a decrease in the biomass of large zooplankton. In response to warming of the temperature of the upper layers of water, many species migrate to deeper water horizons, which have a more stable temperature, however, this leads to disruptions in interactions with phytoplankton [5].

Scientific and practical works show that an important consequence of climate change for aquatic ecosystems and bioresources is the phenological shift. The increase in temperature and the acceleration of early warming of water lead to the early onset of seasonal peak values of zooplankton communities. As a result, the mass development of copepods occurs somewhat earlier than the spring flowering of diatoms, and the greatest development of zooplankton biomass does not coincide with the moment of hatching of fish larvae – this creates the phenomenon of the so-called "trophic imbalance". This is confirmed by monitoring scientific observations in the territory of the Arctic Ocean, where it is noted that over the past 30 years the peak of the number of many zooplankton species has shifted approximately 10-22 days earlier and caused the degradation of populations of certain species of fish and seabirds [6].

Numerous scientific studies confirm the fact that temperature influences the reduction of zooplankton body size. According to the metabolic theory of ecology, an increase in temperature stimulates faster development of individuals, but they reach sexual maturity at a smaller body size. In warmer waters, the energy expenditure for maintaining metabolism increases faster than the body's ability to absorb food, which makes large body sizes energetically disadvantageous [7]. Accordingly, this leads to the predominance of small species of copepods, protozoa, and rotifers.

In scientific research, special attention is paid to the process of ocean acidification, which also has a significant negative impact on zooplankton communities. Thus, the absorption of anthropogenic CO_2 leads to a decrease in pH and a decrease in the saturation of water with calcium carbonate, in particular calcite and aragonite. This process has a very critical impact on pteropods, coccolithophores and foraminifera [8].

It should be noted that an important aspect of global climate change is the «gelatinization» of plankton. The phenomenon is directly related to the rapid development and predominance of cnidarians and jellyfish in the species composition of zooplankton. This is facilitated by the appearance of all the conditions necessary for their development, in particular, a warmer winter period and a longer growing season [9]. Scientific studies show that there is a general trend in the world to reduce the total biomass of zooplankton. According to forecasts, it is expected that by 2100 the total biomass of zooplankton in the World Ocean will decrease by approximately 10-20%, which will lead to a decrease in fish productivity in the future. And the expansion of oxygen minimum zones will complicate the vertical migration of many fish species.

Formulation of the objectives of the article (task statement). The aim of the study is to assess the impact of modern climate change on zooplankton communities based on the analysis of changes in zooplankton indicators of Lake Geneva, as well as to identify the main patterns of zooplankton transformation under the influence of climatic factors. In accordance with the aim, the following tasks were set: to analyze modern trends in the temperature regime of the lake; to determine the features of the structure, dynamics and functioning of zooplankton communities under the influence of climatic factors; to generalize the patterns of zooplankton transformation and assess their ecological consequences.

Materials and methods of the research. The information basis of the research was the works of leading world scientists. The study of the dynamics of climatic indicators was carried out by statistical methods regionally and in the context of the reservoir, in particular using the climatic indicators GISS Surface Temperature Analysis [10] and World meteorological organization [11]. The species composition and dynamics of zooplankton were estimated using the available field work Rapport de la Commission internationale pour la protection des eaux du Léman [12–22].

In the research process, a complex of general scientific and special methods was used, in particular, analysis and synthesis of scientific literature, comparative and systematic analysis, statistical methods of data processing, and generalization of the obtained results.

Research results. Over the past decade, Western Europe has been characterized by a gradual increase in air temperature, which directly affects the increase in water temperature and is a reflection of general global climate transformations. It should be noted that such an increase in temperature affects the extension of the summer stratification period and a decrease in the intensity of mixing of water masses in winter, which negatively affects the saturation of deep water layers with dissolved oxygen. These factors cause stable thermal stratification, which to some extent limits the vertical exchange of energy and substances in the lake.

Lake Geneva, like the entire planet, has been affected by climate change, in particular, the temperature of deep waters (depths over 300 m) has undergone significant changes in the long-term historical trend. Thus, in 1963 it was only 4.4 °C, and in 2016 a temperature of 5.5 °C was already recorded. At the same time, the temperature of surface waters has also undergone changes. In particular, in 1970 it was 10.9 °C, and in 2016 it was 12.9 °C [23].

In Figure 1, we show the dynamics of the average annual water temperature of Lake Geneva for the period 2013 – 2023. Accordingly, during this period, the temperature regime of Lake Geneva water is characterized by general trends towards an increase in average annual temperatures against the background of certain interannual variations.

Thus, in 2013, the average annual water temperature was 10.3 °C. At the same time, in subsequent years, its increase with periodic fluctuations is observed, in particular, up to 12.3 °C in 2018 and 2020 and to a maximum of 12.9 °C in 2022. Despite individual decreases, as in 2016 and especially in 2021, the overall dynamics indicate a steady warming of the lake's water mass. It should be noted that changes in the temperature factor contribute to the development of thermophilic plankton species and may subsequently lead to the complete displacement or reduction of the number of cold-water plankton.

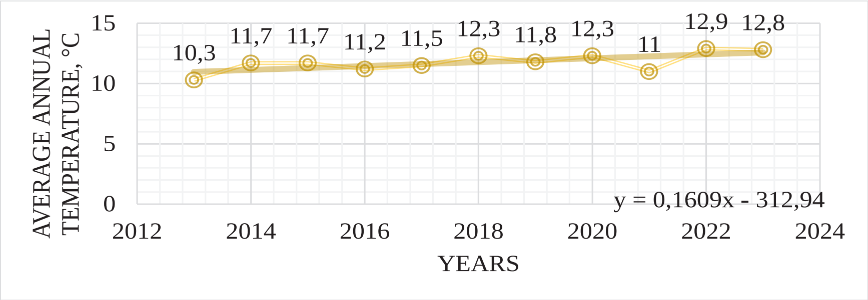


Fig. 1. **Dynamics of changes in the average annual water temperature of Lake Geneva**

Source: developed by the authors based on [24].

An analysis of annual reports revealed that the following groups of zooplankton are widespread in Lake Geneva: copepods (*Copepoda*) and cladocerans (*Cladocera*).

The group of copepod crustaceans that are common within the lake include *Eudiaptomus gracilis* and *Cyclops prealpinus*. The group of branchial crustaceans is represented by plant filter feeders and predators. Plant filter feeders include *Daphnia longispina* (Daphnia) and *Eubosmina sp.* (Bosmina). Predators include *Leptodora kindtii* and *Bythotrephes longimanus.*

At the same time, our study on the dynamics of zooplankton in Lake Geneva indicates that its number has significantly decreased over the period 2013-2023.

Thus, a pronounced tendency to decrease zooplankton communities is characteristic of the ten-year period of research, but there are also insignificant short-term growth phases. In 2013 and 2014, high abundance indicators within the range of 413,000–450,000 individuals/m² are characteristic. A large decline in numbers begins in 2015 and a pronounced downward trend is observed until 2023. In 2023, a slight increase is observed compared to previous years to 109,750 individuals/m², but overall the general trend remains negative. Such trends indicate a long-term decrease in the bioproductivity of zooplankton communities (Fig. 2).

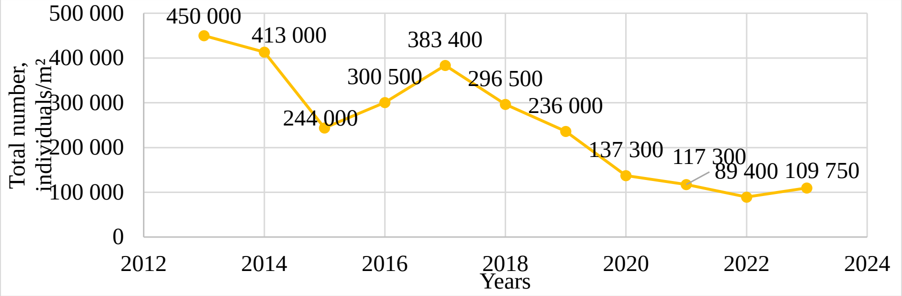
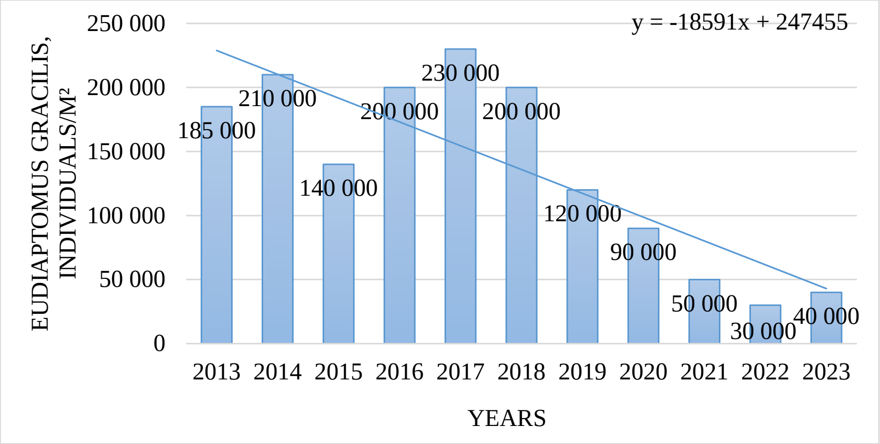


Fig. 2. **Dynamics of zooplankton abundance in Lake Geneva for the period 2013–2023**

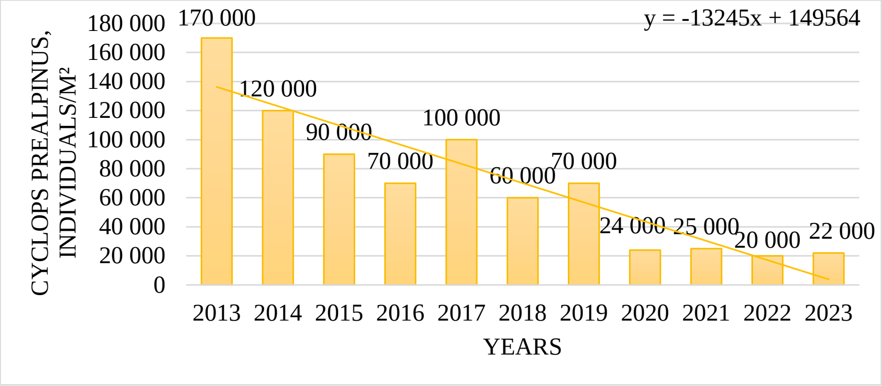
Compiled by the authors based on [12–22].

Structural changes in zooplankton communities are characteristic over the ten-year period. During the studied period, copepod crustaceans, in particular *Cyclops prealpinus* and *Eudiaptomus gracilis,* dominate the zooplankton structure. At the same time, the second half of the studied period is characterized by an increase in the role of branchial crustaceans, in particular – *Daphnia longispina*. At the same time, the analyzed data for a ten-year period indicate that throughout the entire research period, the smallest share in the total zooplankton structure was made up of branching predators, in particular *Bythotrephes longimanus* and *Leptodora kindtii*. Overall, the presented dynamics indicate a simplification of the structure of zooplankton communities and a significant decrease in the role of large planktonic forms.

During the study, we examined the species composition of zooplankton in Lake Geneva. Among the copepod crustaceans in the reservoir are *Eudiaptomus gracilis* and *Cyclops prealpinus*. According to the analyzed abundance indicators, these zooplankton forms are the most common in the reservoir, however, their dynamics towards a decrease over the last 10 years is characteristic. Accordingly, *Cyclops prealpinus* and *Eudiaptomus gracilis* in Lake Geneva are directly related to the complex impact of current climate change, in particular, increased stratification and an increase in the temperature factor. The global increase in temperature leads to a reduction in the period of spring mixing, which in turn causes a decrease in the intensity of nutrient input into the upper layers of the water body. The decrease in the amount of nutrients in the upper layers of the lake negatively affects the number and biomass of phytoplankton, which is the main food resource for copepods, in particular for *Cyclops prealpinus* and *Eudiaptomus gracilis* (Fig. 3).



a) population dynamics of *Eudiaptomus gracilis* (2013–2023)



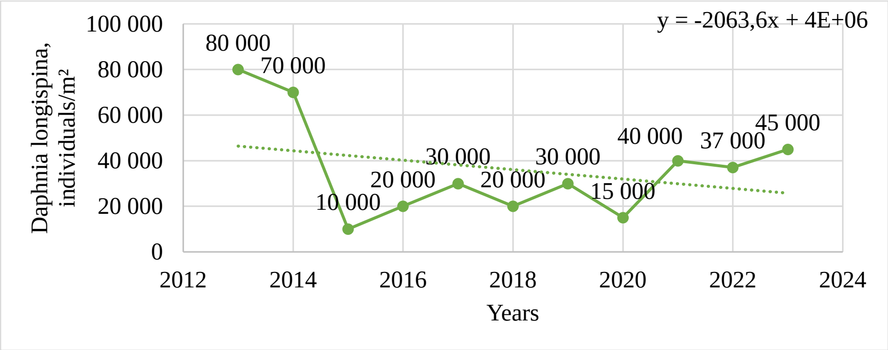
b) dynamics of the number of *Cyclops prealpinus* (2013–2023)

Fig. 3. **Dynamics of the number of copepods (Copepoda) for the period 2012–2023**

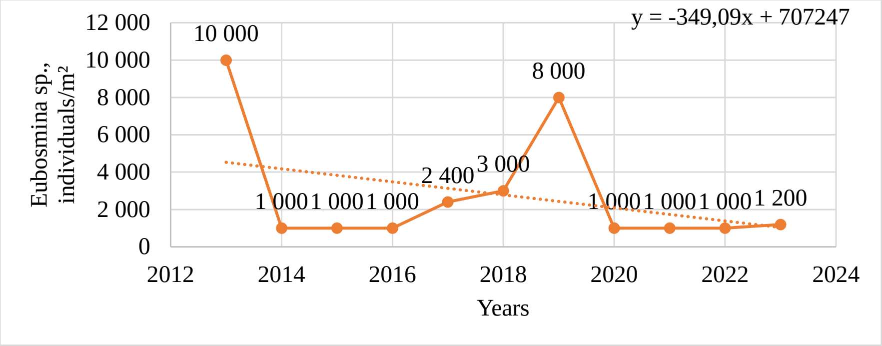
Compiled by the authors based on [12–22].

At the same time, higher temperatures lead to a change in the seasonal synchronization between the development of phytoplankton and zooplankton, which leads to the fact that the optimal highest phases of phytoplankton development do not coincide with the periods of maximum consumption of it as a food resource by zooplankton groups. Comparative analysis indicates a significant reduction in the number of both species in 2023 compared to 2013. Thus, the number of *Eudiaptomus gracilis* decreased by about 78,4%, and *Cyclops prealpinus* – by about 87,1%.

Figure 4 presents the dynamics of the abundance of branchial crustaceans, in particular Daphnia longispina and Eubosmina sp., which are herbivorous.



a) dynamics of the number of *Daphnia longispina* (2013–2023)



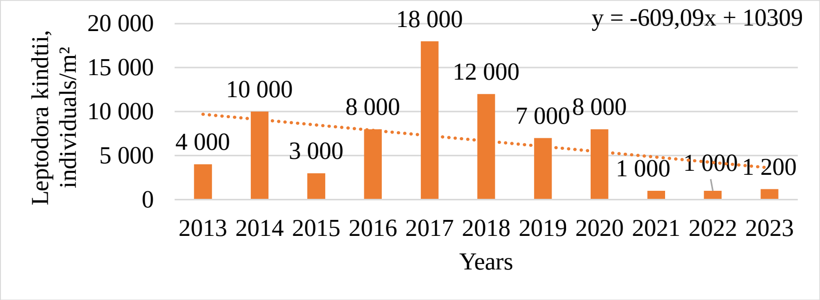
b) dynamics of *Eubosmina sp.* (2013–2023)

Fig. 4. **Dynamics of the number of branchial-breasted crustacean plant filter feeders (Cladocera) for the period 2012–2023**

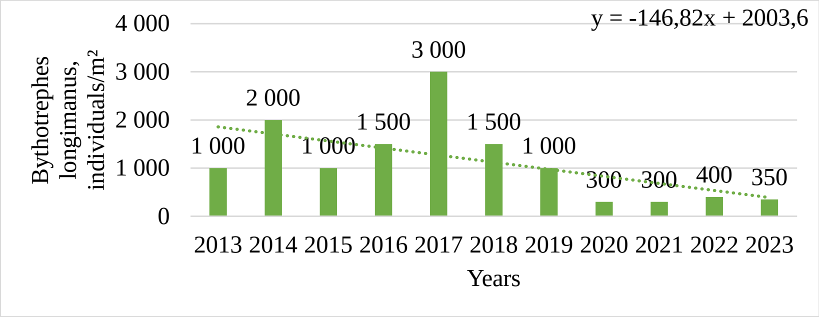
Compiled by the authors based on [12–22].

The increase in temperature has a negative impact on herbivorous cnidarians. This is primarily due to the fact that the structure of phytoplankton communities changes with increasing temperature, in particular, less nutritious and small-celled forms, including cyanobacteria, begin to actively develop. This phytoplankton structure is unfavorable for effective nutrition, in particular, of *Daphnia longispina*, which leads to a decrease in their numbers. At the same time, an increase in temperature causes the activity of predators to increase, which also affects the number of *Daphnia longispina* and *Eubosmina sp.*

Figure 5 presents the dynamics of the abundance of branchial crayfish, in particular Leptodora kindtii and Bythotrephes longimanus, which are predatory.



a) *Leptodora kindtii* population dynamics (2013–2023)



b) Population dynamics of *Bythotrephes longimanus* (2013–2023)

Fig. 5. **Dynamics of the number of branchial barbeled crustaceans (*Cladocera*) for the period 2012–2023**

Compiled by the authors based on [12–22].

These species are the smallest in number in Lake Geneva. It should be noted that throughout the entire period of research, predatory crayfish in Lake Geneva accounted for the smallest share compared to other species. At the same time, it should be noted that during 2013–2023, there is a characteristic trend towards a decrease in their number in the reservoir. It should be noted that the abundance of *Leptodora kindtii* in 2023 decreased by approximately 70% compared to 2013, and the abundance of *Bythotrephes longimanus* in 2023 decreased by approximately 65% compared to 2013. Such trends reflect a significant decline in the role of predatory zooplankton in Lake Geneva and may be directly related to ongoing global climate change.

For *Leptodora kindtii* and *Bythotrephes longimanus*, the availability of cold, deep, and well-oxygenated water layers is important, and an increase in temperature negatively affects the presence of dissolved oxygen in the reservoir. At the same time, the increase in temperature is the cause of the reduction in the number of small zooplankton in the reservoir, which is a food resource for predatory cnidarians. The combined effect of these factors leads to a gradual reduction in the number of this zooplankton group in the reservoir.

Conclusions. During the study of Lake Geneva, a clear trend towards an increase in the average annual water temperature during 2013–2023 was identified, which is accompanied by an increase in thermal stratification of the water column and a limitation of vertical mixing. It was found that zooplankton communities undergo significant structural changes under the influence of climatic factors. In particular, there is a tendency towards a decrease in the size of organisms, the dominance of small forms, a shift in the species composition towards thermophilic species, as well as a disruption of the seasonal dynamics of development. The revealed patterns can be used to predict further changes, improve monitoring systems and develop measures for adaptation and sustainable management of aquatic biological resources under conditions of global warming.

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ОЦІНКА ВПЛИВУ КЛІМАТИЧНИХ ТРАНСФОРМАЦІЙ НА ЗООПЛАНКТОННІ УГРУПУВАННЯ НА ПРИКЛАДІ ЖЕНЕВСЬКОГО ОЗЕРА

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Сучасні кліматичні зміни суттєво впливають на природні екосистеми, особливо на водні, змінюючи температурний, гідрологічний режим та рівень розчиненого кисню, що призводить до трансформацій у структурі та функціонуванні гідробіоценозів. Цілком обґрунтовано виникає потреба в комплексних дослідженнях актуальної тематики: кормових ресурсів акваторій, зокрема, зоопланктону як ключового елементу трофічних ланцюгів. Враховуючи, що негативні зміни в його угрупуваннях можуть дестабілізувати всю екосистему, знизити рибопродуктивність та вплинути на екосистемні послуги тематика набуває актуальності.

Мета дослідження полягає в оцінці впливу сучасних кліматичних змін на зоопланктонні угрупування водних екосистем на основі аналізу змін біологічних показників Женевського озера, а також у виявленні основних закономірностей трансформації зоопланктону під дією кліматичних факторів.

Об’єктом дослідження є зоопланктон водних екосистем в умовах сучасних кліматичних змін на прикладі Женевського озера.

Предметом дослідження є особливості впливу кліматичних змін на структуру, динаміку та функціональні характеристики зоопланктонних угрупувань, а також взаємозв’язки між абіотичними чинниками середовища та станом планктонних спільнот.

На основі аналізу літературних джерел та статистики встановлено, що кліматичні зміни спричиняють структурну перебудову зоопланктонних угрупувань, яка проявляється у зміні видового складу, зменшенні розмірних характеристик організмів, зміщенні фенологічних фаз розвитку та порушенні синхронізації трофічних ланцюгів. Виявлено тенденцію до домінування дрібних форм зоопланктону, що супроводжується зниженням ефективності трофічності у водних екосистемах. Обґрунтовано, що сукупний вплив кліматичних змін має кумулятивний характер і спричиняє зниження ефективності передачі енергії у трофічних ланцюгах, що може мати довгострокові негативні наслідки для рибопродуктивності та загальної екологічної стабільності водних екосистем.

Сучасні кліматичні зміни є визначальним фактором трансформації зоопланктонних угрупувань і водних екосистем загалом. Виявлені закономірності можуть бути використані для прогнозування подальших змін, вдосконалення систем моніторингу та розробки заходів адаптації і сталого управління водними біоресурсами в умовах глобального потепління.

Ключові слова: водойма, трансформації кліматичних параметрів; зоопланктон; видовий склад; температура води.

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