water

Article

Changes in the Characteristics of Zooplankton Communities in Response to Shifts in the Aquatic Environment in the Shallow Waters of Northern Liaodong Bay, China

Jiaxing Li [1], Wenjun Zheng [1,*], Zhonglu Cai [1], Jin Ma [2], Geng Li [1], Bo Ma [3], Jing Zhao [2], Zhonghong Li [1], Shuang Li [1], Mingkang Chen [1] and Chuang Gao [1]

[1] Yingkou Enhancement and Experiment Station, Chinese Academy of Fishery Sciences, Yingkou 115004, China; lijiaxingsai@163.com (J.L.); caizhonglu@126.com (Z.C.); malg126@163.com (G.L.); lizhonghong12345@126.com (Z.L.); lishuangzb6@163.com (S.L.); chenmingkang1202@126.com (M.C.); gaochuang0919@163.com (C.G.)

[2] College of Marine Living Resource Sciences and Management, Shanghai Ocean University, Shanghai 201306, China; jma@shou.edu.cn (J.M.); jzhao@shou.edu.cn (J.Z.)

[3] Heilongjiang River Fisheries Research Institute, Harbin 150076, China; hsymabo@163.com

* Correspondence: dajun0417@126.com

Abstract: The characteristics of zooplankton communities and the relationships with the aquatic environment in the shallow waters of northern Liaodong Bay were investigated. Spot sampling surveys were carried out in April, June, September, and November 2018 to assess zooplankton species composition and diversity, abundance, biomass, and dominant species, and the associated relationships with environmental factors. A total of 45 species of zooplankton were recorded in the survey, comprising 18 Copepoda, 2 Amphipoda, 1 Mysidacea, 1 Decapoda, 1 Chaetognatha, 7 Hydrozoa, 1 Tunicate, and 14 planktonic larvae. Overall, the most dominant species was *Aidanosagitta crassa* (Tokioka, 1938), with copepods and planktonic larvae also dominating the zooplankton community. However, there was a seasonal alternation of species dominance. A cluster analysis showed that the zooplankton community in spring differed from other seasons and was mostly influenced by suspended particulate matter. Bioenv analysis indicated the main environmental factor affecting the zooplankton community in spring was suspended particulate matter. In summer, the determining variables were temperature, dissolved inorganic nitrogen (DIN), nitrate, and sediment pH. In autumn, temperature, DIN, and nitrate were determining variables, and dissolved oxygen (DO) and DIN in winter. Zooplankton abundance and biomass were influenced by salinity, suspended particulate matter, chemical oxygen demand (COD), chlorophyll, and water and sediment pH. In general, the shallow sea area north of Liaodong Bay is rich in zooplankton species and exhibits significant seasonal variations. Human activities have disturbed the biological community to a certain extent, and the environmental factors in this area are closely related to the diversity of zooplankton species.

Keywords: zooplankton; Liaodong Bay; dominant species; Bioenv; RDA

check for updates

Citation: Li, J.; Zheng, W.; Cai, Z.; Ma, J.; Li, G.; Ma, B.; Zhao, J.; Li, Z.; Li, S.; Chen, M.; et al. Changes in the Characteristics of Zooplankton Communities in Response to Shifts in the Aquatic Environment in the Shallow Waters of Northern Liaodong Bay, China. *Water* **2024**, *16*, 2711. https://doi.org/10.3390/w16192711

Academic Editor: Marina Marcella Manca

Received: 13 August 2024
Revised: 14 September 2024
Accepted: 20 September 2024
Published: 24 September 2024

1. Introduction

Zooplankton are an essential part of the energy transfer process in marine ecosystems, serving as a crucial link between primary producers and higher trophic organisms, such as pelagic fish [1–3]. Changes in zooplankton communities affect the community structure of other organisms in the ecosystem and may also reflect aquatic environmental changes [4–7]. Understanding the changes in zooplankton communities can shed light on environmental shifts, making the study of zooplankton communities an important component of marine ecological research [8–12].

Liaodong Bay is one of the three major bays in the Bohai Sea of China. It is a semi-enclosed bay with river input from the Liao and Daling rivers and abundant aquatic biological resources. Due to its unique geographical location and economic value, the Liaodong Bay is more sensitive to human activities and climate change, making it more fragile and complex compared to the open sea. In recent years, human activities, such as urban construction and aquaculture, have caused frequent eutrophication and algal blooms in the bay, with higher pollution concentrations in the northern part of the bay [13,14]. This marine environment is complex with various changes in environmental factors such as nutrients and chlorophyll a, which are the main pollution indicators [15,16]. The rapid economic development of coastal cities in the northern region of Liaodong Bay has had a significant impact on the marine environment, resulting in significant changes in zooplankton communities and, thus, the entire marine ecosystem. Therefore, it is necessary to systematically investigate the zooplankton community and water environment in the northern waters of Liaodong Bay.

To date, many scholars have researched plankton communities in various bays. For instance, Ayón Dejo studied plankton community succession and trophic interactions in Kaya'o Bay, Peru [17]. The results indicated that even a few meters of oxygen-rich water can significantly impact brachiopod zooplankton, as changes in the N:P ratio in the rising water may negatively affect their reproductive activities. Moon et al. revealed seasonal variations in plankton communities in Gamak Bay, South Korea [18]. Their findings showed that fluctuations in zooplankton populations (especially brachiopods) corresponded with gradual increases in temperature and COD concentration. Muthurajah et al. investigated the effects of monsoons and spatial factors on plankton in a tropical bay in Malaysia [19], suggesting that monsoon-driven changes in environmental parameters affect zooplankton communities and species composition. They noted that variations in temperature and salinity are critical for shaping zooplankton communities and biomass. Coria-Monter et al. studied the abundance of summer plankton in Rábida Bay, located in the southwestern Gulf of California, Mexico [20]. Their results demonstrated that summer copepods are most abundant in La Paz Bay, with the relative richness of other zooplankton populations varying with temperature, possibly related to changes in phytoplankton. Mahara et al. elucidated how plankton communities form in complex coastal systems [21], revealing that tidal mixed zones show similarities in zooplankton community structure, likely due to advection processes and zooplankton vertical migration behavior. Sadia et al. analyzed plankton abundance in the northern part of the Bay of Bengal [22], finding zooplankton abundance ranging from 18 to 22,500 cells/L and a negative correlation between zooplankton abundance and water depth. Numerous studies have explored zooplankton community characteristics and their relationship with environmental factors in Bohai Bay [23–25], Laizhou Bay [26–28], and Liaodong Bay [29,30]. The dominant species in Bohai Bay has shifted from *Aidanosagitta crassa* (Tokioka, 1938) to *Paracalanus parvus* (Claus, 1863). In Laizhou Bay, temperature is the main environmental factor, with microzooplankton predation pressure being significantly higher than that of medium zooplankton. The diversity and distribution of zooplankton in Liaodong Bay are primarily influenced by environmental factors like transparency, water temperature, COD, and DO. In northern Liaodong Bay, however, the composition of zooplankton communities has undergone changes associated with shifts in the aquatic environment. To gain a deeper understanding of these changes in zooplankton communities in northern Liaodong Bay, this study utilizes survey data collected in 2018. We analyze variations in the zooplankton community and shifts in dominant species within this region. For the first time, we employ Bioenv analysis to explore the impact of combinations of environmental factors on zooplankton communities across different seasons. This research also investigates how water environmental factors in northern Liaodong Bay influence dominant zooplankton species, providing a detailed examination of which specific factors exert positive or negative effects on the zooplankton community or individual species. The findings will serve as a foundational basis for future ecosystem studies and provide scientific guidance for ecological protection and marine spatial management in the shallow waters of northern Liaodong Bay.

2. Materials and Methods

2.1. Study Area and Data Sources

In the northern part of Liaodong Bay, the Liaohe River and several other rivers flow, with an average water depth of approximately 18 m. The tidal regime is characterized by irregular semi-diurnal tides, with an average tidal range of about 0.95 m. Flow velocities typically range from 0.5 m/s to 1.5 m/s [31]. The salinity of Liaodong Bay generally hovers around 30‰; however, due to freshwater input, salinity tends to be higher in winter compared to other seasons. Seasonal variations in water temperature are significant, with it often exceeding 25 °C in summer and dropping to near freezing in winter [32]. Nutrient levels in this area are influenced by surrounding agricultural and industrial activities, leading to relatively high concentrations of nutrient salts such as nitrogen and phosphorus, which can contribute to eutrophication [33].

This study conducted sampling investigations of plankton and water environment factors in the northern waters of Liaodong Bay in April, June, September, and November of 2018. A total of six sampling sites were established (Figure 1). Planktonic animals were collected using a shallow-water Type I plankton net (mesh size: 505 µm, mouth area: 0.20 m^2, net length: 145 cm, filtration volume: approximately 0.25 m^3). The collection was carried out in accordance with the standards outlined in "GBT 12763.6-2007 [34]". The identification of zooplankton referred to the WORMS website and the book *An Illustrated Guide to Marine Planktonic Copepods in China Seas* (Second Edition).

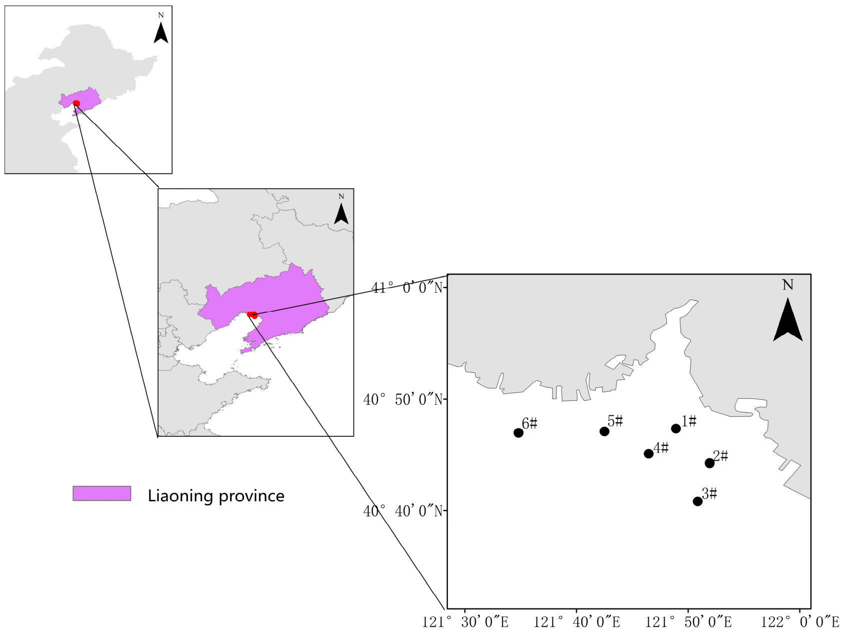

Figure 1. Survey sites in shallow sea in the northern waters of Liaodong Bay.

During the operation, the net was submerged at a speed not exceeding 1 m/s until it reached a depth of 2 to 4 m below the water surface, and then it was retrieved at approximately 0.5 m/s. Once the net emerged from the water, its external surface was rinsed to ensure that all collected samples were retained. The samples were immediately preserved in a 5% formalin solution and subsequently transported to the laboratory for analysis, which included magnification at 100× using an OLYMPUS-CX33 microscope, as well as counting and weighing the specimens.

A portable water quality monitor (YSI-6820) was used to measure water depth, temperature, salinity, pH, dissolved oxygen (DO), and chlorophyll a content. Water samples were collected using a Kemmerer water sampler and placed in clean sampling bottles for the detection of dissolved inorganic nitrogen, nitrite, nitrate, ammonia nitrogen, dissolved inorganic phosphorus (DIP), and chemical oxygen demand (COD) indicators. Sampling and analysis were conducted according to the guidelines of "GBT 12763.4-2007 [35]". In the laboratory, the concentrations of dissolved inorganic nitrogen, nitrite, ammonia nitrogen, and dissolved inorganic phosphorus (DIP) were determined using spectrophotometry; nitrate concentration was measured using the chemical reduction method; and chemical oxygen demand (COD) was assessed through the potassium dichromate method.

Surface sediment samples (approximately 5 cm deep) were collected using a grab dredger, and the sediment samples were sampled and analyzed according to "GBT 17378.5-2007 [36] The Specification for Marine Monitoring Part 5: Sediment Analysis". In the laboratory, the Kjeldahl method was utilized to determine the total nitrogen content in the sediment; the high-temperature combustion method was used to measure organic carbon content; spectrophotometry was employed for the determination of sulfides in the sediment; an oxidation-reduction potential meter was used on site to measure the oxidation-reduction potential of the sediment; and the potentiometric method was applied for field measurement of sediment pH.

2.2. Data Processing

Filtration volume calculation formula:

$$\mathrm{V} = \mathrm{S} \times \mathrm{L}$$

Abundance calculation formula:

$$\mathrm{N} = \frac{\mathrm{n}}{\mathrm{V} \times \mathrm{a}}$$

Biomass calculation formula:

$$\mathrm{B} = \frac{\mathrm{S}}{\mathrm{V}}$$

In the formulas above, V represents the filtration volume, measured in cubic meters (m^3); S denotes the area of the plankton net opening, measured in square meters (m^2); L is the length of the sampling rope, measured in meters (m); N refers to the number of individuals per cubic meter of water, expressed as individuals per cubic meter (individuals$\cdot m^{-3}$); n is the count of individuals obtained from sampling, measured in individuals; a is the ratio of the sampled volume to the total volume of the sample; B signifies the wet biomass, measured in milligrams per cubic meter (mg/m^3); and S represents the wet weight of the sample, measured in milligrams (mg).

All data were stored and processed in Microsoft Excel 2010 and Primer 5.0 was used for biodiversity analysis, cluster analysis, similarity percentage analysis (SIMPER), and one-way analysis of variance (ANOVA). Zooplankton community diversity was analyzed using the Shannon–Wiener diversity index, the Pielou evenness index, the Margalef richness index, and the species dominance index using the following equations:

Shannon–Wiener diversity index (H′) [37]:

$$H' = -\sum_{i=1}^{S} P_i log_2 P_i$$

Pielou's evenness index (J) [38]:

$$J = H'/\log_2 S$$

Margalef's richness index (D) [39]:

$$D = (S-1)/lnN$$

Species dominance index (Y) [40]:

$$Y = (\mathrm{n_i}/\mathrm{N})\mathrm{f_i}$$

In the above equations, S represents the total number of species; P_i represents the ratio of the number of individuals in the *i*-th species to the total number of samples N, i.e., Pi = n_i/N, where n_i represents the number of the *i*-th species; and f_i represents the frequency of occurrence of the *i*-th species. When Y > 0.02, this indicates the dominant species in the community.

Cluster analysis was used to analyze seasonal zooplankton communities where a square root transformation was performed on the seasonal abundance of sampling points. When calculating the Bray–Curtis similarity coefficient matrix, non-metric multidimensional scaling (NMDS) was used for two-dimensional scaling and hierarchical clustering to investigate the structure of the zooplankton communities. The credibility of the NMDS analysis results was evaluated based on the stress coefficient, whereby stress < 0.05 indicates good representativeness, 0.05 $\leq$ stress $\leq$ 0.1 indicates a trustworthy result, 0.1 < stress $\leq$ 0.2 indicates an explanatory significance, and 0.2 < stress indicates unreliability [41].

Differences in the community characteristics of plankton organisms among different seasons and regions were determined using ANOVA. Differences were considered significant at $p < 0.05$ and highly significant when $p < 0.01$.

Similarity percentage analysis (SIMPER) was utilized to assess the average contribution of different species to within-group similarity and between-group differences.

All environmental factors, except for pH, and zooplankton abundance were log (x + 1) transformed. Various analyses (Bioenv analysis, correlation analysis, and detrended correspondence analysis (DCA)) were carried out using R version 4.2.2. Furthermore, in addition, according to the lengths of gradient, the first axis of the DCA was used to determine the following canonical correspondence analysis (CCA) and redundancy analysis (RDA). If the value is greater than 4.0, CCA should be selected for the association analysis of environmental factors and zooplankton; if the value is between 3.0 and 4.0, both RDA and CCA are used; if the value is less than 3.0, use RDA. The DCA revealed that the values of the lengths of gradient were less than 3 (the length of the gradient was 2.4638). Therefore, this study employed RDA to investigate the relationship between the zooplankton community and environmental factors.

Using R version 4.4.1, we conducted non-metric multidimensional scaling (NMDS), Bioenv analysis, detrended correspondence analysis (DCA), and redundancy analysis (RDA), and generated correlation heatmaps.

3. Results

3.1. Species Composition

A total of 8 classes zooplankton, comprising 45 species, were found in the survey, including 18 Copepoda, 2 Amphipoda, 1 Mysidacea, 1 Decapoda, 1 Chaetognatha, 7 Hydrozoa, 1 Tunicate, and 14 pelagic larvae (Table 1).

Table 1. List of shallow sea zooplankton in northern Liaodong Bay.

Arthropoda		
Copepoda		
	Paracalanus parvus (Claus, 1863)	*Centropages tenuiremis* Thompson I.C. & Scott A., 1903
	Acartia pacifica Steuer, 1915	*Corycaeus (Ditrichocorycaeus) affinis* McMurrich, 1916
	Centropages dorsispinatus Thompson I.C. & Scott A., 1903	*Centropages abdominalis* Sato, 1913
	Tortanus spinicaudatus Shen & Bai, 1956	*Microsetella norvegica* (Boeck, 1865)
	Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881)	*Acartia hongi* Soh & Suh, 2000
	Candacia sp.	*Paracalanus crassirostris* (Dahl F., 1894)
	Acartia (Acartiura) clausi Giesbrecht, 1889	*Tortanus (Eutortanus) derjugini* Smirnov, 1935
	Pontellopsis tenuicauda (Giesbrecht, 1889)	*Labidocera euchaeta* Giesbrecht, 1889
	Calanus sinicus Brodsky, 1965	*Oithona similis* Claus, 1866
Amphipoda		
	Themisto compressa Goës, 1866	
	Gammarus sp.	

Table 1. *Cont.*

Mysidacea		
	Acanthomysis longirostris li, 1936	
Decapoda		
	Acetes chinensis Hansen, 1919	
Chaetognatha		
	Aidanosagitta crassa (Tokioka, 1938)	
Cnidaria		
Hydrozoa		
	Rathkea octopunctata (M. Sars, 1835)	*Turritopsis nutricula* McCrady, 1857
	Bougainvillia britannica (Forbes, 1841)	*Bougainvillia muscus* (Allman, 1863)
	Eirene ceylonensis Browne, 1905	*Eirene kambara* Agassiz & Mayer, 1899
	Podocoryne minina (Trinci, 1903)	
Chordata		
Tunicate		
	Oikopleura (Vexillaria) dioica Fol, 1872	
Pelagic larva		
	Macrura larvae	Zoea larva (Brachyura)
	Ophiopluteus larva	Polychaete larva
	Ophiuroidea larva	Gastropoda larva
	Nauplius larva (Copepoda)	Brachyura megalopa
	Echinodermata larva	Lingula larva
	Lamellibranchia larva	Fish larva
	Alima larva	Fish egg

Species richness varied between seasons, with 22 species identified in spring, 19 in summer, 28 in autumn, and 17 in winter. Copepoda and pelagic larvae were dominant across seasons, with Hydrozoa also dominating in autumn (Figure 2).

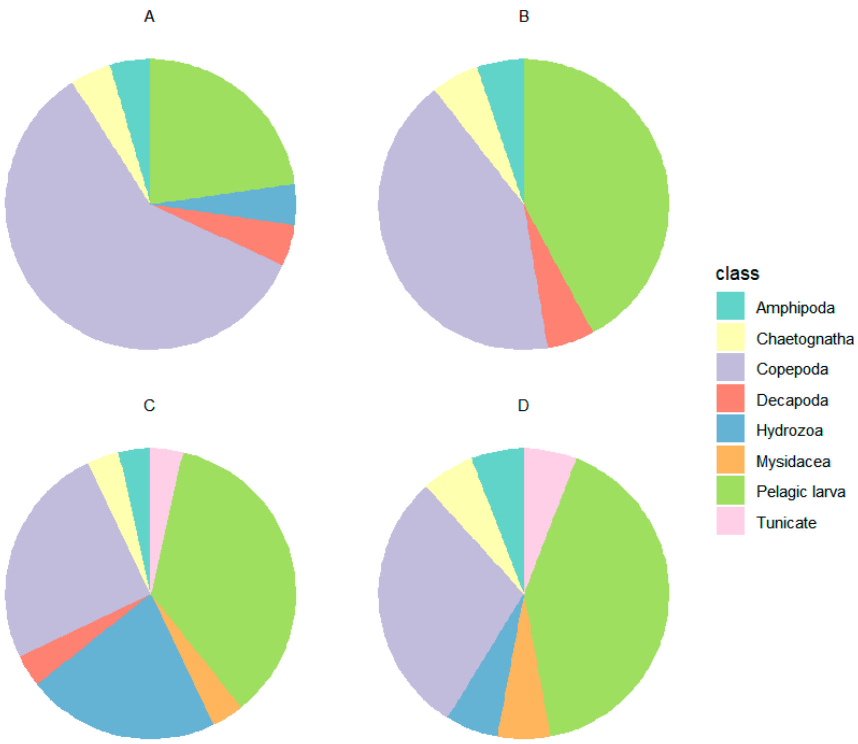

Figure 2. Seasonal composition of zooplankton in the shallow waters of northern Liaodong Bay. Note: (**A**) represents spring, (**B**) represents summer, (**C**) represents autumn, and (**D**) represents winter.

3.2. Seasonal Variation Characteristics of Environmental Factors

The seasonal average temperature in the study area is 16.8 °C, with a water body pH of 7.99, indicating slightly alkaline conditions. The concentration of suspended solids is higher in summer and autumn compared to spring and winter. Dissolved oxygen content in spring surpasses that of other seasons, and levels of dissolved inorganic nitrogen, ammonia nitrogen, nitrate, nitrite, and dissolved inorganic phosphorus are also elevated in spring. Chlorophyll a content peaks in autumn. Regarding sediments, total nitrogen content is elevated in spring and summer but lower in autumn. Organic carbon content is highest in winter and lowest in summer. Sulfide content in sediments is greatest in spring and lowest in autumn. Sediments exhibit the highest oxidation-reduction potential in winter and the lowest in autumn. ANOVA indicates that, except for sediment pH, all environmental factors significantly influence seasonal variations (Table 2).

Table 2. Data on water environmental factors in the northern waters of Liaodong Bay.

Environmental Factors	Spring		Summer		Autumn		Winter		Annual Summary	
	Variation Range	Average Value	Variation Range	Average Value	Variation Range	Average Value	Variation Range	Average Value	Variation Range	Average Value
Temperature/°C	11.5–11.7	11.6	22.7–22.8	22.73	24.2–24.3	24.25	8.6–8.9	8.8	8.6–24.3	16.8
Salinity/S	29.8–30.5	30.1	29.1–30.2	29.7	28.6–30.1	29.15	29.6–30.4	29.93	28.6–30.5	29.72
Suspended particulate organic matter/mg·L^{-1}	3.42–4.21	3.82	4.52–5.11	4.93	4.96–5.81	5.46	1.96–2.41	2.2	1.96–5.81	4.1
Total suspended particulate matter/mg·L^{-1}	9.52–16.25	12.43	24.32–32.14	29.21	29.38–39.81	34.11	5.63–6.74	6.315	5.63–39.81	20.52
Water pH	7.88–8.01	7.96	7.98–8.06	8.01	8.0–8.1	8.04	7.89–8.01	7.97	7.88–8.1	7.99
Dissolved oxygen mg·L^{-1}	5.7–6.7	6.4	3.9–4.7	4.4	2.7–3.6	3.3	5.1–7.2	6.3	2.7–7.2	5.07
Dissolved inorganic nitrogen/μg·L^{-1}	986.54–1481.22	1280.32	418.38–629.81	484.42	35.61–302.11	216.36	237.66–458.51	341.04	35.61–1481.22	580.5
Nitrite/μg·L^{-1}	116.52–147.38	133.74	32.84–62.31	46.55	19.86–35.14	27.3	24.22–45.32	32.42	19.86–147.38	60
Nitrate/μg·L^{-1}	812.35–1246.37	1069.06	345.23–501.23	390.16	185.64–281.43	227.73	204.89–395.46	306.14	185.64–1246.37	498.27
Ammonia/μg·L^{-1}	54.12–84.32	72.96	29.68–64.12	43.34	9.24–26.91	18.9	4.69–14.69	8.07	4.69–84.32	35.82
Dissolved inorganic phosphorus/μg·L^{-1}	38.47–54.33	48.91	27.81–37.42	32.98	28.12–38.12	33.98	32.12–42.16	37.07	27.81–54.33	38.23
Chemical oxygen demand/mg·L^{-1}	0.48–0.89	0.65	0.78–1.28	1.08	0.97–1.41	1.23	0.89–1.19	1.06	0.48–1.41	1.01
Chlorophyll a/μg·L^{-1}	2.13–3.56	2.98	3.89–5.02	4.56	4.96–6.32	5.68	1.56–2.49	2.17	1.56–6.32	3.85
Sediment total nitrogen/%	0.04–0.11	0.08	0.06–0.09	0.08	0.02–0.05	0.04	0.04–0.08	0.07	0.02–0.11	0.06
Sediment organic carbon/%	0.36–0.48	0.42	0.32–0.46	0.4	0.36–0.54	0.47	0.45–0.62	0.53	0.32–0.62	0.46
Sediment sulfide/mg·kg^{-1}	29.78–37.21	34.72	9.86–15.31	12.76	6.54–14.97	11.09	21.36–35.42	27.62	6.54–37.21	21.55
Sediment redox potential/mV	26.7–36.2	31.17	24.86–39.45	32.39	19.36–40.21	29.18	38.21–67.22	53.16	19.36–67.22	36.48
Sediment pH	7.4–7.8	7.6	7.5–8.0	7.7	7.4–7.9	7.7	7.4–7.8	7.6	7.4–8.0	7.63

3.3. Composition of Dominant Species

There was a clear seasonal shift in species dominance in the bay. Overall, there were 16 dominant species, including 11 Copepoda, 4 pelagic larva, and 1 Chaetognatha, with the number of dominant species slightly changing across seasons (8 in spring, 9 in summer, 5 in autumn, and 7 in winter). *Paracalanus parvus* Claus, 1863, *Calanus sinicus* Claus, 1863, and *Aidanosagitta crassa* (Tokioka, 1938) were common, among which *A. crassa* was present in all seasons (Table 3).

Table 3. Dominance index (Y) of seasonal dominant species of zooplankton in northern Liaodong Bay.

Species Name	Species Code	Spring	Summer	Autumn	Winter
Paracalanus parvus (Claus, 1863)	SP1	0.161	0.032		0.021
Acartia pacifica Steuer, 1915	SP2	0.226			0.028
Centropages dorsispinatus Thompson I.C. & Scott A., 1903	SP3	0.028			
Tortanus spinicaudatus Shen & Bai, 1956	SP4	0.029			
Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881)	SP5	0.068			
Calanus sinicus Brodsky, 1965	SP6	0.138		0.088	0.304
Acartia hongi Soh & Suh, 2000	SP7		0.076		
Paracalanus crassirostris (Dahl F., 1894)	SP8		0.025		
Macrura larvae	SP9		0.135	0.036	0.038
Tortanus (Eutortanus) derjugini Smirnov, 1935	SP10		0.07		
Labidocera euchaeta Giesbrecht, 1889	SP11		0.021		
Lamellibranchia larvae	SP12		0.037		
Brachyura zoea	SP13	0.045	0.042		
Oithona similis Claus, 1866	SP14			0.025	0.036
Polychaeta larvae	SP15			0.205	0.04
Aidanosagitta crassa (Tokioka, 1938)	SP16	0.06	0.188	0.481	0.391

3.4. Diversity and Structural Analysis of Zooplankton Communities

The Shannon–Weiner diversity index (H′) was highest over summer (2.54 ± 0.42) and spring (2.50 ± 0.24), indicating higher species diversity during these seasons. During summer, this index varied the most across sampling stations. Similarly, the Pielou evenness index (J) was highest over summer (0.72 ± 0.12) and spring (0.73 ± 0.10), indicating a higher relative abundance in these seasons compared to winter and autumn. During autumn, species evenness varied the most across sampling stations. The Margalef richness index (D) was highest in autumn, indicating greater species richness compared to the other seasons. Species richness varied the most across sampling stations in winter (Table 4).

Table 4. Seasonal diversity indices of zooplankton communities.

Site	H′	J	D	Site	H′	J	D
A1	2.34	0.63	1.59	C1	1.38	0.34	1.82
A2	2.53	0.73	1.49	C2	2.06	1.43	1.90
A3	2.28	0.64	1.76	C3	1.81	0.46	2.10
A4	2.23	0.67	1.75	C4	2.32	0.59	2.30
A5	2.75	0.87	1.53	C5	2.07	0.56	2.04
A6	2.86	0.86	2.04	C6	2.25	0.61	2.12
mean ± SD	2.50 ± 0.24	0.73 ± 0.10	1.69 ± 0.19	mean ± SD	1.98 ± 0.31	0.67 ± 0.35	2.05 ± 0.15
B1	2.58	0.70	1.47	D1	2.58	0.70	2.03
B2	3.07	0.78	1.94	D2	1.73	0.54	1.37
B3	1.77	0.48	1.69	D3	2.04	0.64	1.32
B4	2.94	0.79	1.77	D4	2.22	0.64	1.94
B5	2.40	0.76	1.21	D5	2.68	0.84	1.79
B6	2.52	0.84	1.20	D6	1.59	0.53	1.37
mean ± SD	2.54 ± 0.42	0.72 ± 0.12	1.55 ± 0.28	mean ± SD	2.14 ± 0.40	0.65 ± 0.11	1.64 ± 0.29

Notes: A represents spring, B represents summer, C represents autumn, D represents winter, and each number represents a sampling station.

3.5. Community Similarity

A clustering analysis indicated significant seasonal differences in zooplankton communities (ANOSIM: R = 0.65, p = 0.001), with similarity values of zooplankton communities being highest in spring (Figure 3). The data can be divided into six distinct groups based on a 50% similarity threshold: Group I (containing only site A1); Group II (containing five sampling sites, A2 to A6, all from spring); Group III (containing sites B2 to B6, all from summer); Group IV (containing sites C2 to C6 and site D5, predominantly autumn sites); Group V (containing sites D1, D2, D3, D4, D6, and site C1, predominantly winter sites); Group VI (B1).

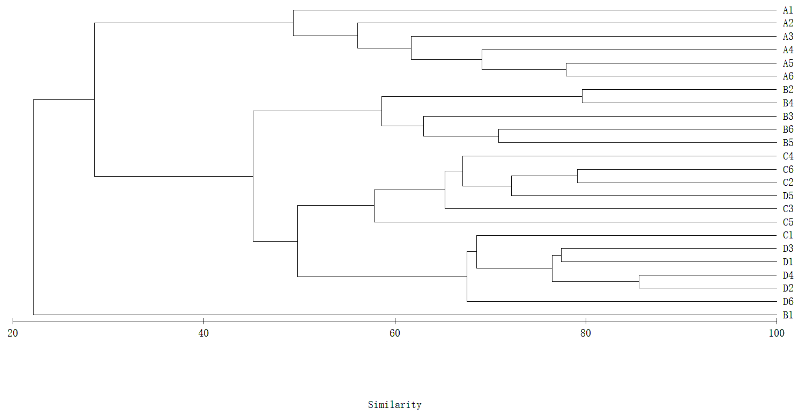

Figure 3. Cluster analysis of zooplankton communities in northern Liaodong Bay.

Further analysis of community composition using SIMPER based on the four seasonal groups (Group II, Group III, Group IV, and Group V) revealed that Group II has an average similarity of 62.58%, with seven species contributing to a cumulative similarity contribution rate exceeding 90%, listed as Calanus sinicus Brodsky, 1965, Aidanosagitta crassa (Tokioka, 1938), Paracalanus parvus (Claus, 1863), Acartia pacifica Steuer, 1915, Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881), Centropages dorsispinatus Thompson I.C. & Scott A., 1903, and Tortanus spinicaudatus Shen & Bai, 1956. Group III exhibits an average similarity of 62.81%, with nine species contributing to a cumulative similarity contribution rate exceeding 90%, namely, Aidanosagitta crassa (Tokioka, 1938), Tortanus (Eutortanus) derjugini Smirnov, 1935, Zoea larva (Brachyura), Macrura larvae, Labidocera euchaeta Giesbrecht, 1889, Calanus sinicus Brodsky, 1965, Gastropoda larva, Lamellibranchia larva, and Polychaete larva. Group IV shows an average similarity of 65.00%, with eight species contributing to a cumulative similarity contribution rate exceeding 90%, which are Polychaete larva, Aidanosagitta crassa (Tokioka, 1938), Macrura larvae, Oithona similis Claus, 1866, Zoea larva (Brachyura), Acartia pacifica Steuer, 1915, Paracalanus parvus (Claus, 1863), and Echinodermata larva. Finally, Group V demonstrates an average similarity of 72.06%, with seven species contributing to a cumulative similarity contribution rate exceeding 90%, specifically, Aidanosagitta crassa (Tokioka, 1938), Calanus sinicus Brodsky, 1965, Oithona similis Claus, 1866, Macrura larvae, Polychaete larva, Labidocera euchaeta Giesbrecht, 1889, and Acartia pacifica Steuer, 1915.

The NMDS had a stress value of 0.125, indicating that there is certain explanatory significance. Consistent with the clustering analysis, spring is separated from the other three seasons, with summer, autumn, and winter intersecting with a degree of similarity (Figure 4).

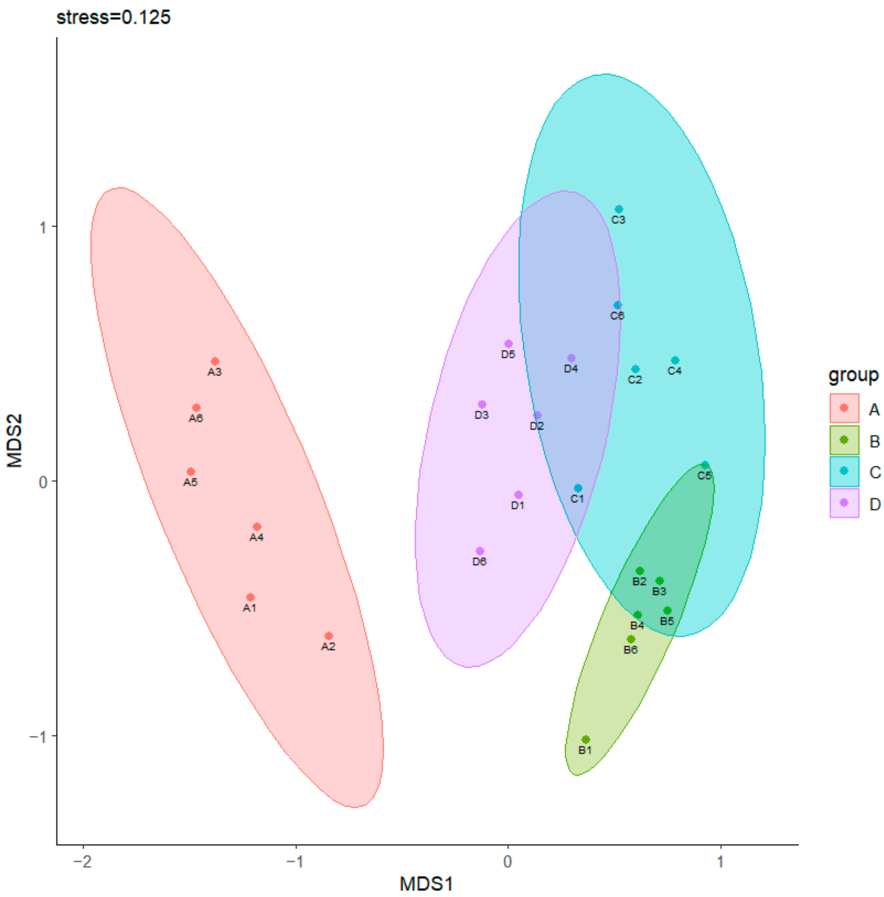

Figure 4. NMDS test results of zooplankton communities in northern Liaodong Bay.

3.6. The Relationship between Dominant Species Abundance and Environmental Factors

A Bioenv analysis indicated that suspended particulate matter content had the greatest impact on the zooplankton community in spring (correlation coefficient = 0.5571). In summer, water temperature, DIN, nitrate content, and sediment pH influenced the zooplankton community (correlation coefficient = 0.7). Similarly, temperature, DIN, and nitrate content greatly influenced the zooplankton community in autumn (correlation coefficient = 0.675). A combination of many environmental factors influenced the zooplankton community in winter, including DO, DIN, sediment organic carbon content, sediment sulfide content, sediment redox potential, and sediment pH (correlation coefficient = 0.2929).

The dominant species of zooplankton can be divided into six groups (Figure 5). The first group comprises *Oithona similis* Claus, 1866 and Polychaete larva, and the abundance is negatively correlated with nitrate, DIN, and nitrite. The second group comprises Macrora larvae and Zoea larva (Brachyura), and the abundance is positively correlated with water pH, chlorophyll a, and suspended particulate organic matter, and negatively correlated with salinity, DO, and sediment sulfides. The third group includes *Tortanus (Eutortanus) derjugini* Smirnov, 1935, *Labidocera euchaeta* Giesbrecht, 1889, and *Aidanosagitta crassa* (Tokioka, 1938) and the abundance is negatively correlated with DIP and sediment sulfides. The fourth group comprises *Paracalanus parvus* (Claus, 1863), *Paracalanus crassirostris* (Dahl F., 1894), *Acartia hongi* Soh & Suh, 2000, and Lamellibranchia larva, and the abundance is positively correlated with sediment and water pH, ammonia nitrogen, and nitrite, and negatively correlated with water depth and salinity, respectively. The fifth group includes Centropages dorsispinatus Thompson I.C. & Scott A., 1903, Tortanus spinicaudatus Shen & Bai, 1956, and Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881). The abundance is negatively correlated with the COD, and positively correlated with DIP, total sediment nitrogen, ammonia nitrogen, nitrite, DIN, and water nitrate. The sixth group includes *Acartia pacifica* Steuer, 1915 and *Calanus sinicus* Brodsky, 1965, and the abundance is positively correlated with DO, DIP, and sediment sulfides, and negatively correlated with water temperature, suspended organic matter, and COD.

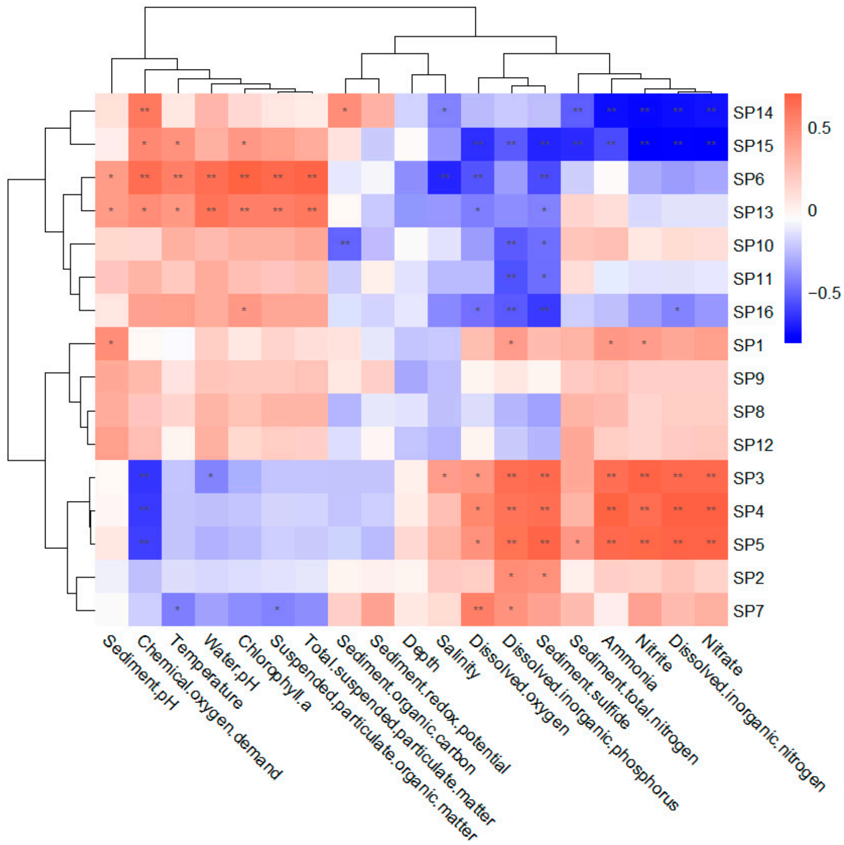

Figure 5. Heat map of the correlation between dominant species of zooplankton and environmental factors. Note: "*": Indicates a significant correlation at the 5% significance level ($p \leq 0.05$). "**": Indicates a significant correlation at the 1% significance level ($p \leq 0.01$).

The RDA indicated that various environmental factors and seasons explain 59.96% of the zooplankton community variation (Figure 6). The zooplankton communities in spring are clustered apart from the other three seasons, while these somewhat overlap over summer, autumn, and winter. The environmental factors that correlate with the first principal axis are COD, water temperature, suspended particulate matter content, chlorophyll a, and water pH. Those that correlate with the second principal axis are ammonia nitrogen, total sediment nitrogen, nitrate, nitrite, DIN, and sediment pH. For the dominant species *Acartia (Acanthacartia) bifilosa* (Giesbrecht, 1881), *Tortanus spinicaudatus* Shen & Bai, 1956, and *Centropages dorsispinatus* Thompson I.C. & Scott A., 1903, sulfide, DIP, nitrate, nitrite, DIN, DO, and sediment ammonia nitrogen have the greatest influence on abundance, showing a positive correlation (Figure 7). Species such as *Labidocera euchaeta* Giesbrecht, 1889, *Tortanus (Eutortanus) derjugini* Smirnov, 1935, Macrura larvae, and Zoea larva (Brachyura) are influenced by water temperature, suspended particulate matter, chlorophyll a, water pH, and suspended particulate organic matter, showing a positive correlation. Sediment pH is the primary factor influencing the abundance of *Paracalanus crassirostris* (Dahl F., 1894) and *Acartia hongi* Soh & Suh, 2000. For *Oithona similis* Claus, 1866, COD and sediment organic carbon are positively correlated with abundance, and total sediment nitrogen, water ammonia nitrogen, DIN, nitrate, and nitrite are negatively correlated with abundance. Chlorophyll a, COD, and water temperature have a relatively strong positive correlation with the abundance of *Aidanosagitta crassa* (Tokioka, 1938), while DO, DIP, DIN, and sediment sulfides have a negative correlation with the abundance. Most of the environmental variables show a positive correlation with *Paracalanus parvus* (Claus, 1863) abundance, with water depth, salinity, and the sediment redox potential having a negative correlation with the abundance. Overall, the RDA results are consistent with the correlation heatmap analysis results.

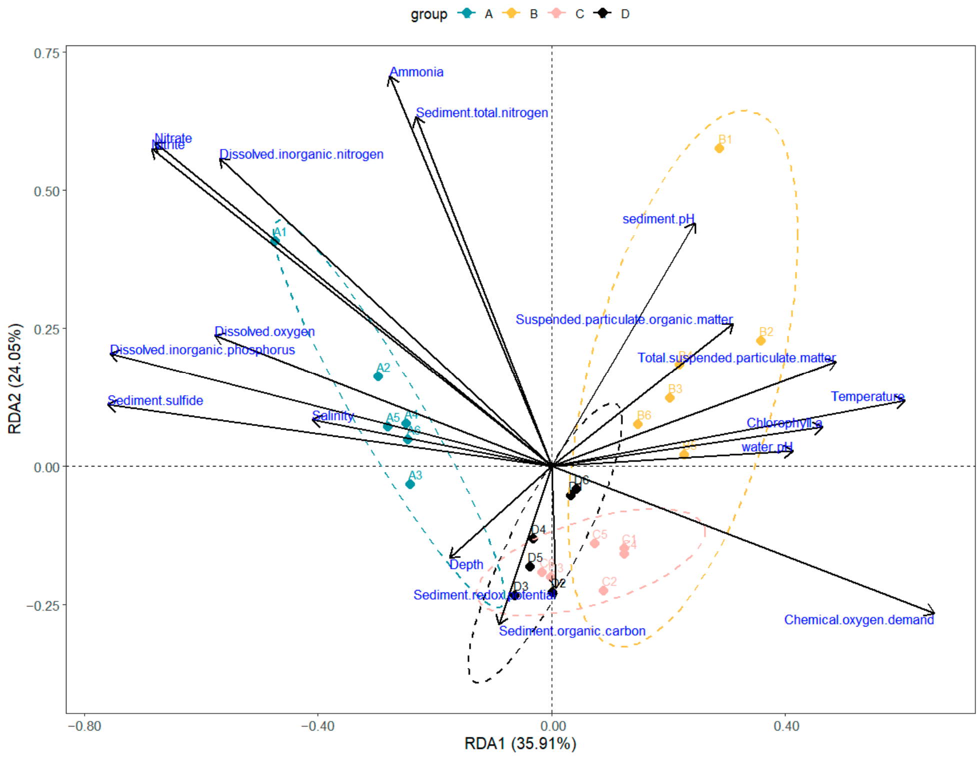

Figure 6. RDA of zooplankton communities and water environmental factors.

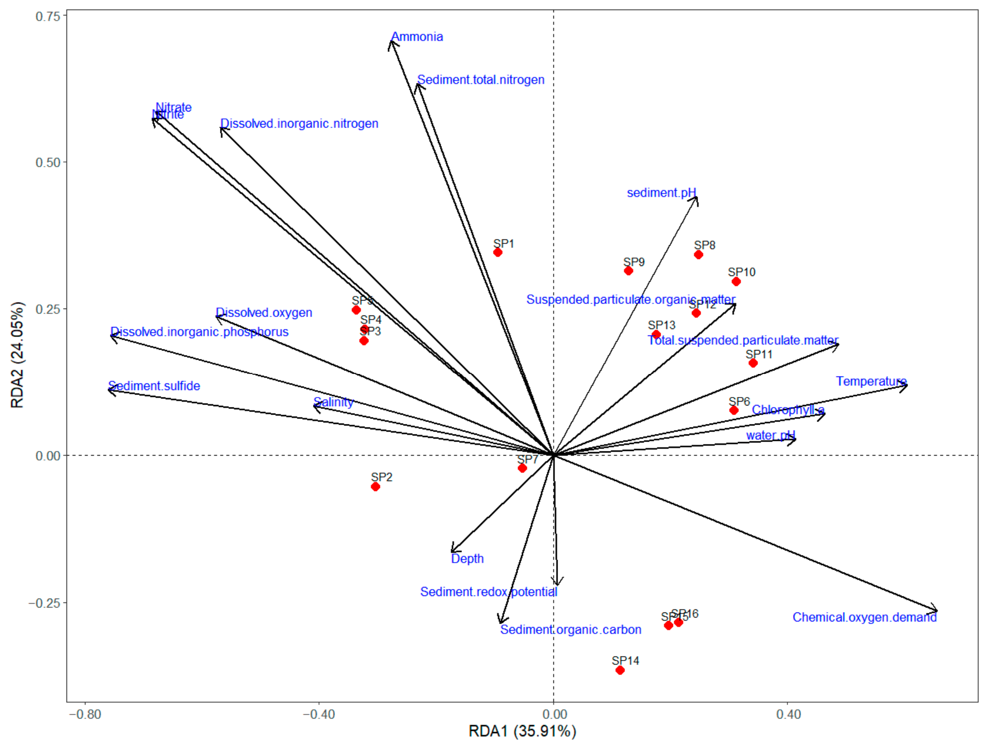

Figure 7. RDA of dominant zooplankton species and water environmental factors.

A correlation analysis showed that the abundance of zooplankton was positively correlated with suspended organic matter, suspended particulate matter, water and sediment pH, and chlorophyll a ($p < 0.01$), and negatively correlated with salinity and water depth ($p < 0.05$). The biomass of zooplankton was positively correlated with suspended particulate matter, water pH, COD, and sediment pH ($p < 0.05$), and negatively correlated with salinity ($p < 0.01$). The Shannon–Wiener diversity index (H′) was positively correlated with DIN, nitrate, and water ammonia nitrogen ($p < 0.05$). The Pielou evenness index (J) did not show a significant correlation with environmental factors, with the highest positive correlation with DIN and the highest negative correlation with sediment organic carbon. The Margalef richness index (D) was negatively correlated with DO, DIN, nitrite, and total sediment nitrogen ($p < 0.05$) (Table 5).

Table 5. Correlation analysis between zooplankton communities and environmental factors.

	Abundance	Biomass	H'	J	D
Depth	−0.490 *	−0.274	−0.084	−0.008	−0.164
Temperature	0.373	0.251	−0.114	−0.14	0.375
Salinity	−0.647 **	−0.569 **	0.343	0.39	−0.226
Suspended particulate organic matter	0.620 **	0.403	−0.137	−0.222	0.333
Total suspended particulate matter	0.644 **	0.428 *	−0.161	−0.198	0.224
Water pH	0.650 **	0.483 *	−0.277	−0.374	0.235
Dissolved oxygen (DO)	−0.24	−0.242	0.162	0.136	−0.410 *
Dissolved inorganic nitrogen (DIN)	0.05	−0.086	0.471 *	0.374	−0.410 *
Nitrite	0.133	−0.025	0.379	0.257	−0.428 *
Nitrate	0.099	−0.015	0.444 *	0.317	−0.395
Ammonia	0.317	0.074	0.474 *	0.262	−0.129
Dissolved inorganic phosphorus (DIP)	−0.03	−0.285	0.084	0.13	−0.115
Chemical oxygen demand (COD)	0.404 *	0.440 *	−0.397	−0.336	0.221
Chlorophyll a	0.629 **	0.441 *	−0.17	−0.231	0.3
Sediment total nitrogen	0.201	0.184	0.395	0.242	−0.512 *
Sediment organic carbon	−0.122	−0.013	−0.4	−0.391	0.028
Sediment sulfide	−0.287	−0.365	0.213	0.332	−0.326
Sediment redox potential	−0.217	−0.124	−0.297	0.037	−0.377
Sediment pH	0.608 **	0.412 *	0.039	−0.077	0.036

Note: * indicates significant correlation $p < 0.05$, ** indicates significant correlation $p < 0.01$.

4. Discussion

A total of 45 species of zooplankton were identified in this study, of which many were Copepoda and pelagic larvae. This is consistent with the findings of Bian et al. [29] and Wang et al. [42] and correlates to the seasonal distribution characteristics of zooplankton species in estuarine areas. Zooplankton species richness was greatest in autumn, with the dominant species comprising Copepoda across seasons, which may be related to their strong adaptability to temperature and salinity [43–46].

This study’s correlation analysis indicates a significant relationship between seasonal environmental factors and biological communities, suggesting that seasonal variations are crucial drivers of environmental changes. This finding is consistent with the research conducted by Ojok et al. [47]. In spring, the concentrations of dissolved inorganic nitrogen, ammonia nitrogen, nitrate, nitrite, and dissolved inorganic phosphorus in the study area are higher than in other seasons. This may be due to rising temperatures in spring and ice melting in estuarine rivers, which releases nitrogen and phosphorus. Additionally, spring marks the beginning of farming activities, where farmers apply fertilizers, leading to an increase in nitrogen and phosphorus levels in the rivers and further elevating the concentrations of these elements in the study area. In autumn, the concentration of chlorophyll a in the water body is the highest, indicating a potential situation of eutrophication. This phenomenon may result from increased human activities, such as the end of the fishing ban in autumn, leading to more fishing and boat traffic in estuarine areas.

In this study, there was a significant seasonal alternation of dominant species. For example, *Centropages dorsispinatus* Thompson I.C. & Scott A., 1903 and *Tortanus spinicaudatus* Shen & Bai, 1956 only dominated in spring, *Acartia hongi* Soh & Suh, 2000 and *Paracalanus crassirostris* (Dahl F., 1894) in summer, and *Oithona similis* Claus, 1866 and Polychaete larva in autumn and winter. There were more dominant species in summer compared to eight in spring, five in autumn, and seven in winter. This may be due to the temperature and, thus, a greater abundance of phytoplankton for the zooplankton to feed on. *Aidanosagitta crassa* (Tokioka, 1938) was dominant across the four seasons, with the highest dominance index in all seasons except spring, making it the absolute dominant species in northern Liaodong Bay. This is consistent with studies on S. crassa in other areas [48,49].

The diversity index represents the degree of disturbance to biological communities [50]. In this study, the diversity index of zooplankton communities was consistently below 3 across all seasons, indicating a notable level of disturbance which peaked in summer. This suggests that the communities experienced relatively less disturbance in summer compared to other seasons. This phenomenon can be attributed to government policies, such as the implementation of summer fishing bans in the Liaodong Bay area. These fishing bans restrict the activities of fishing vessels, thereby reducing the potential impacts associated with human fishing practices, such as habitat alteration from trawling, sewage discharge, and nutrient enrichment caused by deceased organisms during capture. Consequently, these measures alleviate anthropogenic effects on plankton communities. The lowest diversity index of zooplankton community in autumn indicates the highest level of disturbance, which may be attributed to the peak season of fishing activities in autumn, when human fishing activities are more frequent. The evenness index is used to indicate species distribution and community stability [51]. In this study, the evenness index was greater than 0.5 across seasons, indicating an even distribution of zooplankton in northern Liaodong Bay. The richness index represents the richness of species in a community [52]. The results of this study indicate that species are more abundant in summer and less abundant in autumn, which is consistent with the findings of Bian et al. [29]. Our results also indicated a significant difference in species abundance in spring compared to the other seasons, which may be due to lower temperatures and less frequent zooplankton reproduction in spring. Based on the results of cluster analysis, the differences in the plankton communities across the four seasons are significant, indicating that seasons have a considerable impact on the composition of plankton communities. The grouping results demonstrate that the dominant species contributing to each seasonal group are mostly the dominant species of that particular season, suggesting that the changes in dominant species have a substantial effect on the variations in plankton community structure. In the clustering results, spring site 1 and summer site 1 are each classified into their own group, showing low similarity with other groups. Through the analysis of the data from these two sites, it was found that the abundances of species Acartia pacifica Steuer, 1915 and Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881) at spring site 1 are significantly higher than those at other sites in different seasons. Conversely, Acartia hongi Soh & Suh, 2000 and Paracalanus crassirostris (Dahl F., 1894) show relatively high abundances at summer site 1, which is situated closer to the river mouth. This difference may be attributed to the varying reproductive strategies and life cycles among different copepod species. For instance, species Acartia hongi Soh & Suh, 2000 and Paracalanus crassirostris (Dahl F., 1894) may be more active during the summer, while species Acartia pacifica Steuer, 1915 and Acartia (Acanthacartia) bifilosa (Giesbrecht, 1881) may thrive more in the spring. This pattern reflects the different adaptive strategies of copepods to environmental changes, aligning with the findings of Giraldo et al. [53]. Moreover, competitive and predatory interactions among species may also affect their abundances [54].

The aquatic physicochemical environment is important for the growth and reproduction of zooplankton, as well as for the structure of zooplankton communities. Studies have shown that temperature, salinity, nitrite, and COD influence the density, population structure, and dominant species composition of zooplankton communities [55–57]. Our

Bioenv analysis results showed a high correlation between water temperature, DIN, and nitrate, and zooplankton abundance. This is due to the gradual increase in temperature over summer and autumn making the water temperature suitable as the abundance of phytoplankton increases, which affects the abundance of zooplankton. During spring and winter, the environmental factors were less correlated to zooplankton abundance compared to during summer and autumn, which may be due to the influence that lower temperatures have on zooplankton communities. Overall, salinity, suspended particulate matter, water and sediment pH, COD, and chlorophyll a had the greatest effect on zooplankton biomass. Particularly, salinity is negatively correlated with zooplankton abundance and biomass, which is consistent with other studies carried out in the Arabian Gulf [58], East China Sea [59], South Yellow Sea [60], and Bohai Sea [29]. However, this is slightly different from some scholars' research on zooplankton in the Yangtze Estuary (the abundance in autumn is highly positively correlated with salinity) [61], which may be due to the influence of spatial differences, which makes the zooplankton community specific. In summary, salinity affects the abundance of various zooplankton classes. Moreover, various factors may also influence the abundance and biomass of zooplankton. Research by Harvey et al. indicates that hydrodynamic factors can affect the distribution and migratory behaviors of zooplankton through water flow dynamics [62]. These hydrodynamic factors facilitate thorough mixing of nutrients in the water, thereby enhancing phytoplankton productivity, which subsequently impacts the abundance and biomass of zooplankton. The presence of predators can also affect the population dynamics of zooplankton; when predation pressure is high, zooplankton numbers may decrease [63]. In summary, the abundance and biomass of zooplankton are influenced by the interactive effects of multiple environmental and biological factors.

According to the correlation heatmap of dominant species and RDA results, temperature had a positive correlation with the abundance of most zooplankton species as well as zooplankton larvae such as Polychaetes, Macrurae, and Zoeae (Brachyura), with the greatest effect on Macrura larva. Therefore, temperature may be a key factor in promoting the growth and development of zooplankton larvae. Nutrients not only directly provide energy for zooplankton life cycles, but they also affect the population structure of phytoplankton, thereby indirectly affecting the community structure of zooplankton [64,65]. We found that DIP, DIN, ammonia nitrogen, nitrite, and sediment sulfides were significantly correlated with multiple dominant species, such as Centropages dorsispinatus, Tortanus spinicaudatus, and Acartia bifilosa. These factors are important sources of nutrients for phytoplankton, which may result in changes in the distribution of zooplankton that feed on phytoplankton. Dissolved oxygen is a key factor for the growth and development of many pelagic organisms in waters [66]; the changes in DO can directly affect zooplankton [67,68] and an increase in DO can have a negative impact [69]. However, future investigations should be based on the range of DO and how this affects certain zooplankton species. Our results show a positive correlation between DO and the abundance of *Centropages dorsispinatus* Thompson I.C. & Scott A., 1903, *Tortanus spinicaudatus* Shen & Bai, 1956, *Acartia (Acanthacartia) bifilosa* (Giesbrecht, 1881), *Acartia pacifica* Steuer, 1915, and *Calanus sinicus* Brodsky, 1965. Most of these species only dominated in spring when the DO content was highest, indicating that, within this range of DO (5.7–6.7 mg/L), these zooplankton species thrive.

5. Conclusions

This study posits that the northern shallow waters of Liaodong Bay exhibit a rich diversity of zooplankton species characterized by significant seasonal variations in environmental factors and pronounced shifts in biological communities. Our findings indicate that *Aidanosagitta crassa* (Tokioka, 1938) is the most dominant species throughout the year. The zooplankton community appears to be disturbed to some extent due to human activities, with the degree of disturbance being lowest in summer and highest in autumn. Furthermore, temperature, nutrients, DO, and pH are closely related to zooplankton abundance and biomass. In summary, changes in the species composition and abundance of zooplankton are critical to the dynamics of zooplankton communities. Furthermore, zooplankton exhibit high sensitivity to shifts in environmental factors such as water quality, making them potential ecological monitoring indicators for assessing the ecological health of the marine environment.

Liaodong Bay is one of the important bays in China with abundant fishery resources and many port projects and artificial breeding areas. Therefore, future research on zooplankton in this region should not only consider seasonal variation and the impacts of changes in the aquatic environment but also the effects of human activities. Studying the changes in planktonic organisms in the Liaodong Bay from multiple perspectives can provide more comprehensive scientific research support for the management planning of Liaodong Bay, ensuring the health of the ecosystem.

Author Contributions: Methodology, J.L.; Investigation, J.L., Z.C., M.C. and C.G.; Data curation, J.L.; Writing—original draft, J.L. and S.L.; Writing—review & editing, J.L., W.Z, J.M., B.M., J.Z. and Z.L.; Visualization, J.L.; Funding acquisition, W.Z., G.L. and B.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the research fund support of the Central Public-interest Scientific Institution Basal Research Fund, CAFS (NO.2016HY-JC0106).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. Due to privacy concerns, these data are not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Davies, C.H.; Armstrong, A.J.; Baird, M. Over 75 years of zooplankton data from Australia: Ecological Archives E095-278. *Ecology* **2014**, *95*, 3229. [CrossRef]
2. Lin, C.; Su, J.; Xu, B. Long-term variations of temperature and salinity of the Bohai Sea and their influence on its ecosystem. *Prog. Oceanogr.* **2001**, *49*, 7–19. [CrossRef]
3. Wei, Y.; Ding, D.; Gu, T.; Jiang, T.; Qu, K.; Sun, J.; Cui, Z. Different responses of phytoplankton and zooplankton communities to current changing coastal environments. *Environ. Res.* **2022**, *215*, 114426. [CrossRef] [PubMed]
4. Zhou, J.; Qin, B.; Zhu, G.; Zhang, Y.; Gao, G. Long-term variation of zooplankton communities in a large, heterogenous lake: Implications for future environmental change scenarios. *Environ. Res.* **2020**, *187*, 109704. [CrossRef] [PubMed]
5. Zhao, W.; Dai, L.; Chen, X.; Wu, Y.; Sun, Y.; Zhu, L. Characteristics of zooplankton community structure and its relationship with environmental factors in the South Yellow Sea. *Mar. Pollut. Bull.* **2022**, *176*, 113471. [CrossRef] [PubMed]
6. Goździejewska, A.M.; Koszałka, J.; Tandyrak, R.; Grochowska, J.; Parszuto, K. Functional responses of zooplankton communities to depth, trophic status, and ion content in mine pit lakes. *Hydrobiologia* **2021**, *848*, 2699–2719. [CrossRef]
7. Heneghan, R.F.; Everett, J.D.; Blanchard, J.L.; Sykes, P.; Richardson, A.J. Climate-driven zooplankton shifts cause large-scale declines in food quality for fish. *Nat. Clim. Chang.* **2023**, *13*, 470–477. [CrossRef]
8. Lomartire, S.; Marques, J.C.; Gonçalves, A.M. The key role of zooplankton in ecosystem services: A perspective of interaction between zooplankton and fish recruitment. *Ecol. Indic.* **2021**, *129*, 107867. [CrossRef]
9. Keister, J.E.; Winans, A.K.; Herrmann, B. Zooplankton Community Response to Seasonal Hypoxia: A Test of Three Hypotheses. *Diversity* **2020**, *12*, 21. [CrossRef]
10. Evans, L.E.; Hirst, A.G.; Kratina, P.; Beaugrand, G. Temperature-mediated changes in zooplankton body size: Large scale temporal and spatial analysis. *Ecography* **2020**, *43*, 581–590. [CrossRef]
11. Garzke, J.; Sommer, U.; Ismar-Rebitz, S.M. Zooplankton growth and survival differentially respond to interactive warming and acidification effects. *J. Plankton Res.* **2020**, *42*, 189–202. [CrossRef]
12. Li, K.; Ma, J.; Huang, L.; Tan, Y.; Song, X. Environmental drivers of temporal and spatial fluctuations of mesozooplankton community in Daya Bay, northern South China Sea. *J. Ocean Univ. China* **2021**, *20*, 1013–1026. [CrossRef]
13. Luo, M.; Zhang, Y.; Xiao, K.; Wang, X.; Zhang, X.; Li, G.; Li, H. Effect of submarine groundwater discharge on nutrient distribution and eutrophication in Liaodong Bay, China. *Water Res.* **2023**, *247*, 120732. [CrossRef]
14. Wu, J.H.; Li, Q.; Song, G.J. Comprehensive Assessment of Eco-Environmental Quality of Fishery Waters in the Northern Liaodong Bay in 2008–2017. *J. Ecol. Rural Environ.* **2019**, *35*, 1000–1008.
15. Guo, W.; Zou, J.; Liu, S.; Chen, X.; Kong, X.; Zhang, H.; Xu, T. Seasonal and spatial variation in dissolved heavy metals in Liaodong Bay, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 608. [CrossRef] [PubMed]
16. Wang, K.; Wei, Q.; Jian, H.; Gao, Z.; Yao, Q. Variations in the nutrient concentration and composition in Liaodong Bay under long-term human activities. *Marine Pollut Bull.* **2022**, *182*, 114016. [CrossRef] [PubMed]

17. Ayón Dejo, P.; Pinedo Arteaga, E.L.; Schukat, A.; Taucher, J.; Kiko, R.; Hauss, H.; Dorschner, S.; Hagen, W.; Segura-Noguera, M.; Lischka, S. Zooplankton community succession and trophic links during a mesocosm experiment in the coastal upwelling off Callao Bay (Peru). *Biogeosciences* **2023**, *20*, 945–969. [CrossRef]
18. Moon, S.Y.; Kim, H.Y.; Oh, H.J. Seasonal variation of the zooplankton community of Gamak Bay, Korea. *Korean J. Environ. Biol.* **2020**, *38*, 231–247. [CrossRef]
19. Muthurajah, S.D.; Leong, S.C.Y.; Kuwahara, V.S.; Moh, P.Y.; Ross, O.B.H.; Yoshida, T. Monsoonal and spatial influence on zooplankton variation in a tropical bay, North Borneo, Malaysia. *Reg. Stud. Mar. Sci.* **2021**, *47*, 101952. [CrossRef]
20. Coria-Monter, E.; Monreal-Gómez, M.A.; León, D.A.S.D.; Durán-Campos, E. Zooplankton abundance during summer in the Bay of La Paz (southwestern Gulf of California, Mexico). *Lat. Am. J. Aquat. Res.* **2020**, *48*, 794–805. [CrossRef]
21. Mahara, N.; Pakhomov, E.A.; Dosser, H.V.; Hunt, B.P.V. How zooplankton communities are shaped in a complex and dynamic coastal system with strong tidal influence. *Estuar. Coast. Shelf Sci.* **2021**, *249*, 107103. [CrossRef]
22. Sadia, N.; Ahmed, M.K.; Khondkar, M.M.; Rani, S.; Alam, M.J.; Al Karim, A.; Khan, M.I. Horizontal and vertical distribution and abundance of zooplankton around the Swatch-of-No-Ground of Northern Bay of Bengal. *Dhaka Univ. J. Earth Environ. Sci.* **2021**, *10*, 1–8. [CrossRef]
23. Xu, D.H.; Zhou, R.J.; Du, X.Y.; Wang, T.S.; Liu, X.; Qi, Y.P.; Guan, X.Y.; Zhang, Q.B.; Sun, B.B.; Zhou, H. Community characteristics and factors influencing zooplank ton in the Bohai Bay during autumn. *Mar. Sci.* **2022**, *46*, 90–98.
24. Xu, D.H.; Qi, Y.P.; Liu, X.; Pan, Y.L.; Du, X.Y.; Wang, T.S. Community characteristics of planktonic copepods in the Bohai Bay. *Mar. Sci.* **2022**, *46*, 69–80.
25. Li, D.; Wen, Y.; Zhang, G. Effects of terrestrial inputs on mesozooplankton community structure in bohai bay, China. *Diversity* **2022**, *14*, 410. [CrossRef]
26. Li, H.R.; Liu, G.X.; Ma, J.; Wang, W.M.; Chen, H.J. Ecological characteristics of zooplankton in the eastern coastal waters of Laizhou Bay in summer. *Period. Ocean Univ. China* **2017**, *47*, 37–45.
27. Zhang, M.L.; Qi, Z.L.; Li, B.; Wang, F.; Han, H.H. A preliminary study on energy contribution of terrestrial organic carbon to zooplankton in the Laizhou Bay. *Mar. Fish.* **2018**, *40*, 319–325.
28. Jiang, H.C.; Liu, D.Y.; Ma, Y.Q.; Su, B.; Liu, N.; Zhang, J.; He, J.L.; Qin, H.W.; Song, X.K.; Sun, S.; et al. Decadal Response of Mesozooplankton Assemblages to Nutrient Load Reductions in Laizhou Bay, China. *Front. Mar. Sci.* **2022**, *9*, 849739. [CrossRef]
29. Bian, S.W.; Han, L.; Mei, P.W.; Wang, J.G.; Yuan, Y.X.; Zhang, Z. Community structure of zooplankton and its relationship with environmental factors in summer and autumn in Liaodong Bay. *J. Tianjin Norm. Univ. (Nat. Sci. Ed.)* **2020**, *40*, 44–49.
30. Song, L.; Zhou, Z.M.; Wang, N.B.; Ma, Z.Q.; Xue, K.; Tian, J.; Yang, S.; Wang, Z.H.; Wu, J.H. Zooplankton diversity of Liaodong Bay and relationship with oceanic environmental factors. *Marine Sci.* **2010**, *34*, 35–39.
31. Li, W.W.; Sun, Z.C.; Liang, S.X. Effects of the Liao river discharge on the dispersion of pollutants. *Mar. Environ. Sci.* **2019**, *38*, 294–302.
32. Li, D.H.; CHAO, L.; ZHAO, F.Z.; Lei, K.; Li, Y.Y. Characteristics of hydrodynamics and pollutant transport into the sea in the LiaodongBay. *Adv. Mar. Sci.* **2022**, *40*, 423–434.
33. Zhao, Q.; Wang, M.J.; Ding, D.W.; Chen, W.B. Study on hydrodynamie characteristies in the eastern part of LiaodongBay Mouth based on long term observation. *Haiyang Xuebao* **2016**, *38*, 20–30.
34. *GB/T 12763.6-2007*; Specifications for Oceanographic Survey Part 6: Marine Biological Survey. Standardization Administration of China: Beijing, China, 2007.
35. *GB/T 12763.4-2007*; Specifications for Oceanographic Survey Part 4: Survey of Chemical Parameters in Sea Water. Standardization Administration of China: Beijing, China, 2007.
36. *GB/T 17378.5-2007*; The Specification for Marine Monitoring Part 5: Sediment Analysis. Standardization Administration of China: Beijing, China, 2007.
37. Shannon, C.E. A mathematical theory of communication. *Bell Syst. Tech. J.* **1948**, *27*, 379–423. [CrossRef]
38. Pielou, E.C. An introduction to mathematical ecology. *Bioscience* **2011**, *24*, 7–12.
39. Margalef, D.R. Information theory in ecology. *Soc. Gen. Syst. Res.* **1958**, *3*, 36–71.
40. Zhang, L.; Tao, H.H.; Ji, Y.L.; Su, K.; Wang, J.W.; Pu, S.C. Community structure characteristics of zooplankton in the sea area near Dongjiakou Port of Qingdao in spring and autumn. *J. Appl. Oceanogr.* **2023**, *42*, 16–27.
41. Clarke, K.R. Non-parametric multivariate analyses of changes in community structure. *Aust. J. Ecol.* **1993**, *18*, 117–143. [CrossRef]
42. Wang, B.; Dong, Q.; Liu, C.Y.; Sun, M.; Yu, X.G.; Liu, X.Z.; Li, Y.P.; Li, P.J. Distribution of giant jellyfish and major zooplankton in jellyfish release area of Liaodong Bay, Bohai Sea in early summer. *Prog. Fish. Sci.* **2010**, *31*, 83–90.
43. Choi, S.Y.; Lee, E.H.; Soh, H.Y.; Jang, M.C. Effects of temperature and salinity on egg production, hatching, and mortality rates in Acartia ohtsukai (Copepoda, Calanoida). *Front. Mar. Sci.* **2021**, *8*, 704479. [CrossRef]
44. Magouz, F.I.; Essa, M.A.; Matter, M.; Mansour, A.T.; Gaber, A.; Ashour, M. Effect of different salinity levels on population dynamics and growth of the cyclopoid copepod *Oithona nana*. *Diversity* **2021**, *13*, 190. [CrossRef]
45. Kuismanen, L.; Forsblom, L.; Engström-Öst, J.; Båmstedt, U.; Glippa, O. Salinity effects on egg production, hatching, and survival of Eurytemora affinis (Copepoda, Calanoida). *Crustaceana* **2020**, *93*, 429–445. [CrossRef]
46. Mariani, M.; Vignatti, A.; Echaniz, S.; Cueto, G.; Zagarese, H.; Diovisalvi, N. Zooplankton community size structure across lakes within a semi-arid landscape: The effect of temperature and salinity. *J. Plankton Res.* **2023**, *45*, 440–453. [CrossRef]

47. Ojok, W.; Wasswa, J.; Ntambi, E. Assessment of Seasonal Variation in Water Quality in River Rwizi Using Multivariate Statistical Techniques, Mbarara Municipality, Uganda. *J. Water Resour. Prot.* **2017**, *9*, 83–97. [CrossRef]
48. Zuo, T.; Wang, J.; Shi, Y.Q. Seasonal distribution of body length and abundance of *Aidanosagitta crassa* (Tokioka, 1938) in Laizhou Bay, Bohai Sea. *Acta Ecol. Sin.* **2017**, *37*, 5189–5197.
49. Uye, S.I.; Liang, D. Seasonal population dynamics, production, and feeding of the chaetognath *Aidanosagitta crassa* in a temperate eutrophic inlet. *Plankton Benthos Res.* **2022**, *17*, 312–326. [CrossRef]
50. Guo, L.; Mo, L.; Su, Y.; Hu, X.; Xu, D. Studying the Metazoan Zooplankton Community Characteristics and Evaluating the Water Quality Based on the Ecological and Functional Zones in Gaoyou Lake. *Water* **2023**, *15*, 3357. [CrossRef]
51. Zhikharev, V.; Gavrilko, D.; Kudrin, I.; Vodeneeva, E.; Erina, O.; Tereshina, M.; Shurganova, G. Structural organization of zooplankton communities in different types of river mouth areas. *Diversity* **2023**, *15*, 199. [CrossRef]
52. Li, J.; Liang, Y.Y.; Tang, X.X.; Han, Q.; Yin, F.; Guo, M.C.; Lu, W.X. Evaluation of Chaohu Lake metazoan zooplankton communities and their nutritional status in different lakes. *J. Hydroecol.* **2023**, *44*, 73–81.
53. Giraldo, C.; Cresson, P.; Mackenzie, K.; Fontaine, V.; Loots, C.; Delegrange, A.; Lefebvre, S. Insights into planktonic food-web dynamics through the lens of size and season. *Sci. Rep.* **2024**, *14*, 1684. [CrossRef]
54. Wasserman, R.J.; Vink, T.J.; Kramer, R.; Froneman, P.W. Hyperbenthic and pelagic predators regulate alternate key planktonic copepods in shallow temperate estuaries. *Mar. Freshw. Res.* **2014**, *65*, 791–801. [CrossRef]
55. Pinto-Coelho, R.; Pinel-Alloul, B.; Méthot, G. Crustacean zooplankton in lakes and reservoirs of temperate and tropical regions: Variation with trophic status. *Can. J. Fish. Aquat. Sci.* **2005**, *62*, 348–361. [CrossRef]
56. Hamil, S.; Bouchelouche, D.; Arab, S.; Alili, M.; Baha, M.; Arab, A. The relationship between zooplankton community and environmental factors of Ghrib Dam in Algeria. *Environ. Sci. Pollut. Res.* **2021**, *28*, 46592–46602. [CrossRef] [PubMed]
57. Bișinicu, E.; Boicenco, L.; Pantea, E.; Timofte, F.; Lazăr, L.; Vlas, O. Qualitative Model of the Causal Interactions between Phytoplankton, Zooplankton, and Environmental Factors in the Romanian Black Sea. *Phycology* **2024**, *4*, 168–189. [CrossRef]
58. Liu, H.; El-Din, N.N.; Rowe, G.; Al-Ansi, M.; Wei, C.L.; Soliman, Y.; Nunnally, C.; Quigg, A.; Al-Ansari, I.S.; Al-Maslamani, I.; et al. Characteristics and renewal of zooplankton communities under extreme environmental stresses in the oligotrophic hypersaline Arabian Gulf. *Prog. Oceanogr.* **2022**, *201*, 102643. [CrossRef]
59. Ye, W.J.; Du, P.; Shou, L.; Cai, X.X.; Chen, Y.; Tang, Y.B.; Liao, Y.B.; Huang, W.; Liu, X.Y. Spatio-temporal variation of marco and mesozooplankton communities and the controlling factors around Zhoushan archipelago. *Acta Ecol. Sin.* **2021**, *41*, 254–267.
60. Wang, X.; Wang, Z.; Zhang, X.; Liu, P. The distribution of zooplankton and the influencing environmental factors in the South Yellow Sea in the summer. *Mar. Pollut. Bull.* **2021**, *167*, 112279. [CrossRef]
61. Gao, Q.; Xu, Z.; Zhuang, P. The relation between distribution of zooplankton and salinity in the Changjiang Estuary. *Chin. J. Oceanol. Limnol.* **2008**, *26*, 178–185. [CrossRef]
62. Harvey, M.; Therriault, J.C.; Simard, N. Hydrodynamic control of late summer species composition and abundance of zooplankton in Hudson Bay and Hudson Strait (Canada). *J. Plankton Res.* **2001**, *23*, 481–496. [CrossRef]
63. Nicolle, A.; Hansson, L.A.; Brodersen, J.; Nilsson, P.A.; Brönmark, C. Interactions between predation and resources shape zooplankton population dynamics. *PLoS ONE* **2011**, *6*, e16534. [CrossRef]
64. Zhang, S.; Shi, B.J.; Xie, B.; Zhang, H.; Li, D.P. Zooplankton community structure of the sea farming in Haizhou Bay and its relationships with environment factors. *Ecol. Environ. Sci.* **2017**, *26*, 1410–1418.
65. Jiang, H.C.; Chen, H.G.; Song, X.K.; Liu, N.; He, J.L.; Cheng, L.; Wang, Y.X. Zooplankton community structure in Jincheng area of Laizhou Bay and its relationship with environmental factors. *Acta Ecol. Sin.* **2015**, *35*, 7308–7319.
66. Karpowicz, M.; Ejsmont-Karabin, J.; Kozłowska, J.; Feniova, I.; Dzialowski, A.R. Zooplankton community responses to oxygen stress. *Water* **2020**, *12*, 706. [CrossRef]
67. Breitburg, D.; Levin, L.A.; Oschlies, A.; Grégoire, M.; Chavez, F.P.; Conley, D.J.; Garçon, V.; Gilbert, D.; Gutiérrez, D.; Isensee, K.; et al. Declining oxygen in the global ocean and coastal waters. *Science* **2018**, *359*, eaam7240. [CrossRef]
68. Liu, D.; Li, Y.M.; Chen, S.L.; Chen, B.J.; Lv, Z.B.; Wang, Y.B.; Zhang, J.J.; Li, M.; Ren, Z.H. Seasonal variation of zooplankton community structure and its influencing factors in waters adjacent to the Huanghua port, Bohai in 2014. *Mar. Sci.* **2022**, *46*, 81–97.
69. Wang, X.M.; Sheng, H.X.; Liu, S.D.; Fang, G.J.; Yu, H.L.; Tang, Y.L.; Liang, Z.L. Distribution characteristics of *Liza haematocheila* and its relationship with environmental factors in Furongdao artificial reef zones, Laizhou Bay, China. *J. Fish. China* **2019**, *43*, 1914–1924.