limnological review

MDPI

Article

Hydrobiological and Geochemical Responses to Trout Cage Aquaculture in Lake Ecosystem

Artem Lapenkov [1,*], Alina Guzeva [1], Ksenia Zaripova [1], Dina Dudakova [1] and Artem Trifonov [2]

[1] Institute of Limnology of the Russian Academy of Sciences, St. Petersburg Federal Research Center of the Russian Academy of Sciences (SPC RAS), 9, Sevastyanova St., 196105 St. Petersburg, Russia; alinaguzeva2108@gmail.com (A.G.)
[2] Saint Petersburg Branch of "VNIRO" ("GosNIORKH" named after L.S. Berg"), 26 Naberezhnaya Makarova St., 199053 Sankt-Peterburg, Russia
* Correspondence: lapa13art@gmail.com; Tel.: +7-9111710741

Abstract: This study investigates the seasonal dynamics and interrelationships between geochemical and hydrobiological parameters in lake ecosystems impacted by fish cage farming in Lake Ladoga, Russia. Environmental conditions at three trout farms were assessed, focusing on water and sediment quality as well as benthic and zooplankton communities. For each farm, two categories of sampling sites were designated: cage sites and reference sites located 100–600 m away from the cages. Fieldwork was carried out across four seasons in 2023: February, June, August, and November. The findings indicate that intensive fish feeding results in significant organic waste accumulation beneath trout cages, altering the composition and abundance of planktonic and benthic organisms. The organic matter content in sediments beneath the cages during periods of intensive feeding was found to increase 2–5 times compared to the reference sites. In winter, accumulated organic matter in the sediments underwent mineralization, bringing hydrobiological indicators closer to the reference values. The geochemical and hydrobiological parameters analyzed in this study serve as valuable indicators for developing ecological monitoring approaches in freshwater cage aquaculture.

Keywords: environmental pollution; aquaculture impacts; fish farming; sediments; zooplankton; benthos

check for updates

Citation: Lapenkov, A.; Guzeva, A.; Zaripova, K.; Dudakova, D.; Trifonov, A. Hydrobiological and Geochemical Responses to Trout Cage Aquaculture in Lake Ecosystem. *Limnol. Rev.* **2024**, *24*, 593–615. https://doi.org/10.3390/limnolrev24040035

Academic Editor: Gabriel-Ionut Plavan

Received: 27 October 2024
Revised: 25 November 2024
Accepted: 28 November 2024
Published: 3 December 2024

1. Introduction

Aquaculture, particularly cage fish farming, is a relatively young yet rapidly expanding industry. This sector provides significant economic benefits but is also linked to several ecological risks. Among the most pressing environmental concerns are water resource pollution, eutrophication, invasions of alien species, and disease outbreaks in fish populations. A key issue is the leakage of nutrients and organic matter into water bodies, which alters the chemical composition of both water and sediments. Although aquaculture can be conducted sustainably, environmental monitoring is essential to mitigate these risks [1–3].

Sediments act as depositional matrices where chemical elements accumulate. Contaminated sediments not only impact benthic organisms but also serve as potential sources of secondary pollution for the overlying water column. Organic waste accumulating beneath fish cages contributes to anaerobic conditions in sediment layers, potentially leading to the production of methane and hydrogen sulfide—compounds toxic to aquatic communities and fish. Additionally, the excessive accumulation of organic matter reduces RedOx potential (Eh) values, increasing the bioavailability and toxicity of chemical elements. Consequently, geochemical studies are important for ensuring the sustainability and environmental safety of aquaculture practices [4].

Hydrobiological parameters, such as the composition and abundance of benthic and zooplankton communities, are crucial for evaluating the state of aquatic ecosystems and the impacts of aquaculture. Benthic organisms are reliable indicators of the ecological health of lake bottoms, as they directly respond to changes in sediment chemistry. Zooplankton play a central role in aquatic food webs. Hydrobiological studies are therefore crucial for detecting and assessing potential negative impacts of aquaculture on aquatic ecosystems [5,6].

The aim of this study was to comprehensively examine the seasonal dynamics of geochemical and hydrobiological parameters in the lake ecosystem affected by cage trout farming in Lake Ladoga, Russia. This research is necessary to assess the impact of fish farm waste on freshwater resources.

2. Study Area

Lake Ladoga, the largest freshwater body in Europe (Figure 1), is a significant waterbody for aquaculture, especially for trout farming. The volume of Lake Ladoga is 848,000 m^3, and the average capacity of trout farms ranges from 200 to 1000 tons of trout per year. The northern part of the lake is most suitable for fish farming, as the archipelago and islands provide shelter for the cages from strong winds and waves.

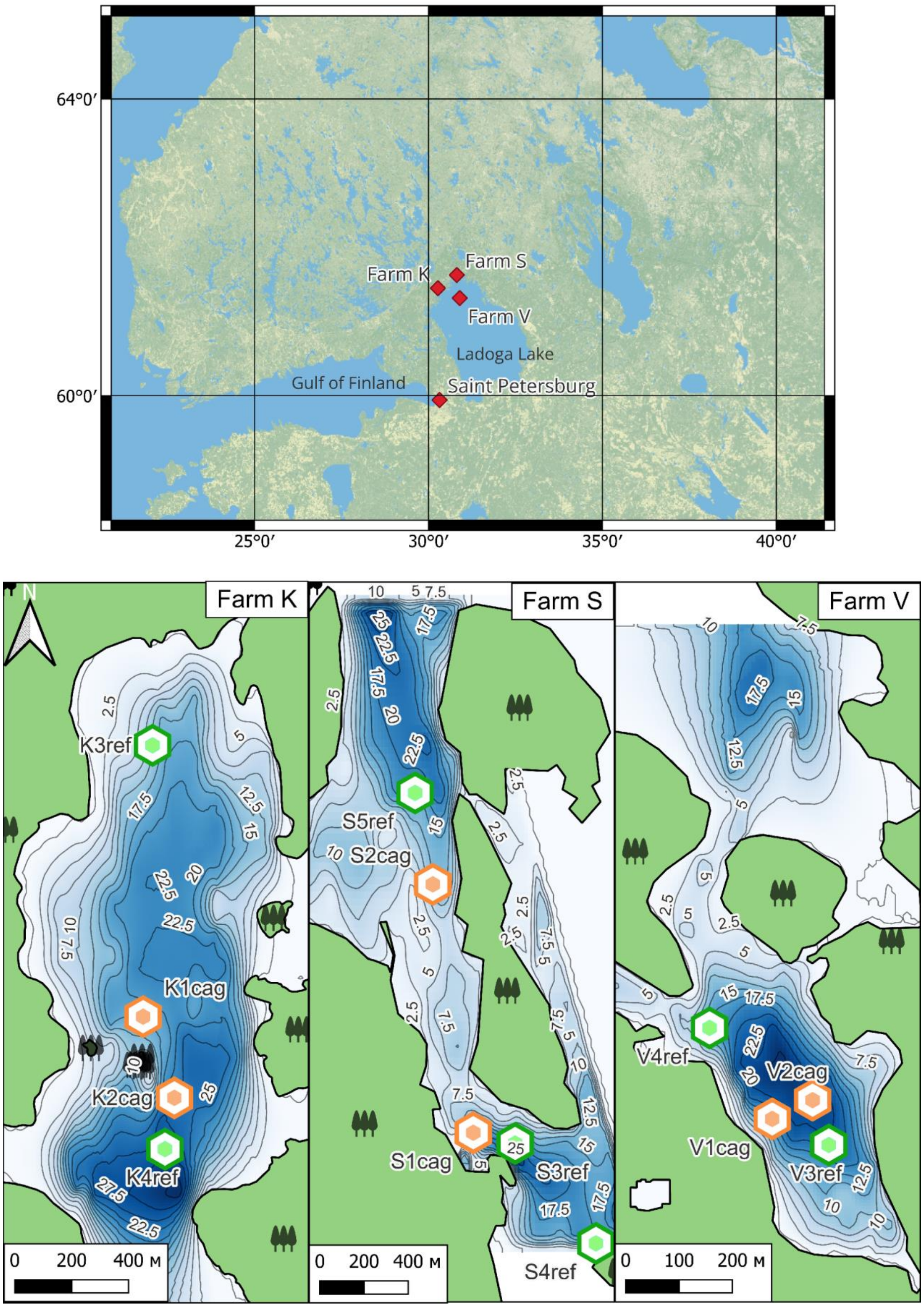

Figure 1. The studied trout cage farms located in Lake Ladoga, Russia; cag—cage sites; ref—reference sites.

This study included three typical trout cage farms in the northern part of Lake Ladoga. The bays where these farms are situated differ in hydrological and morphometric parameters (Figure 1). All the studied fish farms have been in operation for an extended period (about 15 years) and are similar in the type and size of the cages. The sampling sites were chosen in the central part of each fish-breeding area, ensuring that there were fish in the studied cage modules throughout the year.

Farm K is situated in a large bay with many channels. Depths at the cages are around 30 m. The complex network of channels contributes to a variety of hydrological conditions and influences the distribution of sediments and benthic communities.

Farm S is located between islands, with depths at the cages of around 10 to 20 m. Strong currents can form in this area during northern and southern winds, affecting the hydrological regime and the distribution of sediments.

Farm V is located in a closed bay. Depths around the fish farm range from 20 to 30 m, but the channels leading to the main water area of Lake Ladoga are shallower (about 10 m). These morphometric features create stagnant hydrological conditions in the bay.

3. Materials and Methods

3.1. Seasons and Sites of the Sampling Procedure

Fieldwork was conducted during four seasons of 2023: 26–28 of February (winter)—a period when fish feeding is minimal and the area of farms has cleared of organic waste; 2–6 of June (hydrological spring)—initiating active feeding; 22–30 of August (summer)—fish feeding is at its peak; and 20–30 of November (autumn)—feeding activity begins to decrease, and the amount of accumulated organic waste on the bottom under the cages reaches its maximum.

Two categories of sampling sites were defined for each farm (Figure 1). Cage sites were located directly beneath the fish cages to evaluate the impact of farming activities. Reference sites were located at a specified distance (100–600 m) from the fish cages.

3.2. Video Documentation of the Lake Bottom

For a visual assessment of the lake bottom beneath the cages and at the reference sites, video and photographic documentation was conducted during the period of intensive feeding (August). Cameras mounted on an underwater robot were used for this purpose [7]. This method provided detailed imagery of the substrate condition, supporting the evaluation of organic waste accumulation on the bottom.

3.3. Geochemical Studies

Sediment traps were installed beneath the cages during the period of intensive fish feeding (August) to analyze the material entering the aquatic environment from the fish farms. The collection lasted 24 h. A detailed description of the trap design is provided in a previous study [4].

The sediment cores were taken with a gravity corer. The field description of the collected sediments included observations on color, consistency, odor, thickness of the fresh organic layer, and the presence of fish feed or feces. The pH and Eh parameters were measured right after sampling in both sediment cores and water (surface and bottom horizon) using portable pH/Eh-meter (Milwaukee MW500, Glendale, WI, USA).

The content of organic matter was analyzed in 0–10 cm layer of the sediment cores (representing primary benthic habitat) and in the traps' material. The mass % of organic matter was determined by calculating the weight loss of the fully dried sample following ignition at 550 °C for 5 h (LOI, mass %). All analyses were conducted in duplicate, and the result was considered valid if the difference between values did not exceed 10%.

3.4. Hydrobiological Studies

For macrobenthic and meiobenthic sample collection, grab samplers with capture areas of 0.025 m^2 and 0.0028 m^2, respectively, were used. Samples were analyzed for macro- and meiobenthos content. The washing of samples to separate sediment was performed directly at the water's edge using sieves with mesh sizes of 0.82 mm and 0.1 mm. The washed samples were fixed in 4% formalin. In the laboratory, macrobenthic organisms were extracted from the sediment, counted, and weighed using torsion scales with an accuracy of 0.0001 g. The weighing of organisms was conducted by major taxonomic groups. Meiobenthic organism weights were determined using formulas based on the individual size of the meiobenthic invertebrates [8]. For taxonomic composition, organisms were identified to the species level. The primary quantitative metrics for zoobenthos abundance used in the study were biomass and population density, standardized to an area of 1 m^2.

The Juday nets used for zooplankton sampling had a diameter of 18 cm and mesh sizes of 0.070 mm. Samples were collected from three horizons: 0–10 m, 10 m–bottom, and the near-bottom layer. The near-bottom layer was sampled using a bathometer. The volume of the sample collected was 100 L. In the laboratory, the species composition and abundance of zooplankton were analyzed.

The Shannon index was calculated using the Past 4.1 program [9]. The saprobity index for each sample was determined according to the Pantle–Buck index, modified by Sladeček [10,11]. The indicator value of individual invertebrate species was assessed using the works of Sladeček (1973) [10] and Wegl (1983) [12].

3.5. Statistical Tests

The Kruskal–Wallis test was applied to compare hydrobiological and hydrochemical parameters between cage and reference sites. The test provides a reliable method for assessing the statistical significance of differences between the studied groups, even with small sample sizes ($n < 30$) and non-normal data distributions. The Kruskal–Wallis test was calculated using the Past 4.1 program [9].

4. Results

4.1. Underwater Videography

The images (Figure 2) depict the conditions of the lake bottom beneath and around the fish cages and were taken at both the reference (ref) and cage (cag) sampling sites. In Farm K, a significant number of bacterial films accumulated under the cage (K1cag). The sediment layer was uneven and dark, indicating a high level of organic matter accumulation. At the reference site (K3ref), the lake bottom appeared more homogeneous and cleaner, with minimal organic sediment. The sediment surface was light-colored. In Farm S, a dense accumulation of organic material was visible (S1cag), and the sediment surface was dark and heterogeneous. At the reference site (S3ref), the sediment surface was light and homogeneous. In Farm V, significant accumulation of organic material and changes in sediment consistency were observed (V1cag). The sediment surface was dark and uneven. At the reference site (V3ref), the lake bottom appeared clean and light-colored, with minimal organic sediment.

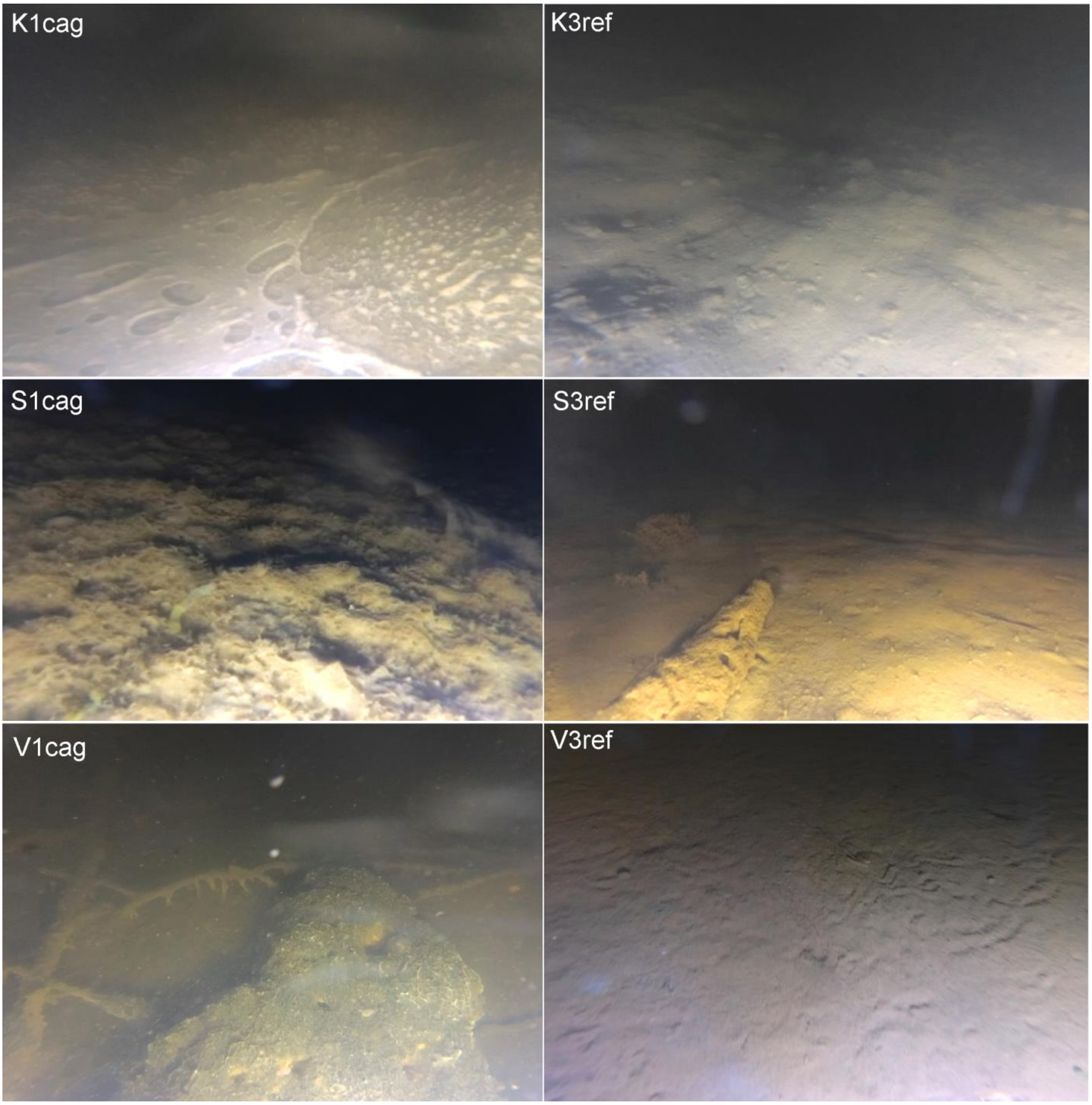

Figure 2. Photos of the bottom around the cage (cag) and reference (ref) sites of the studied trout farms.

4.2. Sediment Traps

The organic material in the traps (Figure 3) consisted of poorly digested feed (light red granules) and fish excrement (dark-brown particles) at all the cage sites of the three studied farms. The volume of the samples varied from 20 to 30 mL. The organic matter content in the trap samples varied from 60 to 75 mass %.

Figure 3. The sediment cores and material from the sediment traps collected at the cage (cag) and reference (ref) sites of the studied farms: a—fresh organic layer; b—background gray silt; c—poorly digested feed.

4.3. Sediment Cores

A visual description of the sediment cores collected during different seasons of the year from the studied trout cage farms is presented in Table 1. Photographs of the sediment cores and sediment trap contents are shown in Figure 3.

Table 1. Description of the sediment cores.

Farm/ Season	February (Reduced Feeding)	June (Start of Feeding)	August (Intensive Feeding)	November (Finishing the Feeding)
Farm K	At site K1cag, the sediment layer of 0–14 cm was brown, soft, heavily watered; there were light-red granules of poorly digested feed. The sediments were characterized by a putrid fishy smell. Gray dense silt was identified in the core layer 14–21 cm (background layers). At site K2cag, the thickness of the fresh organic layer did not exceed 1 cm. At reference sites, sediments were represented by homogeneous gray dense silt.	At site K1cag, the layer of fresh organic silt (0–4 cm) was brown, actively bubbling, and there were pink granules of poorly digested food. The sediments were characterized by a putrid fishy smell. Deeper than 4 cm of the core lay dense gray silt. A whitish mucus (bacterial films) was noted on the surface of the sediment core. At site K2cag, the thickness of the fresh organic layer was 1 cm, in which pink granules of poorly digested feed were found. At the reference sites, sediments had not changed and were represented by gray silts.	In the cage sites, the thickness of the fresh organic layer increased to 12–18 cm, was heavily watered, was actively bubbling, and had a putrid smell. At the reference sites, sediments had not changed.	In the cage sites, the fresh organic layer retained a thickness of 12–18 cm, was heavily watered, contained light-red granules, actively bubbled, and had a putrid smell. At the reference sites, sediments had not changed.

Table 1. *Cont.*

Farm/ Season	February (Reduced Feeding)	June (Start of Feeding)	August (Intensive Feeding)	November (Finishing the Feeding)
Farm S	At cage sites, a flocky light-brown organic layer was visible for 0–2 cm. Sediments bubbled throughout the depth of the core. At site S1cag, a whitish film of bacterial origin existed on the surface of the sediment. The background lower layers of the cage cores and sediments of the reference sites were represented by gray silts.	At cage sites, sediments in the fresh organic layer of 0–5 cm bubbled strongly, had a putrid smell, and contained light-red granules of poorly digested food. At reference sites, the sediments had not changed.	In cage sites, the thickness of the fresh organic layer did not exceed 3 cm; gas bubbles and feed granules were not identified. At reference sites, the sediments did not change.	In cage sites, the thickness of the fresh organic layer was 3–4 cm, light-red feed granules were noted, and the sediments were actively bubbling. A whitish bacterial film was noted on the sediments' surface. At reference sites, sediments did not change.
Farm V	No data	In cage sites, the surface layer of 0–5 cm was represented by dark gray silt. Gas bubbles and rare light-red granules of feed were observed at 0–1 cm. At reference sites, sediments were represented by homogeneous gray dense silt with an admixture of brown sand.	In cage sites, the surface layer of 0–7 cm was represented by dark gray silt. Gas bubbles and rare light-red granules of poorly digested feed were observed at 0–3 cm. At reference sites, sediments did not change.	In cage sites, the thickness of the fresh organic layer reached 10 cm. The light-red granules of poorly digested feed were noted in large quantities. A whitish bacterial film existed on the surface of the sediments. At reference sites, sediments did not change.

Among the three farms studied, the highest content of organic matter in the surface layer of the sediment core (0–10 cm) was observed at the cage sites in Farm K (Figure 4). The maximum values (up to 70 mass %) were measured in the intensive fish feeding period (August–October) and exceeded the background values (K3ref and K4ref; Figure 4) by 2–7 times. At K1cag, within the zone of the oldest cages, the layer enriched with organic matter was present during the winter period (February), but by the beginning of feeding (June), the organic content decreased almost threefold. At reference sites K3 and K4, the organic matter content was relatively stable throughout the year and varied within 1–3 mass %.

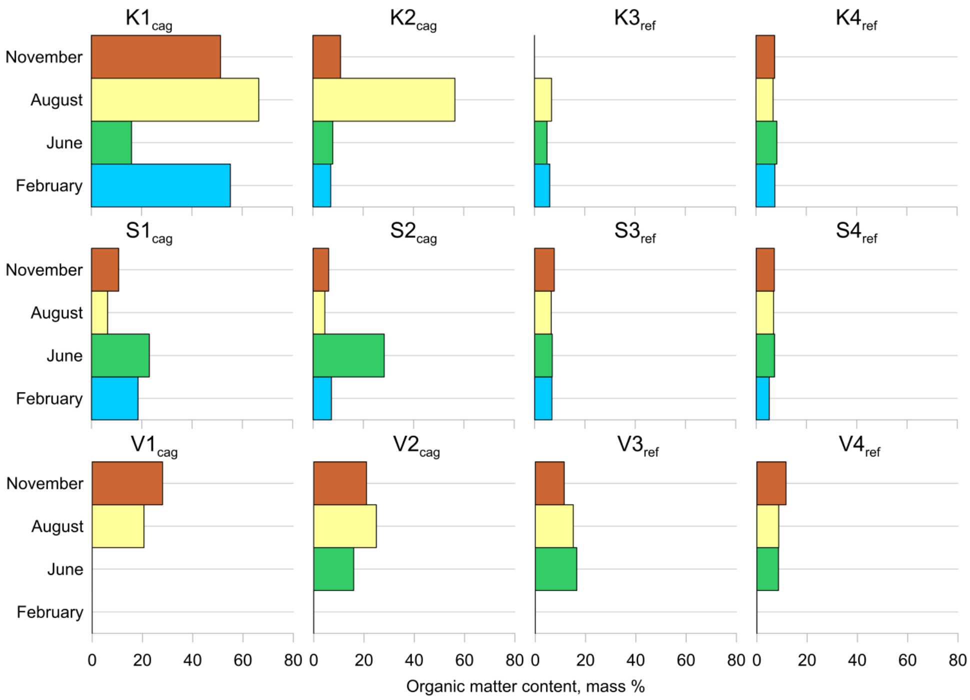

Figure 4. Organic matter content (mass %) in sediment samples (0–10 cm) from the cage (cag) and reference (ref) sites of the studied trout farms.

At Farm S, the maximum content of organic matter in the surface layer was noted at the cage sites (S1cag and S2cag) in June and exceeded the reference values (S3ref and S4ref) by 2–3 times (Figure 4). During the remainder of the year, the organic matter content did not exceed 20 mass %, which was close to the reference level (5–7 mass %).

In Farm V, an increased content of organic matter (2–3 times greater than that at the reference sites) was observed at the cage sites in August and November (Figure 4). However, the maximum values did not exceed 25 mass %.

The results of the pH and Eh parameter measurements in water (surface and bottom layers) and sediments (0–10 cm) are presented in Figure 5. The surface and bottom water layers within the studied farms at all the sites were characterized by slightly acidic–neutral pH values (6.2–7.2) and predominantly oxidizing (Eh > 100 mV) conditions. The exception was Farm K, where negative Eh values were noted in the bottom water layers in June.

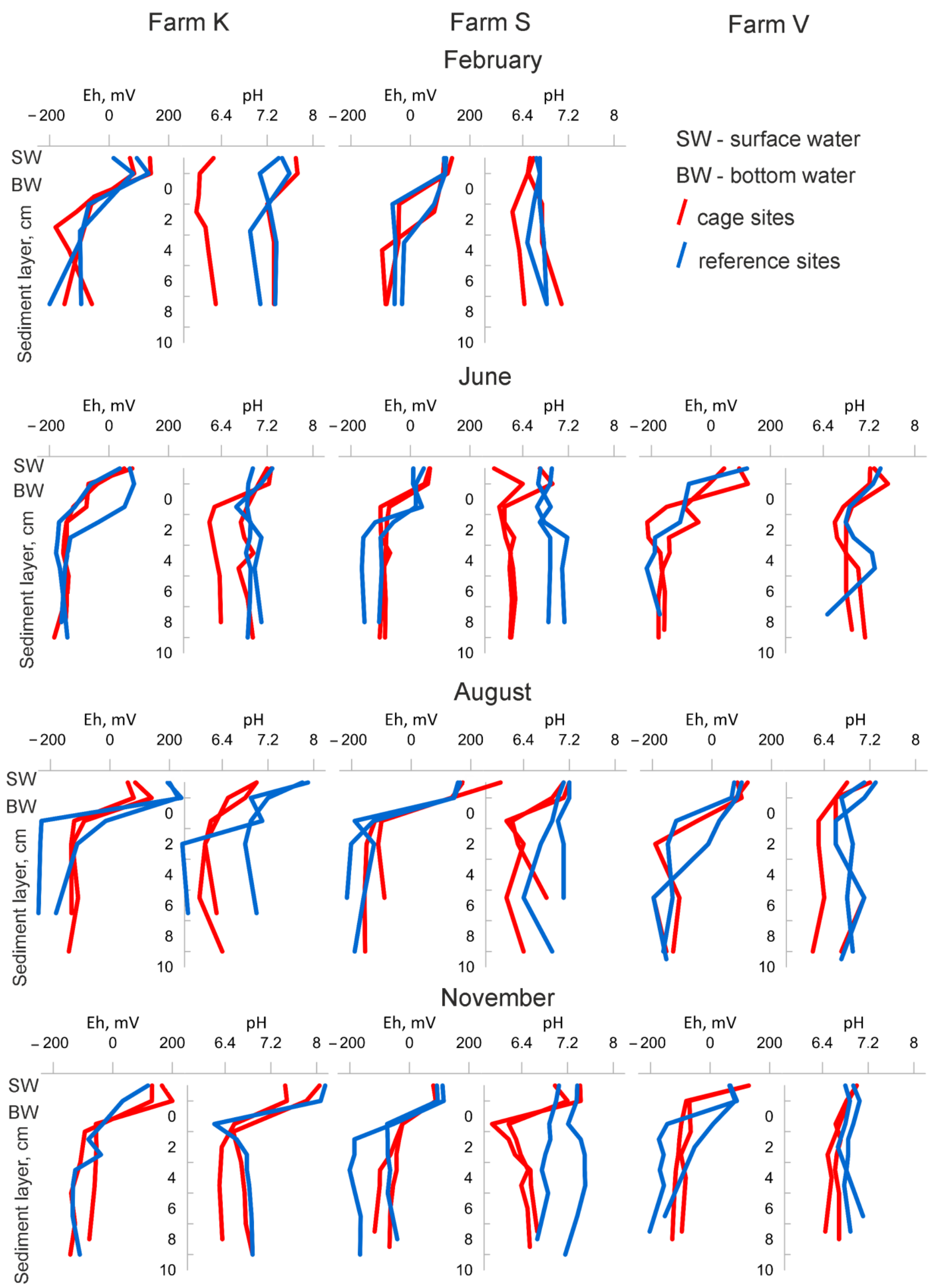

Figure 5. pH and Eh values of the water and sediment at the cage and reference sites at the studied trout farms.

The pH of the sediments varied in the range of 6.2–7.2. Compared with the sediments at the reference sites, the cage sites were characterized on average by a more acidic pH. In the sediments from all the studied farms in all the seasons of the year, predominantly reducing conditions were noted (Eh < 0 mV). Sharply reducing conditions (Eh < −150 mV) were identified in the sediments of Farm K and Farm V at the beginning of the feeding period in June.

4.4. Zooplankton

Throughout the observation period (February, June, August and November), 45 taxa of zooplankton were recorded in Farm K (Rotifera—19, Cladocera—11, Copepoda—15) (Figure 6); 54 taxa in Farm S (Rotifera—20, Cladocera—19, Copepoda—15) (Figure 7); and 48 taxa in Farm V (Rotifera—18, Cladocera—16, Copepoda—14) (Figure 8).

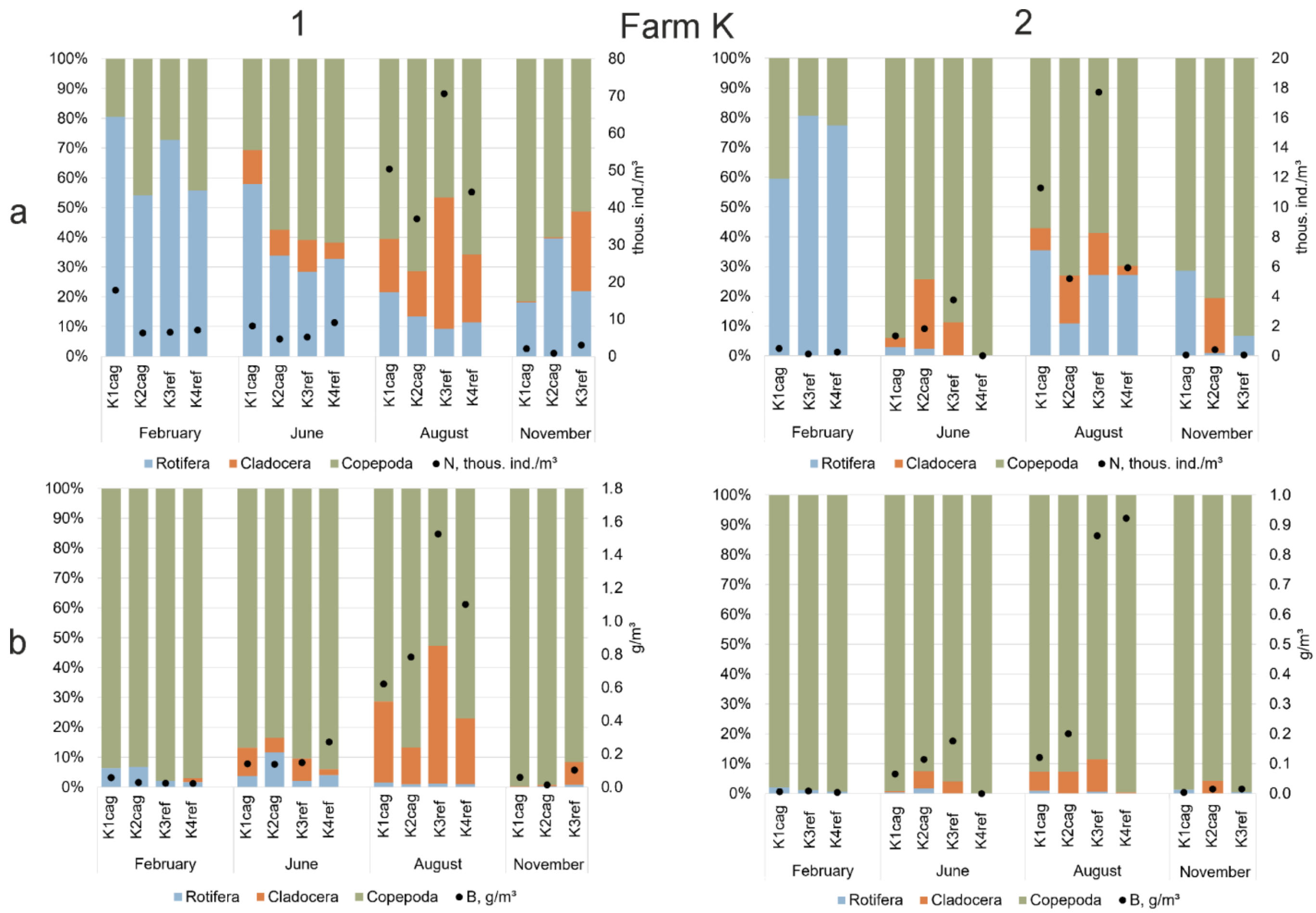

Figure 6. Proportion (%), abundance (**a**) and biomass (**b**) of the main groups of zooplankton in the water column: 1—surface and middle layers; 2—bottom layer.

The complex of mass species of zooplankton included representatives typical for Lake Ladoga from the group of rotifers (*Asplanchna priodonta* (Gosse, 1850), *Conochilus unicornis* (Rousselet, 1892), *Euchlanis dilatata* (Ehrenberg, 1832), *Keratella quadrata* (Muller, 1786), *K. cochlearis* (Gosse, 1851), *Kellicottia longispina* (Kellicott, 1879), *Notolca caudata* (Carlin, 1943), *Polyarthra* sp., *Synchaeta* sp.); cladocerans (*Bosmina longirostris* (O.F. Muller, 1776), *B. coregoni* Baird, 1857, *Chidorus sphaericus* (O.F. Muller, 1785), *Daphnia galeata* (Sars, 1864), *D. cucullata* (Sars, 1862)); and copepods (*Cyclops strenuus* (Fischer, 1851), *Mesocyclops leuckarti* (Claus, 1857), *Thermocyclops oithonoides* (Sars, 1863), *Eudiaptomus gracilis* (Sars, 1863), *Eurytemora lacustris* (Poppe, 1887), *Limnocalanus macrurus* (Sars G.O., 1863)).

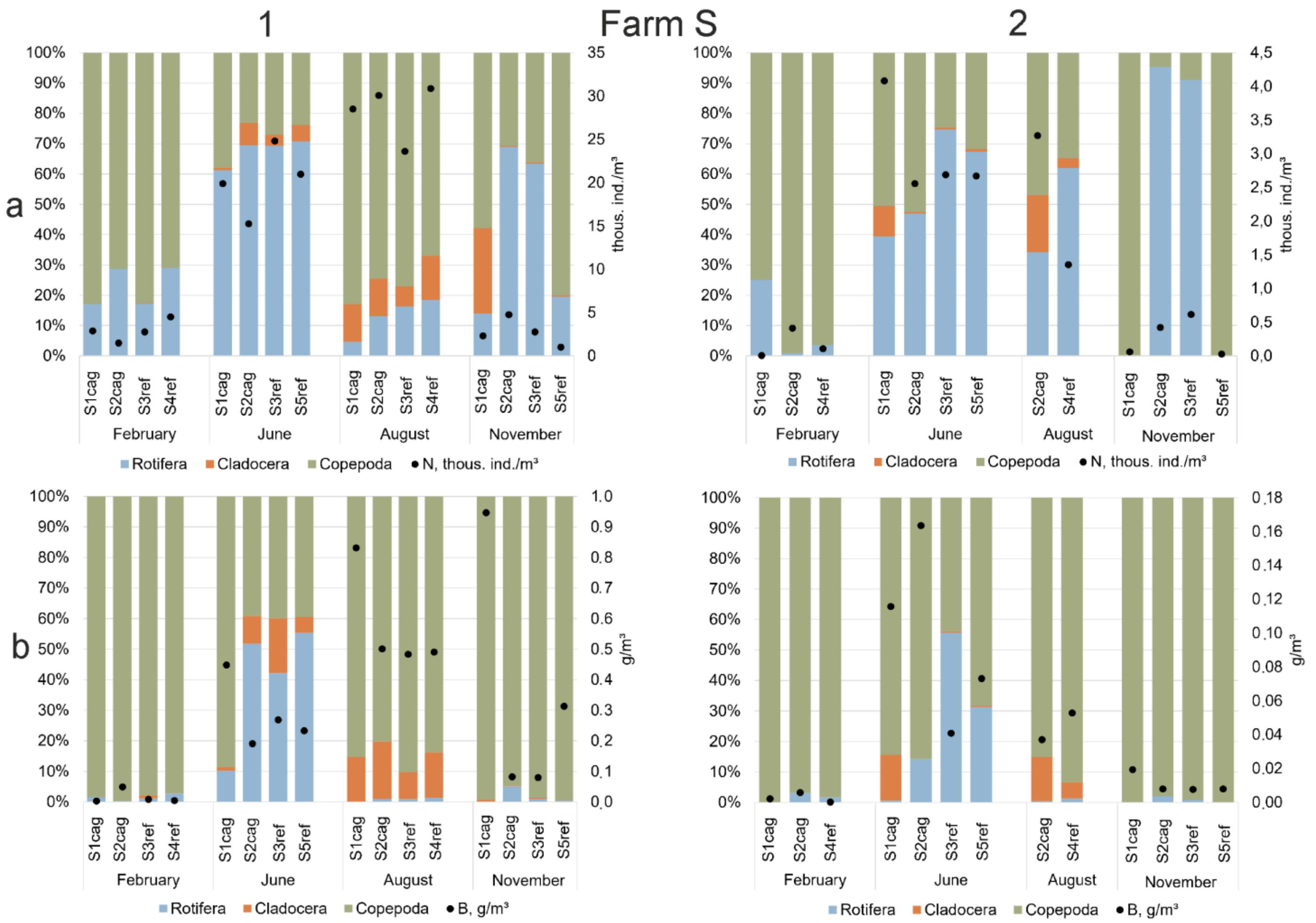

Figure 7. Proportion (%), abundance (**a**), and biomass (**b**) of the main groups of zooplankton in the water column: 1—surface and middle layers; 2—bottom layer.

Farm K. During the study period, the zooplankton in the area of Farm K included 5–13 species of rotifers (Rotifera), 2–8 species of cladocerans (Cladocera), and 5–14 species of copepods (Copepoda). Fewer species were recorded in winter, whereas more species were observed in summer, which is characteristic of plankton communities that develop during the warm period of the year.

The quantitative values of the community varied widely across the seasons (Figure 9). The abundance and biomass of winter zooplankton ranged from 2.92 to 9.43 thous. ind./m^3 and from 0.017 to 0.033 g/m^3, respectively, with the lowest values observed in Farm S and the highest in Farm K. Zooplankton during the "open" water period (June, August, and November) generally presented higher quantitative values. The abundance varied from 2.00 to 50.56 thous. ind./m^3, and the biomass ranged from 0.026 to 1.009 g/m^3. The lowest values, similar across all farms, were noted in June and August, whereas the highest values were recorded in August, especially in Farm K.

Among the rotifers, *Kellicottia longispina*, *Keratella cochlearis*, and species from the genus *Synchaeta* were dominant. The dominant copepods included *Limnocalanus macrurus*, *Eudiaptomus gracilis*, and, to a lesser extent, *Thermocyclops oithonoides* and *Mesocyclops leuckarti*. Additionally, throughout all the seasons, there was an abundance of copepod juveniles (nauplii and copepodid stages), primarily cyclopoids, except in spring, when mass development of calanoid copepods (IV–V stages) of *Limnocalanus* was observed throughout the water body. The predominant species included *Keratella quadrata*; *Asplanchna priodonta* among rotifers; *Bosmina coregoni*; *B. longirostris*; *Daphnia cristata*; *Chydorus sphaericus* among cladocerans; and *Cyclops strenuus*, *C. abyssorum*, *Mesocyclops leuckarti*, *Thermocyclops oithonoides*, and *Eurytemora lacustris* among copepods.

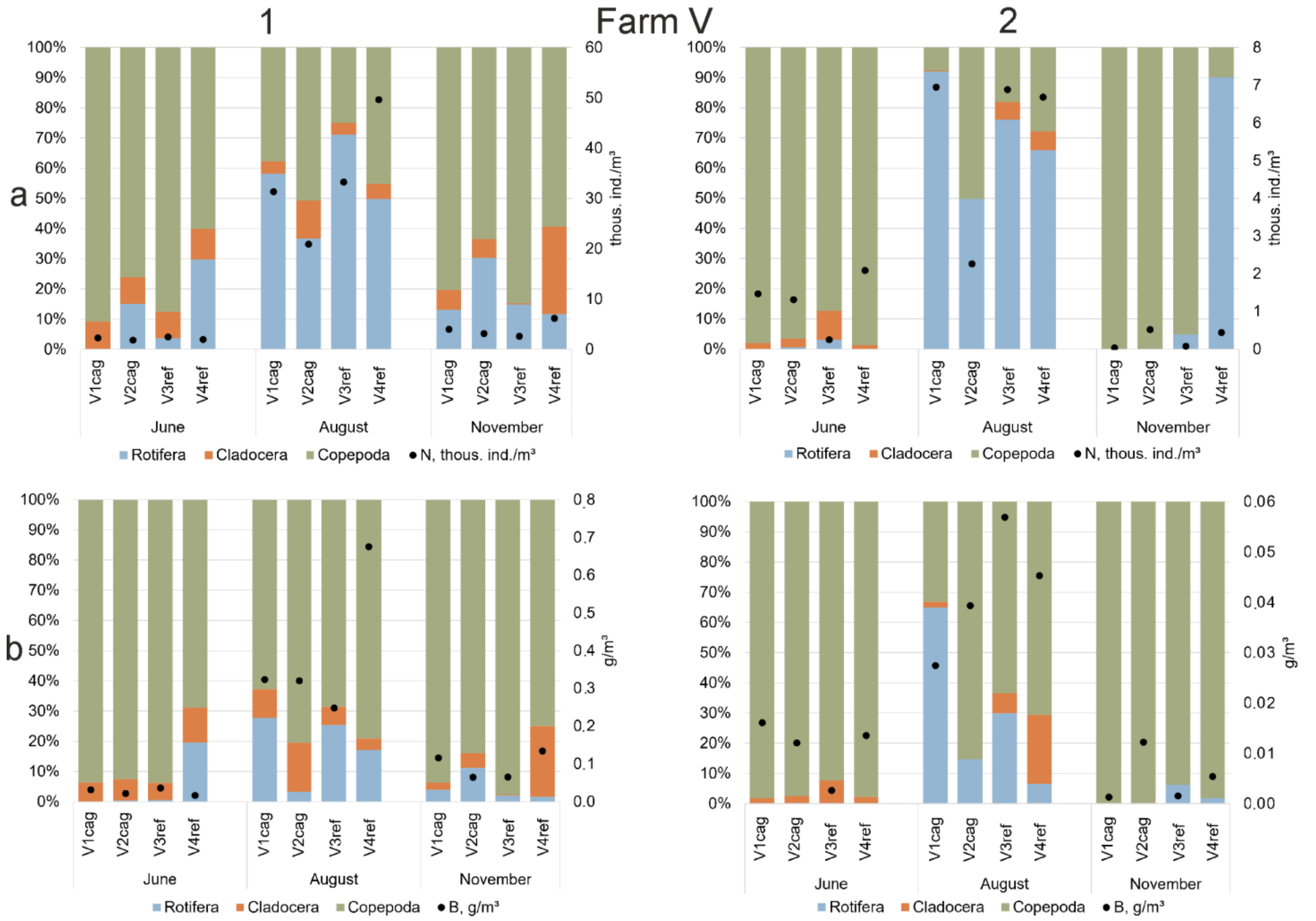

Figure 8. Proportion (%), abundance (**a**), and biomass (**b**) of the main groups of zooplankton in the water column: 1—surface and middle layers; 2—bottom layer.

The maximum accumulation of zooplankton during the study period was observed in the upper water layer, where the abundance of zooplankton varied seasonally from 1.32 to 130.42 thous. ind./m^3 and biomass from 0.002 to 1.837 g/m^3. Higher values were noted during the spring–summer period, which coincided with the gradual warming of the epilimnion. In the middle water layer, the quantitative values were significantly lower, not exceeding 0.51 to 8.34 thous. ind./m^3 in abundance and 0.012 to 0.782 g/m^3 in biomass. The abundance of the bottom layer community was similar to that of the middle layer community, ranging throughout the year from 0.004 to 17.72 thous. ind./m^3. The biomass values were also comparable to those of the middle layer, ranging from 0.0005 to 0.922 g/m^3 (Figure 9).

The distribution of zooplankton species and their quantitative values across sites, both in the water column (surface and middle layers) and in the bottom layer, was uneven.

Throughout the observation period, a greater presence of species was noted at the reference sites (from 7 in winter to 24 in summer) in both the water column and the bottom layer, although the community structure in the latter was simpler and consisted of 1.5–2 times fewer zooplankton species. A similar trend was observed for the quantitative values. The average seasonal abundance at the cage sites (K1cag and K2cag) was 15.92 thous. ind./m^3, whereas at the reference sites (K3ref and K4ref), it was 20.75 thous. ind./m^3. The average biomass across seasons at these sites was 0.231 and 0.458 g/m^3, respectively.

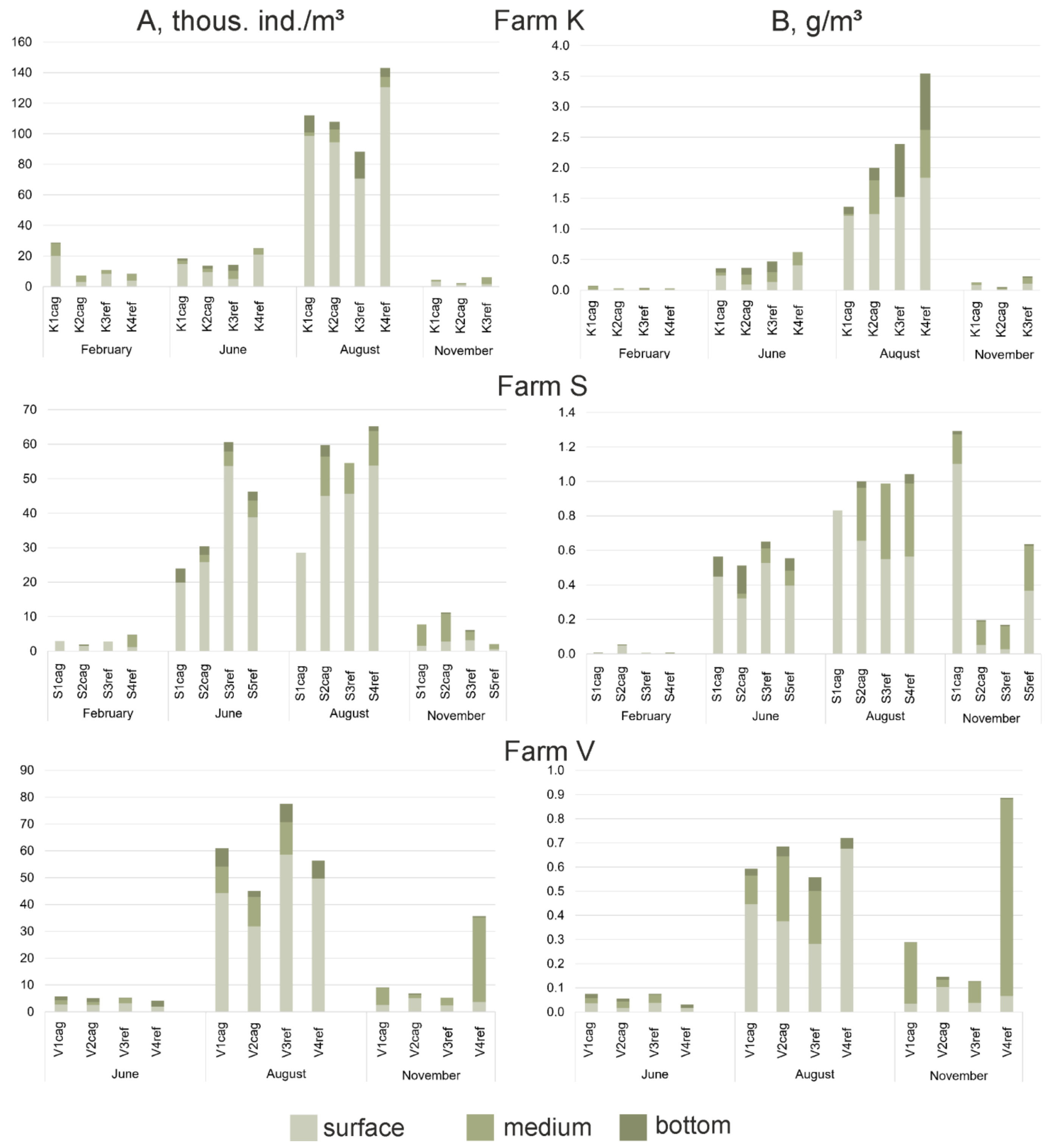

Figure 9. Distribution of the abundance (**A**) and biomass (**B**) of zooplankton across water layers in the studied trout farms.

In the vicinity of the cage sites, rotifers and copepods characterized the majority of the zooplankton abundance throughout all the seasons, indicating broad ecological versatility. Conversely, at the reference sites, crustacean plankton predominated, primarily represented by eurythermal copepod species and, to a lesser extent, by thermophilic cladocerans. Copepods also constituted the main biomass at these sites, with the exception of the summer period, when cladocerans were notably abundant in the water column.

This trend was particularly pronounced at the reference sites, which are distant from the fish cages.

Overall, as the distance from the trout cages increased, the response of the main taxonomic groups in the plankton community showed a doubling in the abundance of crustaceans and a 1.4-fold decrease in the abundance of rotifers in the water column. Conversely, in the bottom layer, the abundance of all zooplankton groups decreased. Biomass increased with distance from the fish cages: it doubled in the water column and more than tripled in the bottom layer.

The calculated Shannon indices characterized the zooplankton conditions as stable. This was especially evident in the summer, when all zooplankton groups showed consistent development, and the Shannon index values were the highest for the study period (Table 2). The extremely low index values in spring and autumn at the reference sites in the bottom layer, compared with those in the water column, were explained by the high concentration of a single species—juvenile *Limnocalanus macrurus* in spring and adult individuals in autumn.

Table 2. Species diversity of zooplankton in the studied trot cage farms; *H*—Shannon index values for abundance (N) and biomass (B).

Study Period	Water Column				Bottom Layer			
	Cage Sites		Reference Sites		Cage Sites		Reference Sites	
	H_N	H_B	H_N	H_B	H_N	H_B	H_N	H_B
				Farm K				
February	1.5	1.2	1.3	0.9	1.6	0.9	1.1	0.8
June	2	1.3	2.1	1	1.5	0.9	0.5	0.2
August	2	1.7	2.1	1.7	2.1	1.8	2.4	1.2
November	1.1	1.1	1.7	1.2	1.2	0.7	1.7	0.2
				Farm S				
February	0.9	0.8	0.7	0.9	1.1	0.6	0.4	0.6
June	2.4	1.6	2.4	1.8	1.5	1	2.1	1.4
August	1.9	1.7	1.9	1.6	1.7	1.3	2	0.8
November	1.1	0.7	1.4	0.5	0.7	0.2	0.7	0.3
				Farm V				
June	1.1	1.2	1.2	1.3	0.7	1.1	0.6	0.9
August	2.5	2.1	2.3	2	2.1	1.7	2	1.8
November	1.7	1.4	1.6	1.4	1	0.7	0.8	0.7

The saprobity index was 1.67 for the water at the cage sites and 1.53 at the reference sites; in the bottom layer, it was 1.61 and 1.58, respectively. The lowest value (1.26) was recorded in February at the reference site (K3ref), whereas the highest values were observed in August (2.05 in K1cag) and November (2.05 in K2cag) at the cage sites. The index values indicate the water quality around Farm K as β-mesosaprobic (moderately polluted water).

Thus, in the surface layer, as the distance from the fish cages increased, there was a general trend toward an increase in community abundance and a decrease in community biomass, whereas in the bottom layer, the quantitative values of zooplankton increased. Additionally, during the vegetation period, an increase in species diversity indices was observed in the water column as the distance from the cages increased, and a decrease in these indices was noted in the bottom layer. The saprobity index values of the indicator species characterized the water area around the cages as more polluted.

Farm S. The species composition of zooplankton at Farm S was in the range of 6–18 species for copepods, 1–13 species for cladocerans, and 4–12 species for rotifers. The highest number of species was typically observed in spring, predominantly at the reference sites.

In both the winter and summer periods, the zooplankton of the surveyed area were characterized by the predominance of copepods (more than 80% in abundance and 95% in biomass). The dominant species were the large calanoids *Limnocalanus macrurus* and *Eudiaptomus gracilis*, whereas *Cyclops strenuus* and *Mesocyclops leuckarti* played secondary roles. Additionally, there was an abundance of nauplii and copepodites, especially in February, when they constituted a significant portion of the plankton (Figure 7).

In spring and autumn, the proportion of rotifers increased (up to 70%), although high biomass values for the group (more than 50%) were noted only in spring. Throughout the year, only one species, *Kellicottia longispina*, dominated the group, while the subdominant species were from the genera *Synchaeta* and *Asplanchna priodonta*, which contributed a large share of the biomass due to their large size. The contribution of cladocerans to the quantitative values of zooplankton was evident only in summer and did not exceed 11% of the total abundance and biomass. In other seasons of the year, the share of cladocerans was insignificant. The group was dominated by *Bosmina coregoni* and *Chidorus sphaericus*.

The surface water layer presented the greatest presence of zooplankton during the study period, with a seasonal abundance ranging from 1.20 to 53.75 thous. ind./m^3 and biomass from 0.002 to 1.102 g/m^3 (Figure 9). High values were recorded during the spring–summer period. The anomalously high biomass in autumn was associated with the predominance of a few, but sizable, *Limnocalanus macrurus*.

In the middle water layer, the quantitative values were significantly lower, not exceeding 11.50 thous. ind./m^3 in abundance and 0.44 g/m^3 in biomass. The abundance and biomass of zooplankton in the bottom layer were more than three times lower than those in the previous horizon, varying throughout the year from 0.01 to 4.08 thous. ind./m^3 and 0.0003 to 0.16 g/m^3, respectively.

The distribution of species and quantitative values of zooplankton across sites, both in the water column (surface and middle layers) and in the bottom layer, was uneven.

During the observation period, a greater presence of species was noted at reference sites (from 5 in winter to 31 in summer) in the water column and in the bottom horizon. However, the community structure near the bottom was represented by a much smaller number of species (from 1–2 in winter to 14–15 in summer).

The abundance values of zooplankton across the studied area were similar at both the reference and cage sites. The seasonally averaged values in the water column near the cage sites (S1cag and S2cag) were 13.16 thous. ind./m^3, at reference sites (S3ref and S4ref)—13.92 thous. ind./m^3, and in the bottom layer—1.53 and 1.35 thous. ind./m^3, respectively. The overall biomass in the same areas tended to decrease, with values of 0.382 (S1cag and S2cag) and 0.236 g/m^3 (S3ref and S4ref), respectively. The bottom layer exhibited a similar trend, with values nearly twice as low (from 0.050 to 0.029 g/m^3).

At the cage and reference sites, copepods typically constituted the majority of both their abundance and biomass. An exception occurred during the spring period (June), when there was a widespread increase in the proportion of rotifers in the quantitative values.

Overall, as the distance from the fish cages increased, the numerical values of crustaceans decreased across all the water layers. Conversely, copepods presented increases in both abundance and biomass. This trend was particularly pronounced in the bottom layer.

The calculated species diversity indices characterized the community conditions overall as stable. This was confirmed primarily by the differences in indices between seasons. Low values were typical for February and November, when copepod juveniles and individual adults of *Limnocalanus macrurus* and *Eudiaptomus gracilis* predominated in the zooplankton. The maximum index values were recorded in spring and summer, when there was regular development across all zooplankton groups (Table 2).

However, the indices of the reference sites for the bottom water horizon were greater in spring and summer than those of the cage sites were, although such dynamics were not observed in the water column. The difference in indicators between the water layers may be explained by the hydrological regime of the study area, specifically the high flow rate, which prevents the formation of stagnant zones with elevated organic matter content in the water column. As a result, the negative impact of the activities of Farm S decreases.

The saprobity indices, which are calculated on the basis of average quantitative values of indicator species, were 1.76 in the water column at the cage sites and 1.73 at the reference sites. The bottom layer exhibited better conditions, with indices of 1.60 and 1.65, respectively. Lower values were observed seasonally during the winter and spring (1.28–1.30) at both the reference and cage sites, whereas higher values occurred near the fish cages during the summer (1.95–1.96). Overall, the index values suggest that the water quality near Farm S is β-mesosaprobic (moderately polluted water).

Thus, the results revealed spatial changes in the structure and quantitative values of zooplankton. While the community abundance was evenly distributed, species aggregation was noted at the reference sites, especially in the surface and middle layers. Moreover, as the distance from the fish farms increased, there was a consistent decrease in the proportion of large crustaceans and an increase in the proportion of small rotifers within the taxonomic groups. This was correlated with the biomass of zooplankton, which was predominantly composed of copepods. Additionally, during the growing season, low species diversity indices and elevated saprobity indices, which were calculated on the basis of indicator species, were observed in the bottom layer near the fish farms.

Farm V. Among the total number of plankton fauna taxa, rotifers comprised 5–17 species, cladocerans comprised 4–14, and copepods comprised 7–12. Fewer species were noted in the spring period, and more were noted in the summer, which corresponds to community development dynamics.

In June and November, copepods dominated both in terms of the abundance and biomass of zooplankton (over 80%). In August, the community consisted of rotifers (57%), whereas copepods predominated in terms of biomass (71%). Branchiopod crustaceans accounted for less than 6–9% of the numerical values throughout the year (Figure 8).

In the copepod group, *Eudiaptomus gracilis* calanoids and cyclopoid nauplii predominated. Adult cyclops (*Thermocyclops oithonoides*, *Cyclops strenuus*) and the calanoid *Eurytemora lacustris* played secondary roles. Among the rotifers, *Kellicottia longispina*, *Keratella cochlearis*, and *Synchaeta stylata* were dominant. Among branchiopods, only one species, *Bosmina coregoni*, predominated.

The distribution of zooplankton across the water layers was uneven. In June and August, its accumulation was observed in the warmer surface layer, where its abundance varied seasonally from 1.98 to 58.54 thous. ind./m^3 and biomass from 0.017 to 0.676 g/m^3. High numerical values were characteristic of August at reference sites V3ref and V4ref. In November, zooplankton were also concentrated at the reference sites, but in the middle water layer, with the maximum abundance (31.6 thous. ind.s/m^3) and biomass (0.815 g/m^3). This was likely due to the faster cooling of the surface water layer and the migration of zooplankton to the warmer middle layer. The abundance of zooplankton in the bottom layer during the observation period was lower than that in the two upper layers, ranging from 0.04 to 6.95 thous. ind./m^3. The biomass values were also not high, ranging from 0.001 to 0.057 g/m^3 (Figure 9). Lower abundance and biomass values were recorded at the cage sites.

The species composition and quantitative values of plankton fauna varied insignificantly across sites. A greater presence of species was characteristic of the water column at the cage sites, where in winter, their number ranged from 3 to 10, and in summer, their number ranged from 25 to 32. In the bottom layer, the zooplankton structure was relatively simple, and species richness shifted toward reference sites, ranging from 4 in November to 16 in August.

There was also a trend of increasing abundance from the cage sites to the reference sites in quantitative terms. The average abundance values at the cage sites (V1cag and V2cag) were 4.18 to 9 (at the bottom) and 21.15 (in the water column) thous ind./m^3, respectively, whereas at the reference sites (V3ref and V4ref), they were 5.47 and 32.04 thous ind./m^3, respectively. The seasonally averaged biomass at the same site varied between 0.036–0.293 and 0.042–0.392 g/m^3. Overall, the community abundance in the water column was 5–6 times greater than that in the bottom layer, and the biomass was 8–9 times greater.

The values of the biodiversity index indicated stable community conditions, which were confirmed by seasonal changes in the indices. Low values were typical for spring and autumn, when the zooplankton were dominated by juvenile copepods (nauplii and copepodites of cyclopoids and calanoids). Relatively high index values were recorded in summer, corresponding to regular development across all zooplankton groups (Table 2).

The saprobity indices, which are calculated on the basis of quantitative values of indicator species by region, were 1.70 in the water column at the cage sites and 1.60 at the reference sites; in the bottom layer, they were 1.80 and 1.73, respectively. Directly at the observation sites, relatively better conditions (1.49) were observed in the spring in the water column at the reference sites (V3ref and V4ref), whereas more polluted conditions were noted in autumn in the bottom layer at the cage sites (1.99) and at the reference sites (2.19). These index values suggest that the water quality in the vicinity of Farm S is β-mesophilic (moderately polluted water).

This study revealed the influence of Fish Farm V on the structure and quantitative characteristics of zooplankton. Across all the studied layers (surface, middle, and bottom), there was a consistent trend toward increased abundance and biomass further away from the fish cages. Additionally, relatively high species diversity indices were observed at the cage sites during the summer–autumn period, which was attributed to the abundance of rotifers, an indicator of the organic load in the aquatic environment. Saprobity index values, particularly in the bottom layer, characterized the studied water body as moderately polluted.

4.5. Benthic Communities

Farm K. The average values of the abundance and biomass of macrozoobenthos at the cage sites varied within 0.33 ± 0.11 thous. ind./m^2 and 0.55 ± 0.25 g/m^2, respectively, whereas at the reference sites, they were 0.77 ± 0.37 thous. ind./m^2 and 1.94 ± 1.02 g/m^2, respectively. The community was represented by two major taxa: oligochaetes and chironomids. Representatives of the Chaoboridae family were found sporadically. Ten species of macrozoobenthos were discovered in the surveyed water area. The number of species under the cages was lower: one species of the Orthocladiinae family, one species of the genus *Procladius* (chironomids), and oligochaetes (three species). In the structure of the dominant complex, oligochaetes predominated (89.4% of total abundance (N) in the background area and 84.8% at the cage sites; in terms of biomass, 84.5% and 95.5% of total biomass (B), respectively).

The average values of the abundance and biomass of meiozoobenthos at the cage sites varied within 21.67 ± 8.93 thous. ind./m^2 and 0.20 ± 0.11 g/m^2, respectively, whereas at the reference sites, these values were 15.60 ± 7.19 thous. ind./m^2 and 0.24 ± 0.11 g/m^2, respectively. In the surveyed areas, 17 species from 8 major taxa were found: Nematoda, Chironomidae, Oligochaeta, Cyclopoida, Ostracoda, Cladocera, Amphipoda, and Turbellaria. Of these, 11 species were found in the trout farm zone. The complex of mass species of meiozoobenthos included typical freshwater forms: nematodes (species identification was not conducted), juvenile forms of oligochaetes, the copepods *Mesocyclops leuckarti*, *Thermocyclops oithonoides*, and *Paracyclops fimbriatus*, the ostracods *Cytherissa lacustris* and *Candona sp*., and turbellarians. Cladocerans of the genus *Alona* and the amphipod *Monoporea affinis* were found sporadically. The role of nematodes in the composition of the dominant complex at the cage sites significantly increased with a simultaneous decrease in the dominance of cyclopoids (Figure 10).

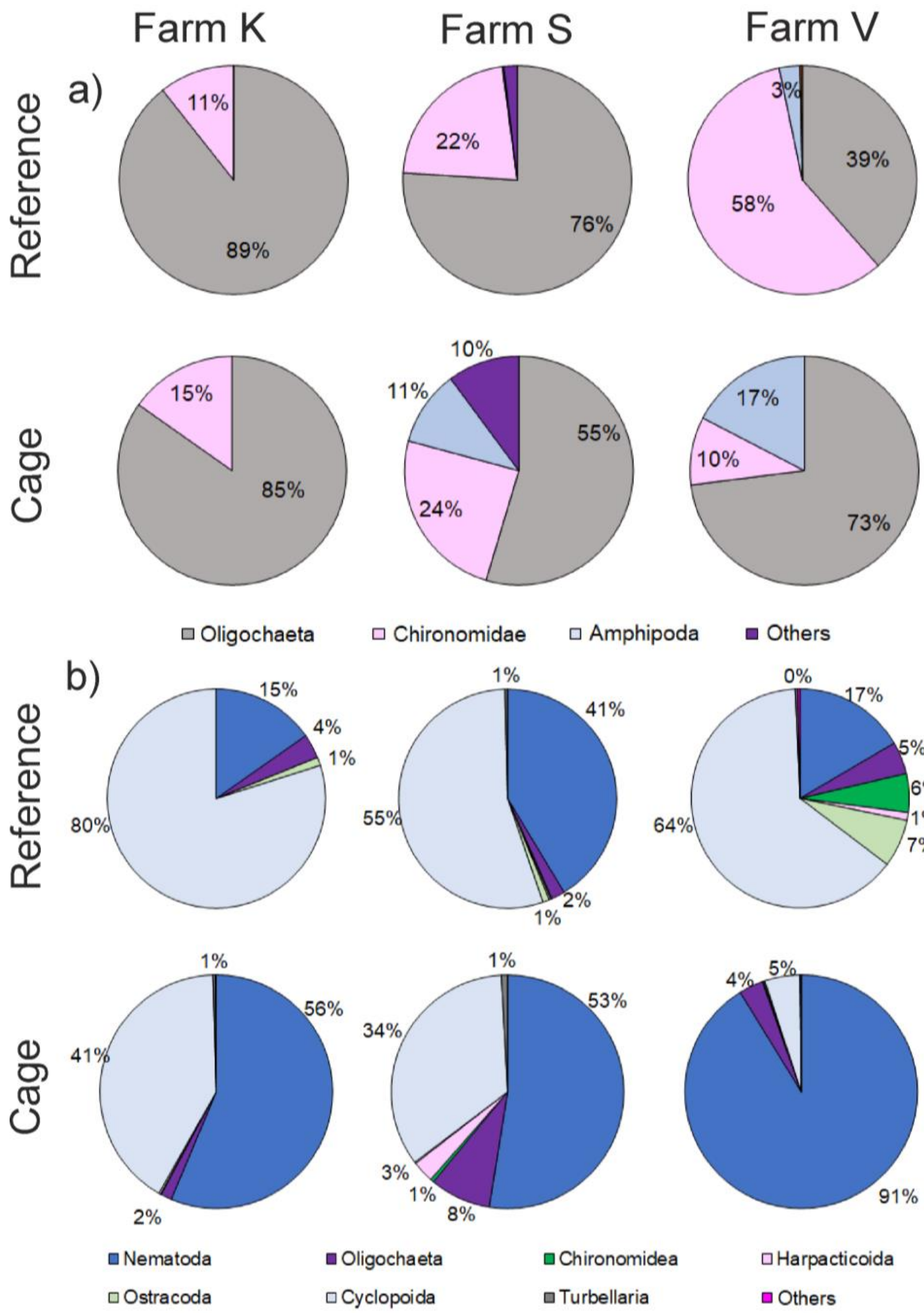

Figure 10. Structure of macrozoobenthos (**a**) and meiobenthos (**b**) at the cage and reference sites of the studied trout farms.

The maximum development in terms of the abundance and biomass of macrozoobenthos was observed in August at the reference sites. The variations in these indicators at the cage sites were less pronounced and slightly greater during the autumn–winter (November) period (Figure 11). For meiobenthos, the greatest degree of community development was noted in the winter period across the entire studied area (Figure 12), characterized by intensive development of nematodes, cyclopoids, and oligochaetes; elevated values of abundance and biomass were also observed in November at the cage sites. In contrast to macrozoobenthos, meiobenthic organisms were less abundant during the summer (August) than during the other seasons.

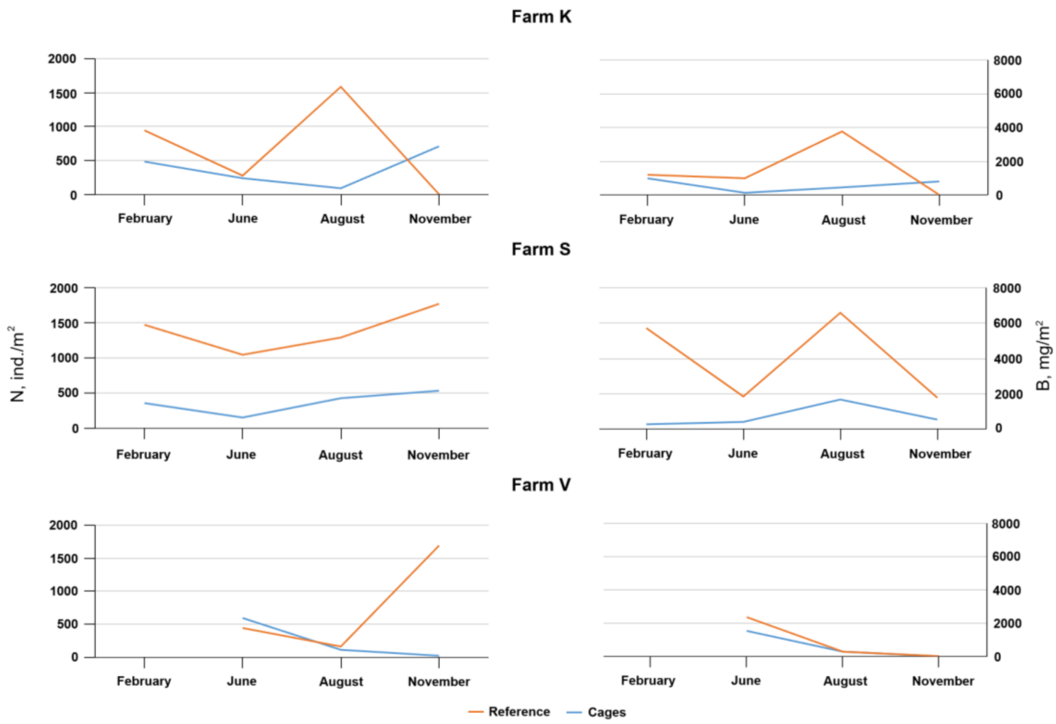

Figure 11. Differences in the abundance and biomass of macrozoobenthos at the reference and cage sites across different seasons of the year.

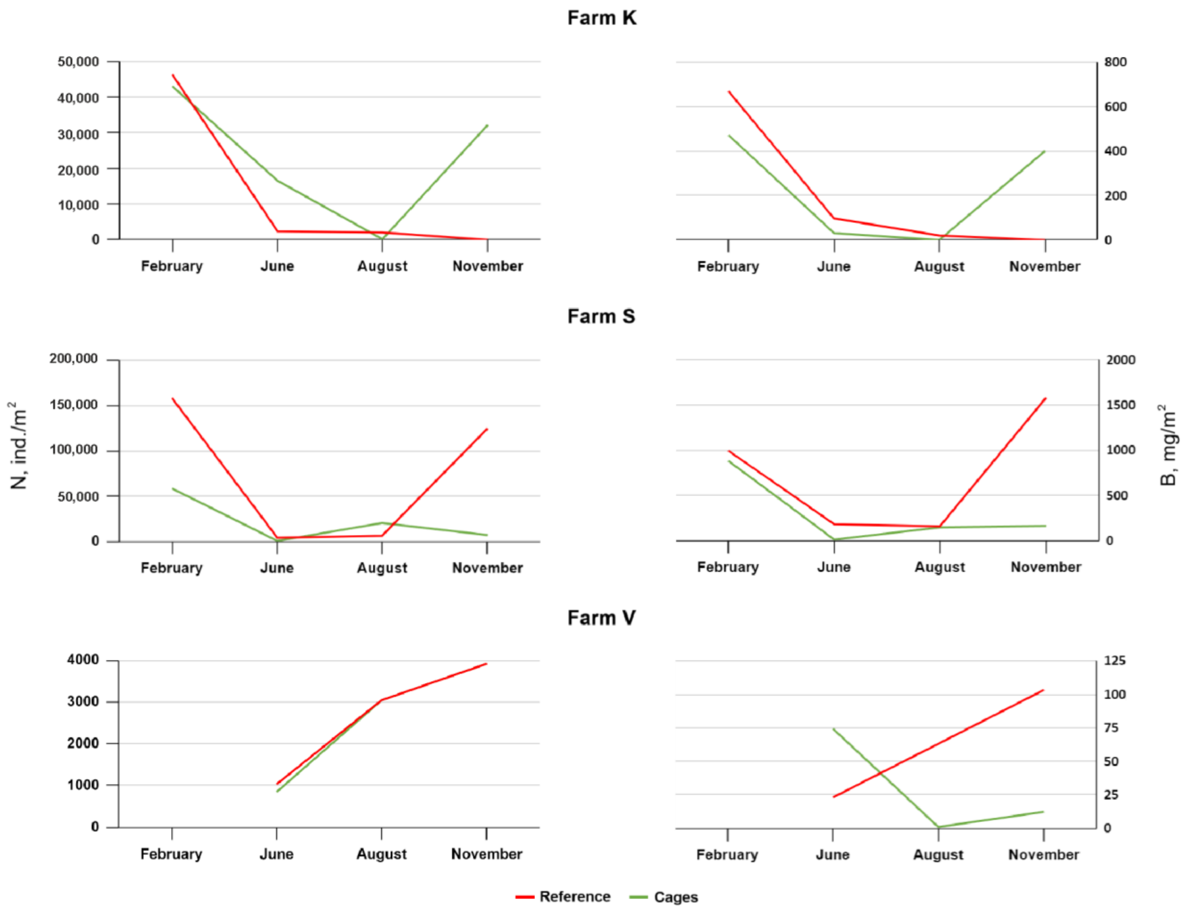

Figure 12. Changes in the abundance and biomass of meiobenthos at the reference and cage sites across different seasons of the year.

Farm S. The average abundance and biomass values of macrozoobenthos at the cage sites varied within the range of 0.28 ± 0.07 thous. ind./m^2 and 0.70 ± 0.25 g/m^2, respectively, whereas at the reference sites, they were 1.38 ± 0.45 thous. ind./m^2 and 4.30 ± 2.16 g/m^2, respectively. The community was represented by two major taxa: oligochaetes and chironomids. Eleven species of macrozoobenthos were found in the study area. Under the cages, the number of species was four: two species of chironomids and two species of oligochaetes. In the area influenced by the trout cages, there was a dominance of oligochaetes in the community structure; however, compared with those at the reference sites, the community structure was lower (76.0 and 54.6% of the total abundance (Figure 10) and 37.5 and 53.2% of the total biomass, respectively).

The average abundance and biomass values of the meiobenthos at the cage sites varied within the range of 17.73 ± 8.88 thous. ind./m^2 and 0.23 ± 0.14 g/m^2, respectively, whereas at the reference sites, they were 66.00 ± 38.45 thous. ind./m^2 and 0.61 ± 0.24 g/m^2, respectively. In the studied areas, 26 species from 11 major taxa were found: Nematoda, Chironomidae (5 species), Oligochaeta (5), Harpacticoida (4), Cyclopoida (4), Ostracoda (3), Amphipoda (1), Tardigrada (1), Acari (1), and Turbellaria (1). Of these, eight species were found in the trout farm zones. The mass species complex of meiobenthos included typical freshwater forms: nematodes (species identification not performed), juvenile forms of oligochaetes from the family Tubificidae and oligochaetes from the family Naididae (genus Nais), the copepods *Canthocamptus staphylinus*, *Mesocyclops leuckarti*, *Thermocyclops oithonoides*, and *Paracyclops fimbriatus*, *Candona* sp. ostracods, and turbellarians. Deep-water amphipods were practically absent, represented by only one species, *Pallasiopsis quadrispinosa*. In the trout cages, the diversity of the community decreased, with the absence of taxa such as chironomids, ostracods, tardigrades, and juvenile amphipods. Harpacticoids were encountered only once (*Canthocamptus staphylinus*). In terms of community structure, the role of nematodes and oligochaetes increased, whereas the share of cyclopoids decreased (Figure 10).

Farm V. The average abundance and biomass values of macrozoobenthos at the cage sites varied within the range of 0.28 ± 0.18 thous. ind./m^2 and 0.72 ± 0.49 g/m^2, respectively, whereas at the reference sites, they were 0.89 ± 0.50 thous. ind./m^2 and 1.59 ± 0.67 g/m^2, respectively. The community was represented by four major taxa: oligochaetes, chironomids, blackflies (Simuliidae), and amphipods. Representatives of the Simuliidae family were encountered only once. In the study area, 11 species of macrozoobenthos were found, including 2 species of oligochaetes, 7 species of chironomids, 1 species of blackfly, and 1 species of amphipods (*Monoporea affinis*). The number of species in the cages was 5. The dominance of oligochaetes in the community structure at the cage sites increased from 38.8 to 73.0% of the total abundance and from 34.2 to 54.6% of the total biomass (Figure 10).

The average abundance and biomass values of the meiobenthos at the cage sites varied within the range of 21.67 ± 8.93 thous. ind./m^2 and 0.20 ± 0.11 g/m^2, respectively, whereas at the reference sites, they were 16.90 ± 7.69 thous. ind./m^2 and 0.26 ± 0.12 g/m^2, respectively. In the studied areas, 14 species from 7 major taxa were found: Nematoda, Chironomidae, Oligochaeta, Cyclopoida, Ostracoda, Acari, and Turbellaria. Of these, eight species were found in the trout farm zones. The mass species complex of meiobenthos included typical freshwater forms: nematodes (species identification not conducted), juvenile forms of oligochaetes, copepods, ostracod *Candona* sp., and turbellarians. Significant changes occurred in the structure of the benthic community in the trout farm zone. The role of nematodes in the dominant complex composition significantly increased at the cage sites (Figure 10).

In terms of seasonality, the highest abundance of macrozoobenthos was observed in November, and the highest biomass was observed in August, whereas in June, the indicators were at their minimum (Figure 11). For meiobenthos, the greatest development was noted in the autumn–winter (November and February) period, with the minimum also occurring in June (Figure 12). At the reference sites, seasonal changes in the structure of the macrozoobenthic community were weakly expressed; oligochaetes dominated in terms of abundance, and both oligochaetes and chironomids dominated in terms of biomass in all seasons. Amphipods were not a major component of the community. At the cage sites, the change in dominant taxa was more pronounced: oligochaetes dominated in June and November, and chironomids dominated in February; in August, the dominant complex of macrozoobenthos included several taxa: mysids, amphipods, and chironomids. In the meiobenthos, seasonal changes associated with seasonal fluctuations in the quantitative development of cyclopoids (minimum abundance, biomass, and contribution to the overall dominant complex structure in June), oligochaetes (greater quantitative development in February and June), and nematodes (their share in the community structure was highest in June and August at the cage sites and in February and June at the reference sites) were observed. The average index of species diversity of benthic communities (Shannon index) in the three studied farms was as follows: Farm K—0.185; Farm S—0.468; Farm V—0.624.

4.6. Statistical Data Processing

Statistical comparison was conducted between geochemical and hydrobiological parameters in cage and reference sites (encompassing all seasons of the year). The results are presented in Table 3.

Table 3. Kruskal–Wallis (K-WH) test results for reference and cage sites.

Sample	K-WH	*p*-Value	Conclusion
Organic matter (mass %)	10.68	0.001082	Significant difference between sample medians
Benthic (species richness)	6.2868	0.0122	
Zooplankton (species richness, water column)	0.1078	0.742	No significant difference between sample medians
Zooplankton (species richness, bottom layer)	0.08732	0.7661	

5. Discussion

5.1. Seasonal Dynamics of Hydrological, Geochemical, and Hydrobiological Parameters

In winter, the lake is covered with ice, resulting in almost no new oxygen supply to the water column. The water temperature is nearly uniform, with the surface layer at approximately 0 °C and the bottom layer around 4 °C. Fish feeding is greatly reduced during this period. The thickness of the accumulated organic layer in the sediments is minimal. The largest mass % of organic matter was observed in the zone of the oldest cage modules at K1cag and S1cag, where values were 2–5 times greater than the reference sites. The cages at these locations have remained stationary for at least 10 years, leading to the accumulation of a substantial amount of organic waste, which is slowly mineralized by bacteria. During the winter, the greatest quantitative development of meiobenthic communities was observed across all studied farms. Macrozoobenthos biomass was lower than that of meiobenthos. Zooplankton populations, in terms of both biomass and abundance, are minimal in winter due to low temperatures, which result in reduced metabolic rates and slower growth. The zooplankton communities primarily consist of copepods.

In spring, the ice melts, and the water column begins to warm up, initiating the vernal turnover. Both surface and bottom layers of the water column receive an influx of oxygen, enhancing oxygenation throughout the lake. Fish feeding activity increases, leading to the intensive accumulation of fresh organic material in the sediments beneath the cages. The organic matter content (mass %) in the surface layers of sediments is higher compared to February. The Eh values of the sediments at all studied sites shifted to a sharply reducing (anoxic) state. The abundance of macrozoobenthos was at its lowest during spring, with oligochaetes as the dominant group. For meiobenthos, this season also showed lower abundance and biomass, with juvenile forms of oligochaetes making significant contributions. Spring marks the onset of active feeding and metabolic activity among zooplankton, resulting in a noticeable increase in diversity and abundance. Rotifera becomes more prominent, contributing to a significant rise in overall zooplankton biomass.

In summer, a pronounced thermocline develops in the water column, limiting free mixing and preventing oxygen flow into the bottom water layers. This stratification results in lower oxygen levels in the deeper water. Fish feeding is intensive, leading to maximum levels of organic waste entering the sediments. Sediment trap analyses revealed that uneaten food and fish excrement are the primary components reaching the bottom. The organic matter content (mass %) in the sediments at the cage sites of Farms K and V reached peak values. An exception is Farm S, which was characterized by better water flow, leading to erosion of the organic layer on the bottom. The pH values at the cage sites were more acidic compared to spring, while Eh values remained in the reducing range throughout the 0–10 cm layer. Summer recorded the highest biomass for macrozoobenthos, with several taxa such as chironomids, amphipods, and mysids being prominent. Meiobenthos showed a reduction in abundance compared to other seasons, with nematodes and cyclopoids being less dominant. The warm water temperatures and increased food availability promote significant growth and activity of zooplankton populations. Summer represents the peak season for zooplankton across all studied fish farms, with high diversity and abundance across groups, including Rotifera, Cladocera, and Copepoda.

In autumn, the water begins to cool, leading to the gradual collapse of the thermocline. This process restores oxygen flow to the bottom water layers. By the end of the feeding period, the thickness of the accumulated organic layer remains similar to that observed in summer. The Eh values shift closer to zero due to the oxygen penetration into the surface sediment layer. The abundance of macrozoobenthos increases again, with oligochaetes emerging as the dominant group. Meiobenthos also exhibited high biomass and abundance, particularly in areas influenced by fish cages. Zooplankton abundance begins to decline as water temperatures drop. However, the community remains relatively diverse, and biomass stays high until late in the season.

5.2. Spatial Dynamics of Hydrological, Geochemical and Hydrobiological Parameters

According to the saprobity index for zooplankton, all studied farms are characterized by a moderate level of water pollution. However, the water flow regime in the areas occupied by the cage farms influences waste accumulation processes in the sediments. For example, the area around Farm S is characterized by freer water flow, resulting in a thinner accumulated organic layer during periods of intensive fish feeding compared to the other farms. In contrast, Farms K and V have local depressions where significant layers of organic waste tend to accumulate. The lowest species diversity of benthic communities was observed at Farm K, where the Shannon index recorded the lowest value among all studied farms.

The results of laboratory analyses (Figure 4) and statistical calculations (Table 3) showed that the influence of fish farming on the accumulation of organic waste in sediments is limited to the area immediately surrounding the cage modules on all trout farms studied. The maximum concentrations of organic matter were observed directly beneath the cages, particularly during periods of intensive feeding. In contrast, the mass percentage of organic matter in sediments at reference sites is significantly lower and remains relatively stable throughout the year. It is noteworthy that organic-enriched sediments provide a substratum for bacterial film development, which was observed in August at all farms under the cage sites (Figure 2).

Oxidation–reduction conditions of water and sediments at the cage and reference sites were similar. However, it should be noted that sediments enriched with biogenic elements [13,14] and microelements [15] accumulate under the cages. Thus, at one of the trout farms examined in this study, the sediments previously exhibited elevated concentrations of zinc and copper compared to the reference areas [16]. The sharply reducing Eh conditions create favorable conditions for the release of chemical elements from sediments into the water, particularly phosphorus [17].

There are spatial differences in the structure of benthic communities, which are more pronounced for meiobenthos. Notably, nematodes play a greater role at the cage sites compared to the reference sites, where cyclopoids dominate. In terms of abundance and biomass, benthic community development is generally lower at the cage sites compared to the reference sites (Table 3). The seasonal dynamics of benthos across all sites follow common patterns of community composition changes. However, within the influence zone of the trout cages, changes in the structure of the dominant complex are characterized by more pronounced fluctuations.

Statistical analysis showed no significant differences in zooplankton species diversity and biomass between cage sites and reference sites (Table 3). However, abundant development of rotifers was observed at the cage sites, unlike at the reference sites, serving as indicators of an intensive nutrient supply. This alteration in zooplankton structure may reflect the influence of trout farming activities. While the dominance of rotifers and copepods was a common feature of both site types, the reference sites consistently exhibited a more balanced and stable zooplankton community.

6. Conclusions

A comprehensive study of the seasonal dynamics and interrelationships between geochemical and hydrobiological parameters of the lake ecosystem within the impact zone of three trout cage farms was conducted. The results indicate that during periods of intensive fish feeding, significant amounts of organic waste accumulate on the lake bottom beneath the cages, influencing the composition and abundance of zooplanktonic and zoobenthic organisms. Organic matter content in sediments beneath the cages during the summer period was found to increase 2–5 times compared to reference sites. Significant variations in the abundance and biomass of benthic communities were observed in summer and autumn, reflecting the influence of fish feeding activity. In winter, the accumulated organic matter in the sediments undergoes mineralization, bringing hydrobiological indicators closer to reference values. The impact of fish farming activities, even during the summer period, is confined to the zone near the cage modules. At reference sites, the seasonal dynamics of geochemical and hydrobiological parameters align with values typical for the studied water body (Lake Ladoga, Russia).

These findings are essential for evaluating the negative environmental impacts of aquaculture on freshwater ecosystems. The hydrobiological and geochemical parameters analyzed in this study can serve as indicators for developing ecological monitoring methods for trout cage farms.

Author Contributions: A.L.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. A.G.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. K.Z.: Data curation, formal analysis, funding acquisition, investigation, and writing—review and editing. D.D.: Data curation, formal analysis, funding acquisition, investigation, and writing—review and editing. A.T.: Data curation, formal analysis, investigation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Russian Science Foundation, project no. 23-24-00202.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author(s) upon reasonable request.

Acknowledgments: The authors are sincerely thankful for the management of the trout farms of Lake Ladoga (Sortavala, Lakhdenpokhya, and Valaam Island) and their logistical assistance in conducting the study.

Conflicts of Interest: The authors declare that there are no known conflicts of interest or financial or personal relationships that may have influenced the work reported in the manuscript.

References

1. Choi, A.; Cho, H.; Kim, B.; Kim, H.; Jung, R.; Lee, W.; Hyun, J. Effects of finfish aquaculture on biogeochemistry and bacterial communities associated with sulfur cycles in highly sulfidic sediments. *Aquac. Environ. Interact.* **2018**, *10*, 413–427. [CrossRef]
2. Petranich, E.; Covelli, S.; Acquavita, A.; De Vittor, C.; Faganeli, J.; Contin, M. Benthic nutrient cycling at the sediment-water interface in a lagoon fish farming system (northern Adriatic Sea, Italy). *Sci. Total. Environ.* **2018**, *644*, 137–149. [CrossRef] [PubMed]
3. Law, B.; Hill, P. Spatial and temporal variation in cumulative mass eroded and organic matter percentage in surface sediments near areas of active salmon aquaculture. *Aquac. Environ. Interact.* **2019**, *11*, 305–320. [CrossRef]
4. Lapenkov, A.; Guzeva, A.; Zaripova, K.; Slukovskii, Z. The seasonal dynamics of geochemical characteristics of sediments in the impact zone of the fish farm (Lake Ladoga, Russia). *Aquac. Fish.* **2023**, *8*, 654–660. [CrossRef]
5. Verhoeven, J.T.P.; Salvo, F.; Knight, R.; Hamoutene, D.; Dufour, S.C. Temporal Bacterial Surveillance of Salmon Aquaculture Sites Indicates a Long Lasting Benthic Impact With Minimal Recovery. *Front. Microbiol.* **2018**, *9*, 3054. [CrossRef] [PubMed]
6. Keeley, N.; Valdemarsen, T.; Woodcock, S.; Holmer, M.; Husa, V.; Bannister, R. Resilience of dynamic coastal benthic ecosystems in response to large-scale finfish farming. *Aquac. Environ. Interact.* **2019**, *11*, 161–179. [CrossRef]
7. Dudakova, D.S.; Anokhin, V.M.; Pozdnyakov, S.R.; Dudakov, M.O.; Yudin, S.N. Underwater landscapes of the islands of Mantsinsaari and Lunkulansaari in the zone of Riphean uplifts in the eastern part of Lake Ladoga. *Izv. Ross. Akad. Nauk. Seriya Geogr.* **2021**, *85*, 433–445. (In Russian) [CrossRef]
8. Kurashov, E. *Meiobenthos as a Component of the Lake Ecosystem*; Slepukhina, T., Ed.; Institute of Limnology of RAS: St. Petersburg, Russia, 1994. (In Russian)
9. Hammer, Ø.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontol. Electron.* **2001**, *4*, 9.
10. Sládecek, V. *System of Water Quality from the Biological Point of View*; Schweizerbart Science Publishers: Stuttgart, Germany, 1973. Available online: http://www.schweizerbart.de//publications/detail/isbn/9783510470051/Archiv_Ergebnisse_d_Limnol_Heft_7 (accessed on 24 November 2024).
11. Shitikov, V.K.; Rozenberg, G.S.; Zinchenko, T.D. *Kolichestvennaya Gidroekologiya: Metody. Kriterii. Resheniya. Kniga 1 [Количественная Гидроэкология: Методы, Критерии, Решения. Книга 1]*; Nauka: Moscow, Russia; Moskva: Moscow, Russia, 2005.
12. Wegl, R. *Index Für Die Limnosaprobität*; Bundesanstalt Für Wassergüte: Koblenz, Germany, 1983.
13. McGhie, T.K.; Crawford, C.M.; Mitchell, I.M.; O'Brien, D. The degradation of fish-cage waste in sediments during fallowing. *Aquaculture* **2000**, *187*, 351–366. [CrossRef]
14. Qi, Z.; Shi, R.; Yu, Z.; Han, T.; Li, C.; Xu, S.; Xu, S.; Liang, Q.; Yu, W.; Lin, H.; et al. Nutrient release from fish cage aquaculture and mitigation strategies in Daya Bay, southern China. *Mar. Pollut. Bull.* **2019**, *146*, 399–407. [CrossRef] [PubMed]
15. Melo Júnior, H.d.N.; de Paula Filho, F.J.; Menezes, J.M.C.; de Araújo, J.A.S.; Gonçalves Santana, J.E.; Melo, H.V.S.; Vieira, R.d.S.; de Morais Oliveira-Tintino, C.D.; Tintino, S.R.; Coutinho, H.D.M.; et al. Impacts of the Residual Trace Metals of Aquaculture in Net Cages on the Quality of Sediment. *Life* **2023**, *13*, 338. [CrossRef] [PubMed]
16. Guzeva, A.; Lapenkov, A.; Zaripova, K.; Slukovskii, Z. Heavy Metal Accumulation in Lake Sediments in the Impact Zone of Trout Cage Farm. *J. Fish. Environ.* **2024**, *48*, 136–147. [CrossRef]
17. Christophoridis, C.; Fytianos, K. Conditions Affecting the Release of Phosphorus from Surface Lake Sediments. *J. Environ. Qual.* **2006**, *35*, 1181–1192. [CrossRef] [PubMed]