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ECOSYSTEMS

The hidden impact of global warming on the structure and dynamics of zooplankton communities in freshwater habitats

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Abstract: This study investigates the impact of global warming on zooplankton community structure in freshwater ecosystems, focusing on the relationship between zooplankton species and environmental factors. Due to rising temperatures and environmental changes, zooplankton are reducing in body size, leading to the appearance of smaller opportunistic species such as rotifers, known for their tolerance to extreme conditions Canonical Correspondence Analysis (CCA) identified some abiotic factors that impact species, such as temperature (T), dissolved oxygen (DO), electrical conductivity (EC), salinity, turbidity (Turb) and pH as significantly influencing zooplankton distribution and diversity. A high diversity of Rotifera species, primarily benthic and cosmopolitan, was observed, commonly found in Turkey's freshwater littoral zones. Cluster analysis emphasizes similarities and differences in species composition sampling site, and complex interactions of abiotic factors that shape zooplankton communities. Global warming supports smaller zooplankton species with changing community structure and reducing their body size. As zooplankton are integral to the aquatic food chain, changes in their populations could impact the dynamics of trophic relationships and the balance of ecosystems. In the study emphasizes the need for comprehensive future research on both abiotic and biotic factors to improve our knowledge of how aquatic ecosystems respond to climate change.

Key words: Abiotic factors, CCA, Global warming, Turkey, Zooplankton.

INTRODUCTION

Global warming adversely affects the flora and fauna of the water bodies. Many experimental studies show that global warming can reduce the aquatic biological diversity of freshwaters (Carosi 2022, Faquim et al. 2021). Climate change directly affects most of the biotic components of fish, benthic macroinvertebrates, and zooplankton in all the world's freshwater ecosystems (Dinh et al. 2022). Through interacting with pollutants, they can induce an additive or substitutive effect depending on taxon, life stage, exposure level, and exposure time (Fernández et al. 2022). The increase in natural and anthropogenic effects of greenhouse gas emissions is destroying the ecosystem integrity in shallow waters, resulting in declines in subaquatic vegetation communities (Zhang 2018). In addition to that, climate change can cause the distribution of plants and animals and changes in the distribution of plants and animals and changes in habitat conditions. Moreover, it can effect the productivity and diversity of aquatic ecosystems (Khan & Patel 2021). Zooplanktonic organisms play a vital role in energy transfer in aquatic ecosystems, from phytoplanktonic organisms that are primary producers in the food chain to predator fish and mammals at the highest trophic levels (Cabral et al. 2020). These are found in all kinds of aquatic habitats such as seas, lakes, ponds, dam lakes, rivers, lagoons, sinkholes, swamps, caves, etc. mainly as microscopic animals (Ustaoğlu et al. 2012, Durmaz et al. 2022, Gürbüzer et al. 2023). Zooplankton species are sensitive to various environmental and biological effects, including eutrophication, pollution, global warming, and environmental issues (Özdemir et al. 2021). Furthermore, they are known as indicator species for determining water quality in their habitats (Kumari & Kumar 2018). They quickly respond to environmental changes in water (Başak et al. 2014). Zooplankton communtiy consists of three main groups: Rotifera, Cladocera, and Copepoda. Various abiotic (light, water temperature, dissolved oxygen levels, pH, electrical conductivity, salinity, nutrient levels, turbidity) and biotic factors (predation, competition within and among species) and also climate, topography, hydrology, and the presence of macrophytes influence the distribution of zooplankton organisms (Brysiewicz et al. 2017, Özdemir et al. 2021).

In this study, zooplankton samples were collected from 91 different locations across various water habitats (lake, reservoir, river, stream, water puddle, trough) in the Çanakkale province, and the effects of global warming on species diversity and the relationships with measured physicochemical parameters at each location were investigated.

MATERIALS AND METHODS

In Çanakkale Province, samples were collected from various aquatic ecosystems, selected randomly, by separately water, sediment, and planktonic organisms (Figure 1). At each sampling site, photographs and videos of the

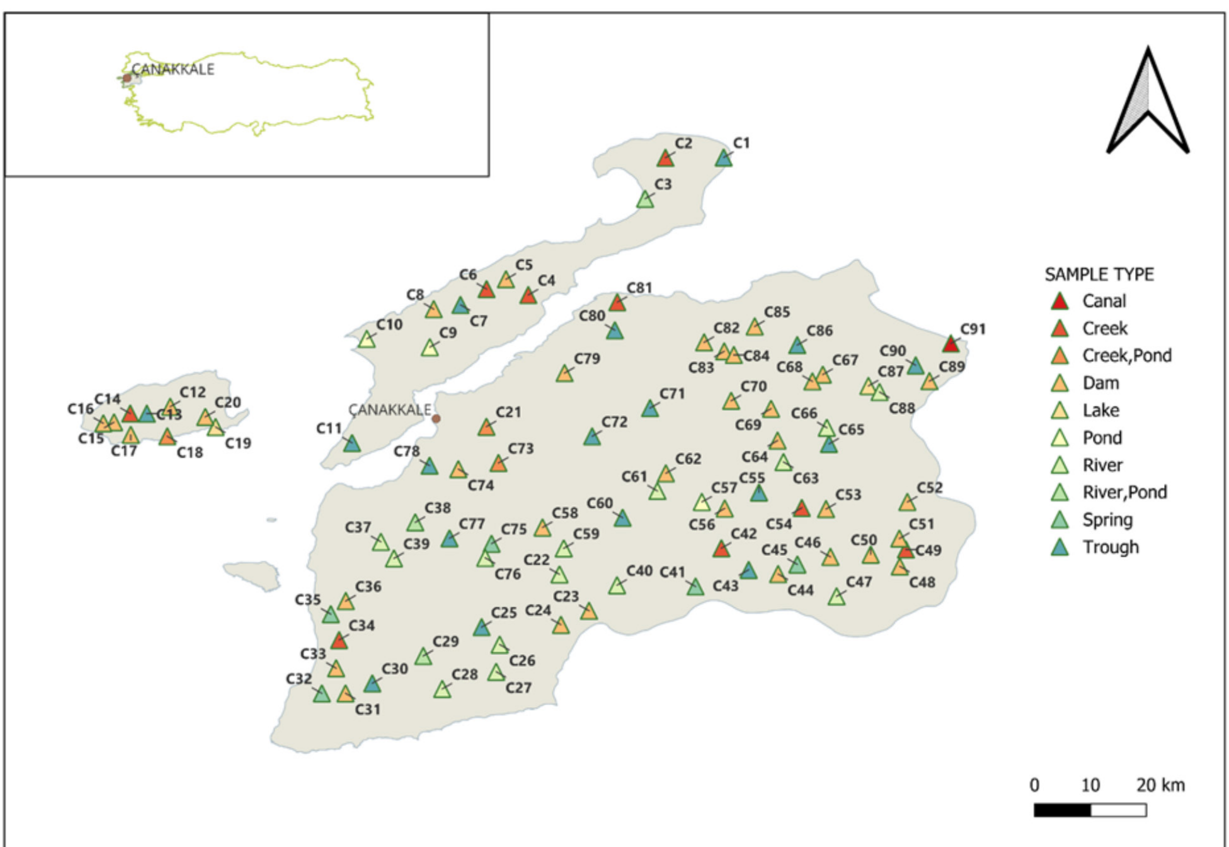

Figure 1. Zooplankton samples locations are shown in the map of Çanakkale.

area were taken, documenting both the land and relevant aquatic environment information. Zooplankton samples were collected using a 55 µm open-type plankton net through horizontal tow sampling. The obtained samples were fixed with 70% ethanol. Samples were stored in 100 ml sterile double-capped plastic collection containers and kept in a cooler. Geographic data (coordinates, altitude, pressure, etc.) at each site's coordinates were recorded using a Global Positioning System (GPS) device. For water analyses, 100 ml sterile double-capped plastic containers were used. Each sample was preserved in a cooler and sent to the laboratory at Eskişehir Technical University for analysis. Statistical analyses included canonical correspondence analysis (CCA) based on linear regression (ter Braak 1986), which measured the effects of abiotic variables on species distributions (McCune 1997). Another statistical analysis applied was Cluster Analysis, which utilized the Euclidean distance measurement formula and the Ward's hierarchical clustering method (Murtagh & Legendre 2014, Legendre & Legendre 2012). All statistical analyses were created using the RStudio Version 2024.12.1+563.

RESULTS

In this study, carried out between October 28 and November 2, 2022, an examination of zooplankton samples collected from 91 locations in Çanakkale revealed the presence of zooplankton at 54 sites (3 ponds, 1 lake, 1 spring, 9 rivers, 3 creek, 26 dams, and 11 troughs) (Table I). The analysis of zooplankton samples from 91 stations in Çanakkale identified a total of 56 species, comprising 45 species (81.35%) from Rotifera, 7 species (11.87%) from Cladocera, and 4 species (6.78%) from Copepoda. The dominant species among the zooplankton included bdelloid rotifers, *Keratella tecta*, *Polyarthra vulgaris*, *Lecane lunaris*, *Lecane luna* from Rotifera, *Bosmina longirostris* and *Chydorus sphaericus* from Cladocera, and *Cyclops strenuus* from Copepoda. The zooplankton species identified in this study are presented in Table II.

DISCUSSION

Zooplanktonic organisms play a significant role in aquatic ecosystems, connecting primary producers, such as phytoplankton, with higher trophic-level organisms. Additionally, nearly all fish species depend on zooplankton during their larval stages, with some fish species continuing to feed on zooplankton throughout their lives (Fontaine & Revera 1986, Kumari & Kumar 2018). The presence and dominance of zooplankton species play an important role in the functioning of fresh water ecosystems. Therefore, zooplanktonic organisms are considered indicators of water quality (Geiger 1983). Due to their short lifespans, zooplankton respond rapidly to environmental changes in water, such as temperature, pH, oxygen, color, smell and taste. Furthermore, zooplankton species are sensitive to numerous environmental and biological effects, including eutrophication, pollution, and global warming (Özdemir et al. 2021).

Zooplankton are divided into three main groups: Rotifera, Cladocera, and Copepoda: Rotifera, Cladocera, and Copepoda. In this study, the dominant species identified belonged to the Rotifera group. The most frequently observed genus within Rotifera were *Lecane* (7 species) and *Trichocerca* (5 species), followed by *Polyarthra* (3 species) and *Colurella* (3 species).

Rotifers are important indicator organisms in water quality assessments, as their community structures are sensitive to ecological environmental changes (Qu et al. 2021). Rotifers constitute a significant component of freshwater

Table I. Stations of zooplankton samples in Çanakkale province, abiotic parameters and coordinates.

Station	Station Name	Station type	pH	DO	EC	T°	Salinity	Turbidity
C1	Çolak Village	Troughs	7,69	9,7	1086	17.26	0.54	0
C5	Fındıklı Village	Dam	9.35	10.23	535	17.40	0.26	48.7
C7	Tayfur Village	Troughs	8.03	9.35	577	14.30	0.28	3.5
C8	Karainebeyli	Dam	9.22	9.32	529	17.07	0.26	28.1
C10	Küçükanafarta Village	Pond	8.71	9.65	2427	15.84	1.26	33.3
C11	Alçıtepe	Troughs	9.85	10.35	518	18.72	0.25	0
C14	Dereköy	Creek	8.03	7,79	720	18.36	0.37	1.8
C15	Dereköy	Dam	9.07	8.77	873	17.11	0.43	35.7
C17	Dereköy-Lazköy	Dam	8.99	9.75	687	16.77	0.34	45.2
C20	Aydıncık Village	Dam	9.15	8.32	748	17.78	0.37	40.1
C23	Çavuşlu	Dam	8.9	8.27	270	14.47	0.13	1.1
C24	Yassıbağ Village	Dam	8.38	6.7	278	13.6	0.14	6.0
C27	Çaltı Village	Spring	8.74	8.81	499	12.22	0.24	0
C28	Ayvacık	Spring	9.28	11.23	358	18.79	0.17	3.6
C30	Çamköy	Troughs	9.1	10.16	533	12.02	0.26	1.2
C31	Taşboğaz Village	Dam	7.89	3.8	1200	16.04	0.60	19.1
C33	Tuzla	Spring	6.81	5.0	87.06	29.58	0.74	36.3
C36	Kemalli	Dam	9.93	9.85	818	15.91	0.41	33.4
C37	Pınarbaşı	River	8.56	6.67	679	16.56	0.33	19.4
C38	Kemerdere	River	8.9	8.63	603	13.15	0.29	0
C39	Ezine Center	River	8.63	6.92	726	16.58	0.36	0
C40	Külcüler	River	8.73	9.26	274	10.48	0.18	0
C41	Karaköy	Spring	8.52	9.75	281	9.82	0.14	0
C43	Zeybekçayırı	Troughs	8.44	8.29	490	11.58	0.24	0
C44	Örencik	Dam	8.58	7.4	2030	15.39	1.05	0
C46	Kurtlar	Dam	8.83	6.93	278	16.41	0.13	1.50
C48	Karaköy	Dam	8.96	8.46	370	15.45	0.18	8.10
C49	Pazarköy	Creek	9.42	13.74	357	17.83	0.17	0
C51	Gümüşler	Dam	9.16	9.72	550	15.78	0.27	12.10
C52	Karaköy	Dam	8.79	9.25	620	17.15	0.30	1.50
C55	Derenti	Troughs	9.1	9.82	485	16.56	0.23	-
C56	Terzialanı	Dam	8.95	6.83	416	15.38	0.20	11.2
C57	Büyükpaşa	Pond	8.37	3.09	388	13.33	0.18	825
C59	Yukarışefik	River	8.83	8.37	636	13.04	0.31	2.70
C60	Muratlı	Troughs	9.22	9.17	127	12.34	0.06	0
C61	Küçüklü	River	8.56	8.37	500	14.04	0.24	5.0

Table I. Continuation.

C63	Çanaklı	River	8.07	4.9	2913	13.81	1.53	245
C65	Ilıcabaşı	Troughs	8.07	7.42	681	14.74	0.33	0
C67	Kaldırımbaşı	Dam	8.9	8.08	466	16.74	0.22	0.10
C68	Akyaprak	Dam	8.99	9.77	366	18.0	0.18	5.70
C70	Gürpınar	Dam	8.82	8.15	341	16.76	0.16	25.7
C71	Balcılar Village	Troughs	8.82	11.85	526	16.19	0.26	0
C74	Aşağıokçular	Dam	9.44	9.2	576	17.31	0.28	19
C78	Çınarlı	Troughs	8.14	7.04	1022	14.08	0.51	39.7
C79	Umurbey	Dam	8.92	7.56	308	13.72	0.15	0
C80	Taşbaşı Village	Troughs	8.06	10.6	886	13.72	0.44	0
C81	Adatepe	Creek	8.4	9.16	942	15.55	0.47	13.9
C82	Beypınar	Dam	9.16	12.34	384	18.85	0.18	8.30
C83	Bürgendere	Dam	9.21	9.67	337	16.26	0.16	8.50
C84	Kozçeşme	Dam	9.03	9.71	379	18.95	0.18	5.40
C85	Otlakdere	Dam	10.1	17.25	654	20.78	0.32	34.6
C87	Kalafat	Lake	9.4	16.01	476	18.65	0.23	126
C89	Hacıpehlivan	Dam	8.94	8.81	432	15.67	0.21	32.8

zooplankton communities. The composition of rotifer communities is influenced by the amount of nutrients and planktivorous fish, invertebrate predators, and competition between species. Rotifers are typically abundant in nutrient-rich aquatic ecosystems (Fontaneto & de Smet 2015). Most rotifers, cladocerans also compete for similar food sources, while some cyclopoid copepods are effective predators on rotifers. Increased rotifer abundance with increased trophic levels has been widely reported in research (Pace 1986, Yoshida et al. 2003). Moreover, abiotic factors such as temperature, pH, oxygen, and turbidity impact rotifer abundance and species distribution (Duggan et al. 2002).

As a result of this study, the most identified species between stations included *Philodina megalotrocha* and *Rotaria rotatoria*, both bdelloid rotifers, which were found at 20 locations, along with other bdelloid species. *Polyarthra vulgaris* was observed in 13 locations, *Keratella tecta* in 10, and two species *Lecane lunaris* and *Lecane luna* in 8 locations. Among Cladocera, *Bosmina longirostris* was found in 7 locations and *Chydorus sphaericus* in 5 locations, while among Copepoda, *Cyclops strenuus* was found in 12 locations.

All of the identified species, appear to be cosmopolitan species commonly found in the littoral zones of various lakes worldwide and in Turkey, predominantly inhabiting nutrient-rich eutrophic waters. Bdelloid rotifers constitute a class within the phylum Rotifera and are known for their resilience to extreme conditions through anhydrobiosis (Ricci 1987). Bdelloids are widespread inhabitants of freshwater and soil, often adhering to surfaces. While primarily benthic, some bdelloid species can occasionally be found in plankton and also inhabit periphyton in both lotic and lentic waters. Another frequently found rotifer species, *Keratella cochlearis tecta*,

Table II. **Zooplankton species identified in Çanakkale province and their respective sampling stations.**

ROTIFERA	References	Station Number
Anuraeopsis fissa	(Gosse, 1851)	5,7,10,80,85,87
Asplanchna priodonta	(Gosse, 1850)	48
Asplanchna sieboldi	(Leydig, 1854)	24,52
Asplanchnopus sp.	(Gosse, 1851)	37
Bdelloid rotifer	(Pallas, 1766)	11,14,27,30,37,41,43,52,60,61,71,74,80,85
Brachionus angularis	(Müller, 1786)	10
Brachionus calyciflorus	(Ehrenberg, 1830)	10
Cehpalodella gibba	(Dixon-Nuttall, 1901)	14,27,37,61,68
Cephalodella ventripes	(Ehrenberg, 1830)	14,37,61,68,82,87
Colurella adriatica	(Ehrenberg, 1830)	14,28,37,39,80,81
Colurella colurus	(Gosse, 1886)	37,61,80
Colurella obtusa	(Harring & Myers, 1928)	37
Colletheca ornata	(Ehrenberg, 1832)	33,48,61
Dicranophorus epicharis	(Ehrenberg, 1838)	61
Euchlanis dilatata	(Ehrenberg, 1834)	27,49,52
Euchlanis sp.	(Gosse, 1851)	49
Encentrum sp.	(Gosse, 1851)	61
Filinia longiseta	(Apstein, 1907)	20,27,33
Keratella cochlearis	(Gosse, 1851)	5,8,33,52,61,74
Keratella tecta	(Schmarda, 1859)	24,27,33,48,51,61,68,83,84,85
Keratella tropica	(Murray, 1913)	15,33
Lecane bulla	(Steinecke, 1916)	37
Lecane closterocerca	(Müller, 1776)	37,49,55,70,78
Lecane nana	(Ehrenberg, 1832)	11
Lecane lunaris	(Daday, 1905)	1,11,14,30,37,78,80,87
Lecane luna	(Ehrenberg, 1834)	7,37,39,49,65,68,78,80
Lecane pyriformis	(Müller, 1786)	37
Lecane paradoxa	(Müller, 1773)	61
Lepadella acuminata	(Ehrenberg, 1832)	37
Lepadella patella	(Idelson, 1925)	37,57
Lepadella ovalis	(Voigt, 1904)	37
Philodina megalotrocha	(Pallas, 1766)	30,52,78,84,85
Polyarthra dolichoptera	(Rousselet, 1902)	24,74,80,83,89
Polyarthra vulgaris	(Ehrenberg, 1832)	8,15,17,24,48,51,52,67,68,74,82,83,89
Polyarthra minor	(Müller, 1786)	48

Table II. Continuation.

Rotaria rotatoria	(Wierzejski & Zacharias, 1893)	33
Synchaeta litoralis	(Gosse, 1851)	83
Synchaeta pectinata	(Jennings, 1903)	8,11,33,48,59,82,83
Scaridium longicaudum	(Wierzejski, 1893)	49
Trichocerca capucina	(Gosse, 1886)	15,46
Trichocerca tenuior	(Müller, 1776)	15,37,49,61,79,80,83,85,87
Trichocerca pusilla	(Jennings, 1903)	51,74
Trichocerca similis	(Sars, 1862)	20,24,46,67,68
Trichocerca longiseta	(Sars, 1862)	56
Trichotria pocillum	(O.F. Müller, 1785)	37
CLADOCERA		
Alona guttata	(O.F. Müller, 1776)	52,78
Coronatella rectangula	(Sars, 1862)	78,80
Bosmina longirostris	(O.F. Müller, 1776)	33,49,52,61,63,68,70
Chydorus ovalis	(Fischer, 1851)	78
Chydorus sphaericus	(Uljanin, 1875)	27,65,71,78,80
Daphnia longispina	(Jurine, 1820)	81
Simocephalus vetulus	(O.F. Müller, 1776)	57
COPEPODA		
Cyclops strenuus	(Fischer, 1851)	14,23,31,36,37,44,48,56,61,78,80,85
Cyclops vicinus	(Uljanin, 1875)	27,80,85
Megacyclops viridis.	(Jurine, 1820)	57
Canthocamptus staphylinus	(Jurine, 1820)	39
Nauplius larvae		8,14,20,23,27,38,60,78,80
Copepodid larvae		14,23,38

is present across water bodies and is reported to develop during the mixing phases of lakes, particularly in spring and winter when water and nutrient inflows are at their peak (Gophen 2021).

It is commonly found in the littoral zones of nutrient-rich lakes and ponds, attaching its eggs directly to littoral vegetation (Edmondson 1959). *Keratella cochlearis tecta* is considered cosmopolitan and adaptable to various aquatic environments, including lakes, ponds, reservoirs, pools, rivers, peat bogs, and saline waters, where it resides in both still and flowing waters, as well as benthic, periphytic, and semi-planktonic habitats enriched with mineral and detrital sediments (Rotifer World Catalog). It is an euplanktonic rotifer species widely present in lakes and reservoirs and has been associated with pollution (Braioni & Gelmini 1983, Koste & Shiel 1991). Another frequently recorded rotifer species, *Polyarthra vulgaris*, is primarily euplanktonic but also found among macrophytes in potamoplankton in freshwater lakes and ponds (Jersabek & Bolortsetseg 2010). This eurythermal species is adapted to cold waters, as noted by several researchers (Ruttner-Kolisko 1972, Bērziņš & Pejler 1989). *P. vulgaris* is euryalkaline, with a pH tolerance ranging from 4.9 to 8.7 (Bielańska-Grajner & Cudak 2014, Osmanov et al. 2018), and commonly found in mesotrophic lakes, even though it can also survive in oligotrophic and eutrophic waters. Sládeček (1983) classified it as a B-mesosaprobic (2:0) species.

The current study found that the most common genus among the identified species was *Lecane, Brachionus,* and *Trichocerca*. Additionally, It was found that benthic and periphytic species that live in clean water, such as *Lecane, Lepadella,* and *Scaridium* (Guermazi et al. 2023). Additionally the genus *Trichocerca*, which was found as dominant, has Laurasian origins. The analysis indicated that over one-third of the observed species exhibit strict cosmopolitanism, with widely distributed taxa accounting for the majority (65.7%). A notable latitudinal variation was observed in 26.9% of *Trichocerca* species, most of which prefer warm water habitats. The genus *Trichocerca* is unique among Rotifera due to its ecological diversity, encompassing freshwater, marine, pelagic, coastal, and psammobiotic species. *T. tenuior*, for example, frequently inhabits psammon (sandy habitats) (Segers 2003). Sládeček (1983) classified all *Trichocerca* species as oligosaprobic and/or beta-mesosaprobic.

Many species are eurycious, yet some display preferences for specific environments such as eutrophic, oligotrophic, or polyhumic waters (Sládeček 1983). The most frequently observed *Lecane* species, *Lecane luna* and *Lecane lunaris*, are cosmopolitan and eurytopic, representing the most widespread species within the genus. *Lecane* is characteristic of littoral habitats rich in nymphaeids, submerged macrophytes, and helophytes (Pejler 1995, Pholpunthin & Chittapun 1998). *Lecane lunaris* is a cosmopolitan species, commonly found in the littoral zone, plankton, and nutrient-rich waters (de Manuel Barrabin 2000). Although typically inhabiting coastal habitats, it can also be found in exotic water environments like psammon and phytotelmata (Pejler & Berzins 1993, Segers 1995).

Among Cladocera, one of the most frequently identified species, *Bosmina longirostris*, is an epi–and euplanktonic species commonly found in lakes and reservoirs, predominantly in littoral regions. It is often recorded in systems with low mineralization and eutrophic conditions (Margaritora 1985, Alonso 1985). *Bosmina longirostris* is a cosmopolitan species, and reported in various water bodies around Turkey as well (Ustaoğlu et al. 2012). Another dominant Cladocera species, *Chydorus sphaericus*, is a cosmopolitan and generally found in the littoral zones of shallow waters, predominantly planktonic and often related to algae and macrophytes (Korovchinsky 2000). Studies have highlighted its tolerance to environmental conditions, despite it's limited tolerance to high chloride concentrations (Margalef et al. 1976). It is habitat littoral and pelagic zones of oligotrophic and eutrophic lakes and has frequently been used as an indicator of eutrophication, particularly when found in high densities (Duigan & Murray 1987). *C. sphaericus* is considered cosmopolitan in Turkey, with a wide distribution across various water bodies, from small ponds to large lakes. Its adaptability is attributed to its tolerance to physicochemical changes, a rounded carapace that provides protection from predation, and the ability to use algae as a substrate when transitioning to a planktonic lifestyle.

Among the Copepoda, *Cyclops strenuus* was the most identified species. Wide distribution shows in Europe, it is commonly reported in small water bodies, ponds, and temporary waters, though it is less frequent along lake shores. *C. strenuus* can survive in low-oxygen environments. During diapause, specimens are found buried up to 5 cm in bottom sediments from April to late autumn (Błędzki & Rybak 2016). This study did not identify any calanoid copepod species. Calanoid copepods are predominantly planktonic, cyclopoid and harpacticoid copepods prefer to live littoral or benthic substrates (Galassi et al. 2009). Cyclopoid and calanoid copepods is that calanoids tend to dominate in oligotrophic conditions, whereas cyclopoids are better adapted to eutrophic conditions (Aygen et al. 2009). Blancher (1984) noted that cyclopoid copepods are more commonly found than calanoids in eutrophic lakes (İpek-Alış & Saler 2016). This study identified only cyclopoid and harpacticoid copepod species, which were primarily observed in the littoral and benthic substrates of the lake. Rotifers and copepods, forming part of the zooplankton group, have been shown to colonize new water habitats more quickly than cladocerans (Badosa et al. 2010).

Effects of Global Warming on Zooplankton Community Structure

Global warming deeply affects aquatic ecosystems worldwide, accelerating the decline of critical plant communities and animal biodiversity and also changing the structure of aquatic habitats. The changes in temperature and environmental conditions disrupt the distribution, behavior, and health of aquatic animals, with potential consequences for marine and freshwater biodiversity. The interdependence of ecosystems worldwide compounded by anthropogenic factors, increases the complexity of these impacts (Sikotariya et al. 2024).

Global warming is rapidly increasing due to multiple stress factors on ecosystems (Miranda et al. 2014, Solomon et al. 2015). Climatic change has already impacted ecosystems, contributing to a global trend of increased extreme weather cast, meaning greater frequency, duration,

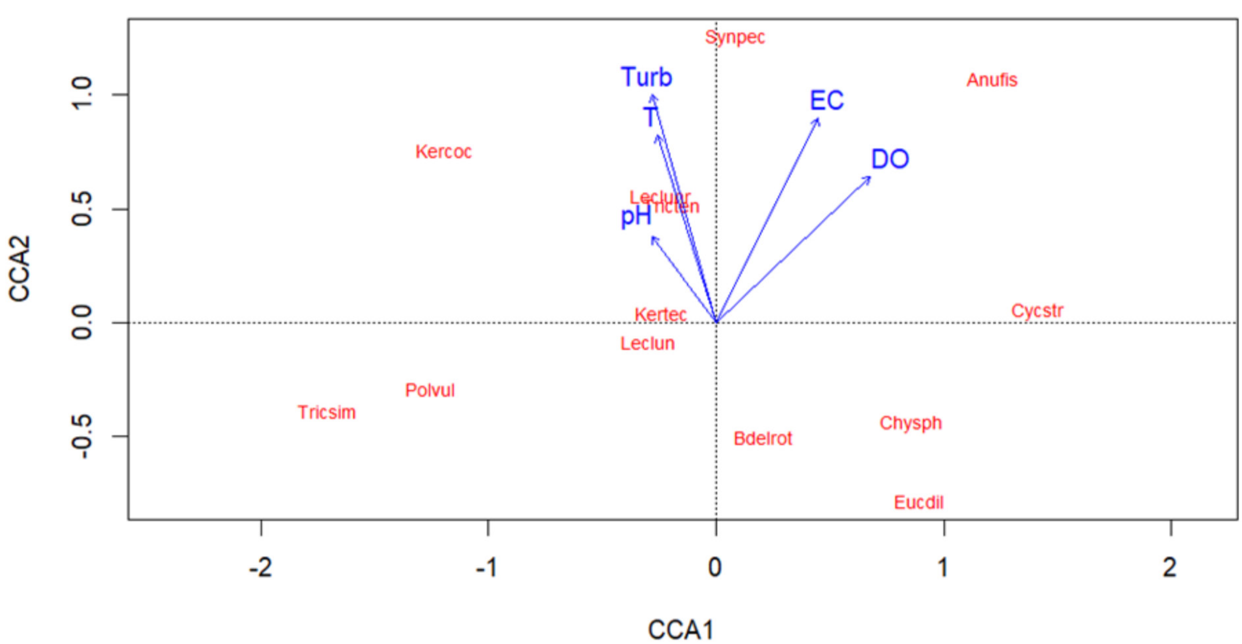

Figure 2. Displaying the relationship between species and environmental variables on a CCA2 graphic.

and intensity of rainfall (IPCC 2022). Change in rainfall patterns and increase in temperatures can maintain the accumulation of terrestrial dissolved organic carbon (tDOC) in lakes and significantly impacting lake ecosystem dynamics (Gudasz et al. 2010). These climate changes, connected with antropogenic effect, deeply influence nutrient cycles in lakes (Tong et al. 2020). Rising temperatures affect the thermal structure of lakes, tDOC inputs increase nutrient availability and cause light limitation, both of which shift the dynamics within food webs (Degerman et al. 2018). Estimates suggest that heated oceans will decrease the size of marine animals due to oxygen limitations (Murthy 2022).

Primary consumers, such as zooplankton, are more homeostatic and generally more tolerant to environmental changes, such as light limitation, than lower trophic levels (Feijoó et al. 2014). However, changes in zooplankton food sources, driven by nutrient dynamics and availability, can have bottom-up solid effects (Liu et al. 2023).

Ecological stoichiometry offers a framework for exploring how the dynamics of pelagic consumers respond to nutrient-driven environmental changes and how consumer biomass is influenced by food resource quality and quantities (Sterner & Elser 2002, Calderó-Pascual et al. 2022). In particular, seston property, including the phosphorus (P) and carbon (C) to phosphorus ratio, plays a significant role in assigned zooplankton biomass and community composition (Urabe et al. 2002). Studies on biodiversity and ecosystem functioning have focused on taxonomic composition (Cardinale et al. 2012). However, recent research has focused on the importance of functional property for ecosystem processes (Pinheiro-Silva et al. 2020). According to that zooplankton body size has emerged as a key functional property linking community structure to ecosystem processes, mainly in energy transfer from lower trophic levels (Litchman et al. 2013, Cadotte 2017).

Empirical evidence suggests that global warming can change zooplankton community structure, supporting smaller-bodied organisms such as rotifers over larger cladocerans (Hart & Bychek 2011, Havens et al. 2015, Zohary et al. 2021). This trend emerges from lower metabolic demands and reduced size-associated costs, offering a competitive advantage in warmer conditions (Hart & Bychek 2011, Havens et al. 2015). Additionally, warming promotes the growth and dominance of cyanobacteria, which tend to be of lower nutritional value and less appealing to zooplankton (Jöhnk et al. 2008) potentially leading to dominance by smaller, selective zooplankton grazers such as *Chydorus*, rotifers, and copepods (Ersoy et al. 2019, Josué et al. 2019, Pinheiro-Silva et al. 2020).

Climate change increases the predation on larger zooplankton by planktivorous fish (Jeppesen et al. 2012). Since the body size of zooplankton is a strong indicator of top-down control on both zooplankton and phytoplankton (Jeppesen et al. 2003, Ye et al. 2013, Gianuca et al. 2016), understanding shifts in size structure can provide valuable insights into changing predator-prey relationships.

This study observed a clear reduction in zooplankton body size as a distinct impact of global warming on zooplankton community structure. This shift was marked by the dominance of small-sized, stress-tolerant species, including rotifers, small-bodied cladocerans like *Alona*, *Bosmina*, and *Chydorus*, and cyclopoid and harpacticoid copepods. The abundance of larger-bodied bdelloid rotifers within the Rotifera group is based on their cryptobiotic characteristics, which tolerate high temperatures. Climatic change generally supports smaller zooplankton species such as rotifers, contributing to reduced zooplankton body size (Zohary et al. 2021).

Previous studies have found that global warming and tDOC can have variable effects on zooplankton (e.g., Nicolle et al. 2012, Hébert et al. 2023, Koizumi et al. 2023). Additionally, the result of this study showed that zooplankton community structure tends to be relatively smaller organisms (Zohary et al. 2021). We suggested that global warming and tDOC negatively impact zooplankton biomass, resource use efficiency, and average body size, likely due to a bottom-up effect initiated by increased microbial activity. These results emphasized multiple synergistic impacts of multiple stressors on lake ecosystems (Yıldız et al. 2022).

Canonical Correspondence Analysis (CCA) was carried out using Multivariate Statistics (Figure 3) to explaine the relationships between environmental factors and zooplankton species. Before the analysis, a correlation analysis was performed using Past 4.0, which showed a high correlation between salinity and EC (electrical conductivity). To avoid issues of multicollinearity, analyses were conducted based on EC. VIF (Variance Inflation Factor) values were calculated to assess the multicollinearity among independent variables. VIF values below 5 indicate that multicollinearity is within acceptable limits. In the CCA analyses, the VIF values of environmental variables were all below 5.

The Canonical Correspondence Analysis (CCA) resulted in eigenvalues for three axes of 0.4582, 0.2832, and 0.2608, respectively, with a cumulative variance explanation rate of 88%, meaning that these three components represent most of the data variation. According to the CCA results, on the CCA 2 axis, EC, temperature, and turbidity showed the most statistically significant positive relationships with *Anureopsis fissa* and *Synhaeta pectinata*. A positive effect of these three environmental variables was also observed on *Keratella cochlearis*. Conversely, *Euchlanis dilatata*, bdelloid rotifers, and *Chydorus sphaericus* negatively correlated with EC, temperature, and turbidity on the CCA 2 axis.

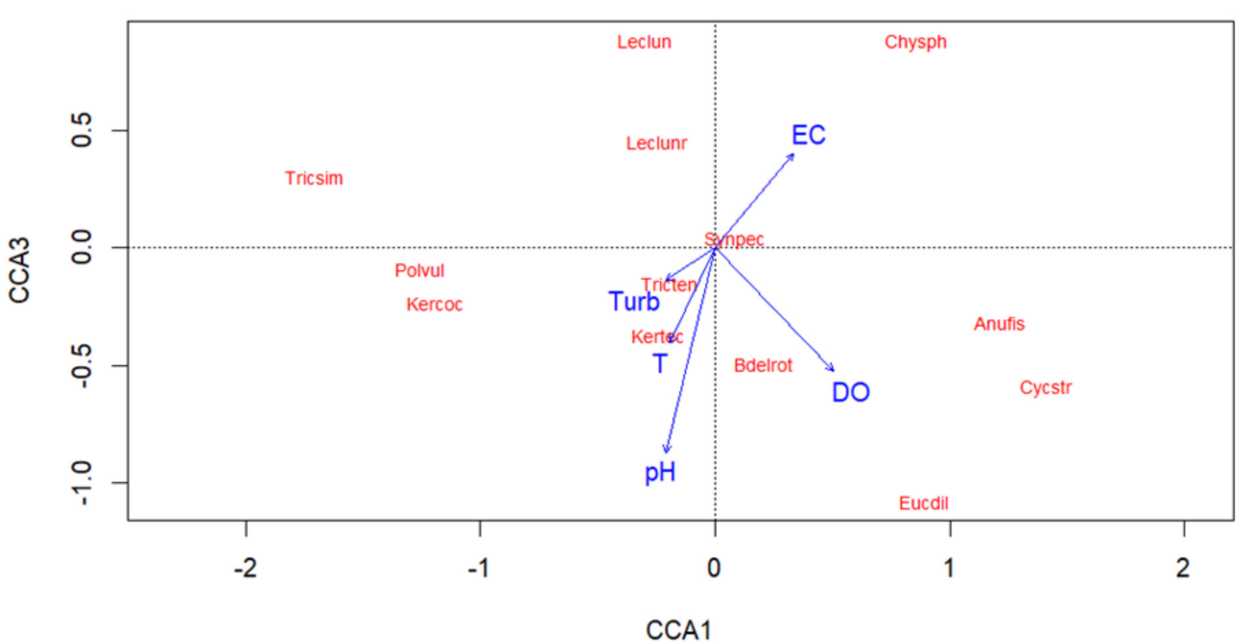

Figure 3. Demonstrating the relationship between species and environmental variables on a CCA3 graphic.

On the CCA 1 axis, dissolved oxygen (DO) showed a positive relationship with Cyclops strenuus, while its effect on *Keratella cochlearis*, *Polyarthra vulgaris*, and *Trichocerca similis* was negative.

While pH and DO positively affected the species *Euchlanis dilatata* and *Cyclops strenuus* on CCA 3 (Figure 3), they negatively impacted *Lecane luna* and *Chydorus sphaericus*.

The canonical correlation analysis has explained the effects of environmental variables on species. These variables, such as pH, electrical conductivity (EC), temperature (T), dissolved oxygen (DO), and turbidity (Turb) showed positive and negative impacts on species. For example, EC, T, and Turb had notably strong effects on *Anureopsis fissa* and *Synchaeta pectinata*. In contrast, *Euchlanis dilatata* and *Cyclops strenuus* displayed distribution patterns dependent on pH and DO levels. Increases in these two variables exerted a suppressive effect on species such as *Keratella cochlearis*, *Polyarthra vulgaris*, and *Trichocerca similis*.

The Cluster analysis (Figure 4) performed to observe the similarities in species diversity between locations within the study area, indicated a strong resemblance between C80 and C85.

However, the species in C80 were significantly different from those in C20 and C46. Additionally, the species in C68 and C67 showed a closer similarity, though not as pronounced as the similarity between those in C20 and C46. Thewidth of the gray zone indicates species diversity, indicating that differences observed among species within this gray zone are greater compared to other groups.

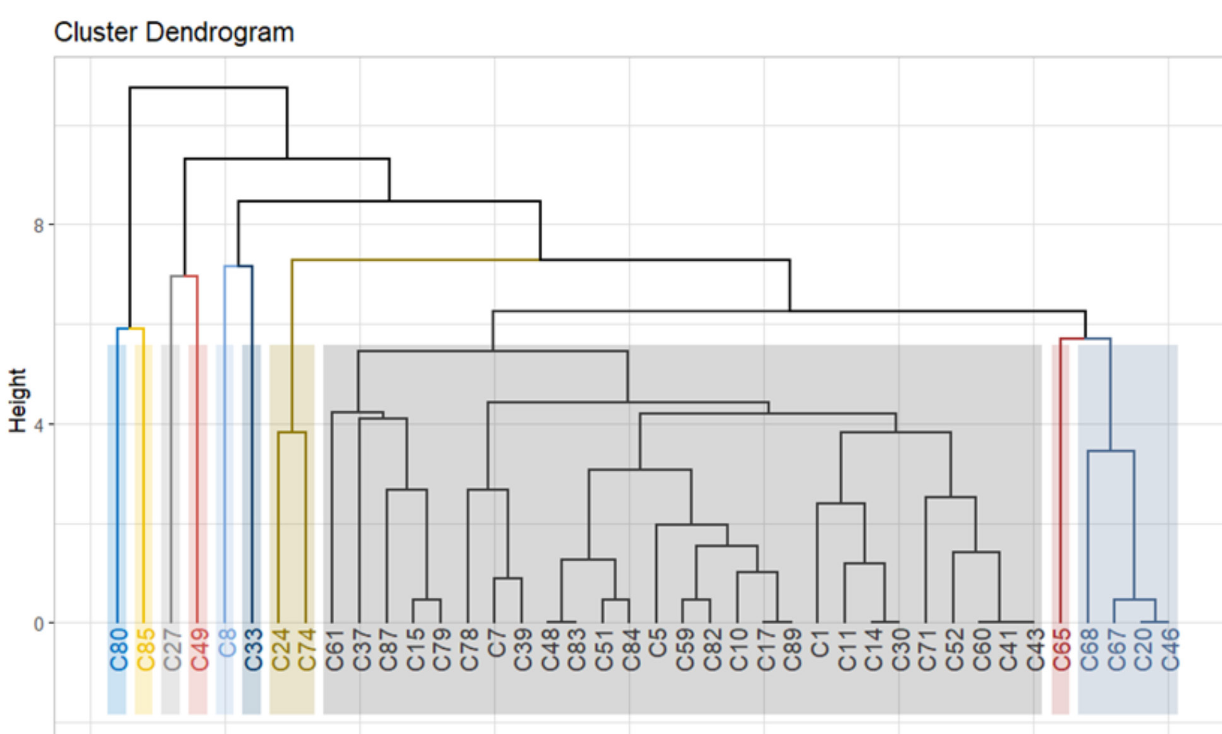

Figure 4. The cluster analysis dendrogram consists of 40 localities from Çanakkale province and species diversity between locations within the study area.

CONCLUSIONS

Zooplankton can respond very rapidly to environmental changes (Başak et al. 2014). In this study, it has been clearly observed that global warming has altered the zooplankton community structure, leading to a reduction in body size. Consequently, global warming may support zooplankton species such as rotifers, which are known as opportunistic species in extreme conditions. This trend could lead to further reduce the overall body size of the zooplankton communites. The study clearly noted high diversity of Rotifera species and the presence of rotifers, which is influenced by the complex interaction of various physicochemical, geographical, biological, and ecological parameters. The rotifer fauna in freshwater ecosystems is essential for maintaining aquatic ecological balance and can serve as a valuable bioindicator of ecological health and trophic levels. As a result, examining physicochemical parameters can help in understanding the trophic dynamics of the freshwater bodies (Vanjare & Pai 2013).

Most of the zooplankton species identified in this study are benthic and cosmopolitan, commonly inhabiting the littoral zones of water bodies, and are species found in Turkey's freshwater bodies. According to CCA, the study identified temperature, dissolved oxygen, EC, salinity, pH, and turbidity as influential factors in zooplankton presence. Blancher (1984) reported that cyclopoid copepods are more abundant than calanoid copepods in eutrophic lakes (İpek-Alış & Saler 2016). According to Sousa et al. (2008), high electrical conductivity values are generally associated with higher trophic levels and significantly explain the relationship between zooplankton species composition and environmental variables.

Zooplankton species can tolerate low oxygen concentrations and use different oxygen levels as a defense against predation (Horpila et al. 2000). Low oxygen concentration has minimal effect on zooplankton (Yang et al. 2012). This study shows that increased water temperatures from global warming favor smaller zooplankton, such as rotifers, leading to a decrease in the community's size structure.

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