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Temporal variation in zooplankton and phytoplankton community species composition and the affecting factors in Lake Taihu—a large freshwater lake in China☆

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A B S T R A C T

Monitoring diverse components of aquatic ecosystems is vital for elucidation of diversity dynamics and processes, which alter freshwater ecosystems, but such studies are seldom conducted. Phytoplankton and zooplankton are integral components which play indispensable parts in the structure and ecological service function of water bodies. However, few studies were made on how zooplankton and phytoplankton community may respond simultaneously to change of circumstance and their mutual relationship. Therefore, we researched synchronously the phytoplankton communities as well as zooplankton communities based on monthly monitoring data from September 2011 to August 2012 in heavily polluted areas and researched their responses to variation in environmental parameters and their mutual relationship. As indicated by Time-lag analysis (TLA), the long-term dynamics of phytoplankton and zooplankton were undergoing directional variations, what's more, there exists significant seasonal variations of phytoplankton and zooplankton communities as indicated by Non-Metric Multidimensional scaling (NMDS) methods. Also, Redundancy Analysis (RDA) demonstrated that environmental indicators together accounted for 25.6% and 50.1% variance of phytoplankton and zooplankton, respectively, indicating that environmental variations affected significantly on the temporal dynamics of phytoplankton as well as zooplankton communities. What's more, variance partioning suggested that the major environmental factors influencing variation structures of zooplankton communities were water temperature, concentration of nitrogen, revealing the dominating driving mechanism which shaped the communities of zooplankton. It was also found that there was significant synchronization between zooplankton biomass and phytoplankton biomass (expressed as Chl-a concentration), which suggested that zooplankton respond to changes in dynamic structure of phytoplankton community and can initiate a decrease in phytoplankton biomass through grazing in a few months.

1. Introduction

Freshwater ecosystems supply humans with a good deal of ecosystem services such as drinking water, sources of aquatic products and venues for entertainment (Strayer and Dudgeon, 2010). However, in the past few decades, changes in natural flow regimes, over exploitation of natural water resources, contamination, habitat degradation and invasion by alien species induced by anthropogenic activities that have put these natural environments at risk and affected biodiversity (Dudgeon et al., 2006; Shakira S.E., 2015). In order to protect and conserve freshwater environments, the essential difficulty is to comprehend impacts of diverse stressors on taxonomic diversity that provides key information with regard to temporal changes in diversity and mechanisms which alter ecosystems, especially under intense anthropogenic pressures (Altshuler et al., 2011). Phytoplankton and zooplankton communities occupy important position in freshwater ecosystems

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(Natalie et al., 2016) and both of them play indispensable parts in keeping biological balance of water environments.

Comprehending processes and mechanisms which impact variations in densities as well as biomasses of zooplankton and phytoplankton have great sense for keeping ecosystems in balance (Paerl et al., 2003). Phytoplankton supply the herbivore with oxygen and nutrients (Sun et al., 2017), whereas zooplankton play an important part in transforming energy from lower trophic organisms to higher ones, regulate phytoplankton growth, shape pelagic ecosystems (Shayestehfar et al., 2010). Results of previous research of zooplankton have payed attention to effect of climate change (George and Harris, 1985; Benjamin A et al., 2013), land utilization (Foley et al., 2005), and variation in physicochemical changes of aquatic ecosystems separately (Dudgeon et al., 2006). However, combined effects of nutrients along with climate change have seldom been researched. Many previous studies have evaluated temporal patterns of either phytoplankton (Sommer et al., 1986) or zooplankton separately (Natalie et al., 2016; Haberman et al., 2017), there are rare studies on synchronous phytoplankton and zooplankton especially in shallow, eutrophic Lake Taihu. Most studies evaluating temporal diversity dynamics of plankton have adopted multiple statistic techniques to investigate the patterns. Rare researches have reported discrepancies between feedbacks of both vital communities towards environmental change. Researchers have used Time Lag Analysis to make a quantitative analysis on temporal change of populations, containing chaotic change, directional trend, as well as periodic developments (Collins et al., 2000). Even though it is impossible to get direct inferences about cause—effect relationships only by environmental monitoring, understanding of complex dynamic patterns will be of great help to investigate the ecological relationships and further understand the processes and mechanisms occurring in water bodies.

The significance of plankton for freshwater ecosystems and eventually for the earth itself is highly admitted. There are complicated and vital mutual interactions between phytoplankton and zooplankton in freshwater ecosystems. Previous studies evaluated toxin-producing phytoplankton (TPP) on temporal change of phytoplankton and zooplankton using mathematical models and harmful cyanobacteria blooms were defined as an essential biological interference to the large, filter-feeding *Cladocerans* of zooplankton communities (Carmichael, 1989; Watanabe et al., 1992; Anas and Bernadette, 1998), however, rare studies have been made to concurrently quantify the temporal dynamics of both communities in this lake. Synchronous research of both communities are of great significance in helping us understand the mechanisms of the biological freshwater ecosystems. The species composition of zooplankton and predation pressure on the primary producer can impact the whole ecosystem. What's more, concurrently quantify the temporal dynamics of both communities can reveal how the dynamic change of phytoplankton can affect the growth of zooplankton and development of biological communities.

Variation in environmental indicators can affect differently on phytoplankton and zooplankton in water bodies. By and large, phytoplankton are primarily controlled by temperature, sunshine hours, nutritive salts (Davis et al., 2015), water level and predation intensity (Silva et al., 2014). Previous research revealed that N and P are the basic nutrients that limited growth of phytoplankton in lakes (Xu et al., 2015; Yang et al., 2016, 2017a,b). Zooplankton is composed of various organism communities which lack the ability to conquer water flow resistance (Hutchinson, 1967), as a result, it can be utilized as a model to fully comprehend the temporal diverse temporal dynamics. Based on the studies of biodiversity of zooplankton, previous research have found that anthropogenic activities have negative effect on these groups, which can result in a reduction in biological diversity and even extinction of partial species (Segers, 2008; Bonecker et al., 2013). More and more apparently, environmental parameters include both biological and abiotic indicators and interspecific interactions can modify diversities of phytoplankton or zooplankton communities. Nevertheless, which parameters make the most contribution to the changes of phytoplankton and zooplankton are in urgent need of additional research. Analyzing simultaneously temporal changes of both communities and the responses to environmental variations are surely to be crucial for deeper understanding the function of ecosystem and eventually guide for recovery and management of lakes (Xu et al., 2015).

In this research, water environment indicators, phytoplankton and zooplankton abundance data at five sampling stations in Lake Taihu were collected from September 2011 to August 2012 on the "National Ecosystem Research Network of China" (CNERN). Environmental parameters monitored included lake water temperature (LWT), sulfate (SO_4^{2-}), total nitrogen (TN), pH, dissolved oxygen (DO), suspended solids (SS), chemical oxygen demand (COD), transparency (SD), conductivity, 5-day biochemical oxygen demand (BOD_5), dissolved total organic carbon (DTOC), *Chlorophyll-a* (Chl-a), ammonia nitrogen ($NH4^+$-N), nitrate (NO_3^--N), silicate (SiO_3^{2-}), total phosphorus (TP), phosphate (PO_4^{3-}-P), trophic state index (TSI), and nitrite (NO_2^--N). The northern areas of Lake Taihu were selected. The aims of this research were as follows: (1) determine temporal changes of phytoplankton and zooplankton during the period of September 2011 to August 2012 in areas where cyanobacterial blooms occurred frequently in Lake Taihu; and (2) account for various responses of both communities to the temporal dynamic environmental indicators, containing their mutual relationship as well as their roles in affecting the phytoplankton community change, also zooplankton community dynamics, in order to contribute to restoration and protection of water environment.

2. Data collection and analysis

2.1. Study area

Lake Taihu ranks the third place in freshwater lakes of China (Li et al., 1994), which is situated near the Yangtze River Delta (S.I. 1). Its area is 2427.8 km^2, but the water area is 2338.1 km^2. The lake shoreline of Lake Taihu is 393.2 km (Qin et al., 2010). The annual water inflow is about 7.6 km^3 (Qin et al., 2007). Lake Taihu locates in the subtropical zone. The average annual temperature and precipitation are between 16.0 and 18.0 °C, 1100–1150 mm, respectively. Lake Taihu supplies humans with vital ecosystem services like agricultural grain production, flood control, fish resources, tourist tour, shipping, etc. What's more, Lake Taihu also acts as a repository for a large quantity of industrial and domestic sewage discharge from the nearby cities, villages as well as industries due to the rapid economic development (Qin et al., 2010).

In this research, phytoplankton and zooplankton abundance data as well as 18 environmental indicators were collected at five sampling stations, which mostly situated in the cyanobacteria-dominated areas of Lake Taihu (S.I.1). Meiliang Bay (ML) is among the most contaminated areas of Lake Taihu and serves as the primary potable water sources for Wuxi city. Lake Center (LC) is lighter polluted than the other sampling stations as a result of diffusion and advective transport. Dapu Kou (DP) lies in the western areas of Lake Taihu. Zhushan Bay (ZS) where algal blooms occur frequently locates in the northwestern part of Lake Taihu. Gonghu Bay (GH) lies in the northeast of Lake Taihu, which is also an essential potable water source for the adjacent cities.

2.2. Data acquisition

Water environment indicators, phytoplankton and zooplankton densities at five sampling stations in Lake Taihu from September 2011 to August 2012 (S.I. 1) were gathered on the “National Ecosystem Research Network of China” (CNERN) (http://cerndis1.cern.ac.cn/data/initDRsearch) (Yu et al., 2013). Water samples were collected half a metre deep in Lake Taihu and each data in one sampling station is the average of multiple sample points. Water quality indicators measured include LWT, pH, DO, COD, BOD_5, NH4+−N, TP, TN, conductivity, transparency and Chl-*a*, DTOC, PO_4^{3}-P, NO_3^--N, NO_2^--N, SO_4^{2-}, SS, SiO_3^{2-}, TSI.

The comprehensive TSI was counted in the light of classical Carlson TSI on the basis of five environmental indicators, they are Chl-a, transparency, TP, TN and COD (Carlson, 1977). Oligotrophic ($0 < TSIc \leq 30$), oligo-mesotrophic ($30 < TSIc \leq 40$), mesotrophic ($40 < TSIc \leq 50$), lighteutrophic ($50 < TSIc \leq 60$), middleeutrophic ($60 < TSIc \leq 70$), and highlyeutrophic ($70 < TSIc \leq 100$), respectively. The computational formula for TSIc is as follows:

$$TLI\ (Chla) = 10(2.5 + 1.086\ln(Chla))$$

$$TLI\ (TP) = 10(9.436 + 1.624\ln(TP))$$

$$TLI\ (TN) = 10(5.453 + 1.694\ln(TN))$$

$$TLI\ (SD) = 10(5.118 - 1.94\ln(SD))$$

$$TLI\ (CODMn) = 10(0.109 + 2.661\ln(COD_{Mn})$$

The unit of Chl-a and SD are mg/m^3, m respectively, the others are mg/L. The computational formula for the comprehensive TSI is as follows:

$$TLI(\sum) = \sum Wj \cdot TLI(j)$$

$TLI(\sum)$ is the comprehensive TSI; Wj is the weight of the nutritional status index of the jth parameter; TLI(j) represents the nutritional status index of the jth parameter.

2.3. Data processing and analysis

Discrepancies in environmental indicators amongst the five sampling stations were compared by use of the Kruskal-Wallis nonparametric test. We adopted the non-metric multidimensional scaling (NMDS) ordination method to research discrepancies of biocoenosis between sample stations according to Bray-Curtis dissimilarity utilizing normalized and square-root conversion data in R software. After that, Adonis function in R software was implemented to test statistically whether differences in values of parameters among four seasons or five sampling stations were significant or not. Procrustes tests (PROTEST) were implemented to check out whether variation of phytoplankton and zooplankton communities are synchronous. To uncover temporal variations of environmental variables and biological communities, we used time lag analysis to explore the linear regressions on Bray-Curtis dissimilarity of biocoenosis (dependent variables) relative to the square root of the time lags (independent variables) and the Euclidean distance of 18 environmental indicators (dependent variables) with regard to the square root of the time lags (independent variables) (Liu et al., 2015; Collis et al., 2000).

This research applied the Monte Carlo permutation tests to select the water quality indicators which could significantly explain ($p < 0.05$) the variation of the phytoplankton and zooplankton communities. We eliminate all explanatory variables whose inflation factors (VIFs) are more than 20 in order to avoid collinearity amongst environmental indicators. Then Redundancy analysis (RDA) was used to identity the physicochemical parameters which significantly impact the spatio-temporal dynamics of both important biological communities. We transformed the phytoplankton and zooplankton data into log10(x+1) format before the forward-selection process. What's more, all water quality indicators were also $\log_{10}(x+1)$ transformed in addition to pH. In this study, we used CANOCO 4.5 (Microcomputer Power, USA),R-language software and Microsoft Excel 16.0 to implement data processing and analysis.

3. Results

3.1. Temporal variation of water quality indicators

Long-term trends of physicochemical and biological variables in Lake Taihu from September 2011 to August 2012 are shown in S.I. 2. Water temperature was lowest in February and highest in August. pH was more than 8.0 during the study period with the exception of May in 2012 and reached the highest value in July at the five stations ranging from 8.66 to 8.92. DO increased dramatically from September 2011 to March 2012, after that it decreased significantly until June. Conductivity rised substantially during February to May at the five sampling stations followed by a decreased tendency from May to August. Mean nutrient concentrations, including total nitrogen, nitrite, ammonia nitrogen, total phosphorous, and phosphate in Zhushan Bay as well as Dapu Kou were evidently greater compared with that of the remaining sampling sites ($p < 0.01$). The least concentrations of TN and TP were both recorded in Gonghu Bay, while the greatest concentration was observed in Dapu Kou, which was more than twice the concentrations in Gonghu Bay. From October to March, concentrations of Chl-a didn't vary much, however, it increased markedly at Dapu Kou and ZhuShan Bay since March and from June to August at the other three stations. DTOC increased from October to February followed by a decrease from March to August at the five sampling stations. The greatest value of TSI was at Dapu Kou, which was significantly greater than that at other stations. From September to January, TSI decreased, since then it increased dramatically and peaked in July to August. Environmental indicators SiO_3^{2-}, SO_4^{2-}, COD and BOD showed a synchronous change tendency at five sampling stations.

3.2. Temporal variation in phytoplankton community composition

Consequences of this research showed that *Cyanophyta* dominated the phytoplankton community from September 2011 to December 2012 and May to August 2012 (Fig. 1), explaining over 96% of the whole phytoplankton abundance on the basis of cell density. From January to April, the relative abundance of *Cyanophyta* decreased gradually, then reached its lowest value (42.7%) in April. Meantime, *Chlorophyta*, *Bacillariophyta, Cryptophyta, Chrysophyta* increased in abundance. From January to April, *Chlorophyta* increased from 6.2% to 31.5%. The relative abundance of *Bacillariophyta* was remarkably larger from January to April compared to other months, accounting for 12.0%, 10.0%, 17.9% and 8.9% of total abundance, respectively. *Cryptophyta* was relatively abundant in April and reached 16.2%. The relative abundance of *Chrysophyta* was 5.4%, 6.5%, 3.4% while it was below the detection limit in other months. Additionally, *Euglenophyta* and *Pyrrophyta* explained less than 5% of the total phytoplankton abundance. The total phytoplankton abundance presented a significant seasonal shift. In September 2011, it reached the greatest value of 5.6×10^8 cells/L, but otherwise remained less than this value throughout the year (S.I.2). From October 2011 to May 2012, total phytoplankton cell

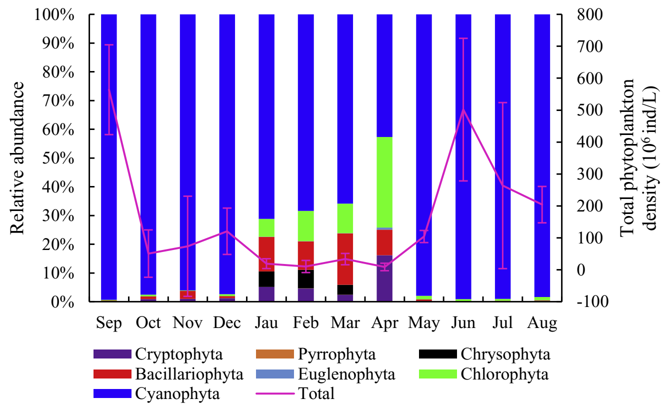

Fig. 1. Seasonal dynamics of various phytoplankton community composition and total phytoplankton cell density from September 2011 to August 2012. (Data are average of five sampling sites and deviation).

density didn't vary much. Afterwards, it increased again from May to August and reached the highest value of 5.0×10^8 cells/L in June.

3.3. Temporal variation in zooplankton community composition

Protozoa dominated the zooplankton community from September 2011 to June 2012 and then in August 2012, when, based on cell density, it explained over 98.4% of the total zooplankton abundance (Fig. 2). From May to July, the relative abundance of *Copepoda, Cladocera* and *Rotifera* increased significantly and peaked in July 2012 at 0.36%, 0.57% and 0.33%, respectively. Total density of zooplankton peaked in December 2011 and April 2012 with the value of 1571 ind/L and 1613 ind/L. Whereas the relative abundance of zooplankton biomass exhibited a more complex change compared to abundance data (Fig. 3). From September to January 2012, *Protozoa* increased from 5.3% to 78.6%, followed by a decreasing trend from February to July 2012. The relative abundance of *Rotifera* was significantly greater from November 2011 to March 2012 compared to other months, accounting for 20.6%, 17.4%, 21%, 21.5% and 21.6% of total biomass, respectively. *Cladocera* peaked in September 2011 at 69.1% of the total zooplankton biomass. Afterwards, it decreased rapidly until December when it reached a total proportion of 17.6%. From January to March, *Cladocera* was less than 1.0% and again reached 59.3% and 59.0% in April and July 2012. *Copepoda* decreased during October to December 2011 and again increased significantly during March to August. Total zooplankton biomass exhibited distinct seasonal

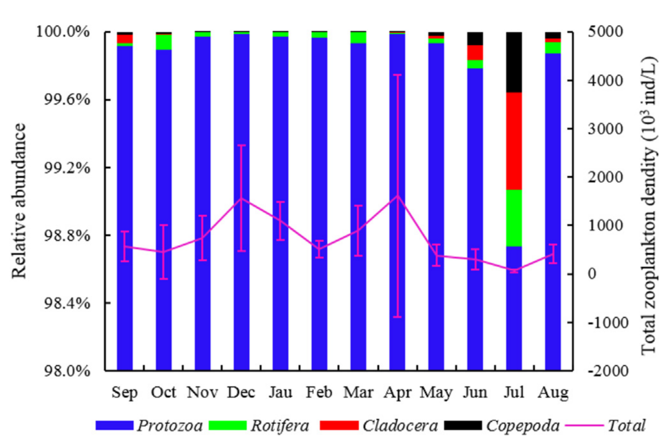

Fig. 2. Seasonal dynamics of various zooplankton community composition and total phytoplankton cell density from September 2011 to August 2012. (Data are average of five sampling sites and deviation).

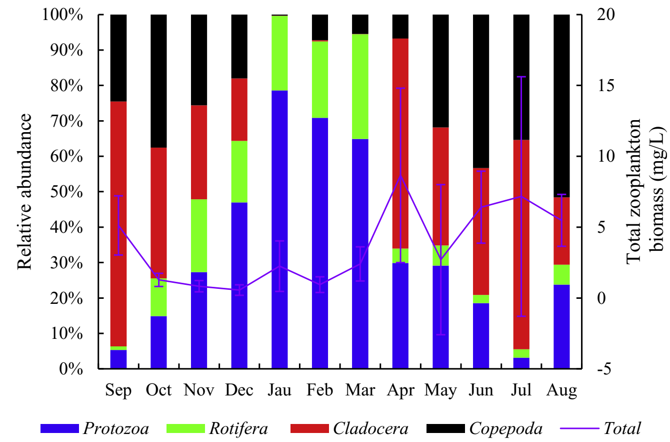

Fig. 3. Seasonal dynamics of various zooplankton community composition and total phytoplankton cell density from September 2011 to August 2012. (Data are average of five sampling sites and deviation).

variation. It decreased from September to October 2011. Afterwards, there wasn't much variation from October to March, followed by an increasing trend from March to April as well as May to August. What's more, zooplankton biomass in every monitoring station from September 2011 to August 2012 tends to show a similar tendency which decrease from September to January and increase from March to August. The same is true with the Cladocera community (Fig. 7).

3.4. Quantitative dynamic changes in communities and environmental parameters

From NMDS plots (Fig. 4), it was observed that phytoplankton density exhibited significant seasonal shifts at the phylum level. Zooplankton density also had a remarkable seasonal shift at the phylum level, however, as indicated by the NMDS plots, there was not much variation in Spring and Autumn. Analysis of similarities (ANOSIM) results further verified distinct discrepancies both in the phytoplankton and zooplankton communities amongst the four seasons ($p < 0.05$) and insignificant discrepancies ($p > 0.05$) of phytoplankton and zooplankton amongst the five studied stations. Last but not least, both the phytoplankton and zooplankton taxa behave synchronously to some extent at the phylum level when facing environmental changes. These results were verified statistically by use of Procrustes tests (protest test) ($r = 0.55$, $p = 0.006$).

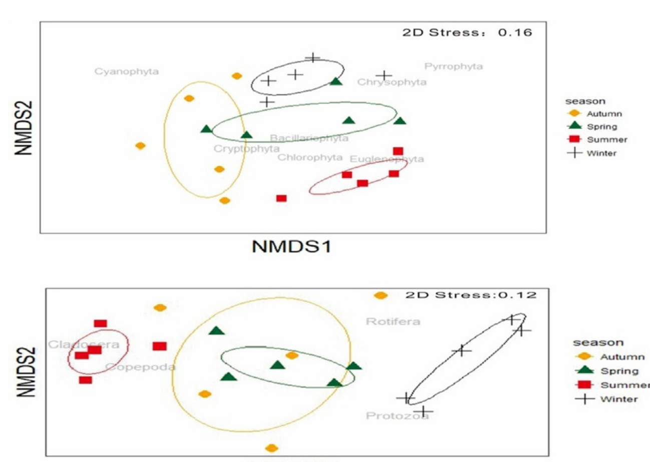

Fig. 4. NMDS ordination plot of abundant phytoplankton and abundant zooplankton. Each group contains the abundance data of five sampling stations.

Results of the Time Lag Analysis regression with both biological communities showed a remarkable positive slope, which indicated that these communities were experiencing a directional variation (Fig. 5). So were the environmental indicators, suggesting environmental parameters were also experiencing a change in direction.

3.5. Relationships between biocenoses and environmental indicators

At the phylum level, environmental parameters explained 25.6% of the variance in phytoplankton and 50.1% variance of zooplankton, which can be seen from results of redundancy analysis (RDA). Relative contributions of significant environmental parameters ($p < 0.05$) to variations of phytoplankton as well as zooplankton were studied, either. (Table 1). In terms of the phytoplankton, WT accounted for the maximum variance (6.0%, $p = 0.002$),then NO_3^--N (3.6%, $p = 0.002$), BOD (2.9%, $p = 0.004$%) and DTOC (2.1%, $p = 0.026$). The whole contributions of both indicators were calculated as much as 67.0% (Table 1). With respect to zooplankton at the phylum level, water temperature accounted for the maximum variance (31.6%, $p = 0.002$), then ammonia nitrogen (3.5%, $p = 0.008$) and phosphate (2.4%, $p = 0.018$).

4. Discussion

4.1. Effect of the environmental factors on temporal changes of phytoplankton

This research discovered that the composition of phytoplankton community in Lake Taihu had significant seasonal changes at five sampling stations,besides, *Cyanophyta* dominated the most of the phytoplankton community discovered in the cyanobacteria-dominated areas of Lake Taihu. Seasonal succession of phytoplankton has been observed in many studies (Pilkaityte and Razinkovas, 2007). For example, physical indicators, limited nutrients, predator pressure, overwintering as well as symbiosis all contribute to temporal variation of phytoplankton community.

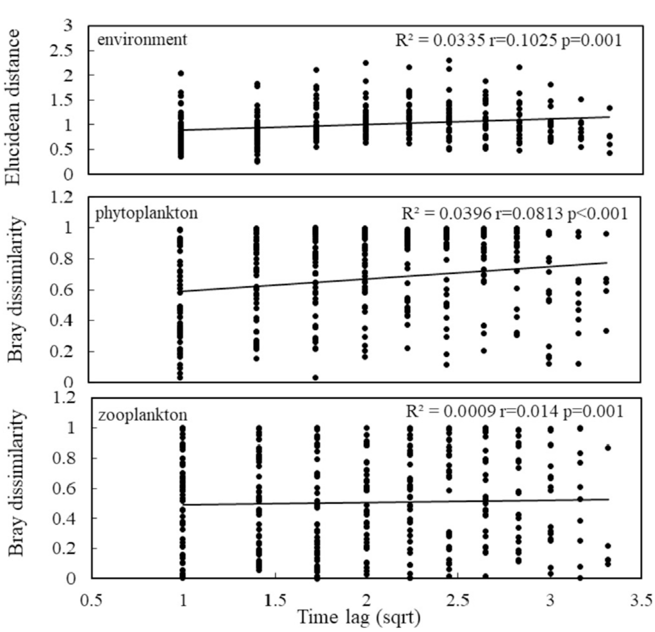

Fig. 5. Results of time lag regression analysis of temporal dynamics of environmental parameters, phytoplankton community species and zooplankton community species.

Table 1
Significant environmental variables identified with RDA results ($p < 0.05$, n = 60).

Communities	Indicators	Explains	Contribution	p
phytoplankton (25.6%)	WT	6.00%	23.80%	0.002
	NO_3^- −N	3.60%	14.00%	0.002
	BOD	2.90%	11.00%	0.004
	DTOC	2.10%	8.20%	0.026
zooplankton (50.1%)	WT	31.56%	63.00%	0.002
	NH4+−N	3.50%	7.02%	0.008
	$P_iO_4^{3-}$-P	2.40%	4.80%	0.018

However, results of this research indicated that water temperature, NO_3^--N, BOD, DTOC occupied the most significant indicators in affecting structures of phytoplankton communities. As the environmental conditions varied, the dynamic variation of phytoplankton tended to display a directional change. Several reasonable explanations may account for this result. First, *Cyanophyta* tended to dominate under higher temperatures owing to its higher optimum growth temperature (Kosten et al., 2012), so when temperature decreased to a lower level from January to April 2012, the abundance of *Cyanophyta* decreased dramatically and *Bacillariophyta*, *Chlorophyta*, *Chrysophyta* and *Cryptophyta* began to dominate. Additionally, higher water temperatures can make surface water viscosity decrease, which can accelerate the sinking of bigger, immovable species, this, combined with their capability of adjusting buoyancy, causes *Cyanophyta* to dominate in the communities (O'Neil et al., 2012). Besides, through an allelopathic mechanism, *Cyanobacteria* might be able to lessen biomasses of other phytoplankton species (Sarma et al., 2005), which might account for its advantages in freshwater ecosystems. Another possible explanation for *Cyanophyta* dominance is owing to its significantly negative relationship with NO_3^--N (Fig. 6), with the decrease of NO_3^--N and increase of TP from May to July 2012, TN:TP mass ratios were relatively low during this period, abundances of nitrogen-fixing *Cyanophyta* may increase dramatically. Last, from the RDA results, it can see that, except for *Cyanophyta*, other phytoplankton communities all have a positive relationship with DTOC. Among them, *Bacillariophyta*, *Pyrrophyta*, *Euglenophyta* and *Chlorophyta* were positively associated with BOD. This might suggest that death and decomposition of blooming alga might play an essential part in increasing dissolved organic matter in Lake Taihu and this changed the physical-chemical properties of Lake Taihu in reverse. Alternatively, the continuous temporal variation in water environment can further affect the succession of phytoplankton communities.

4.2. Effect of the environmental factors on temporal changes of zooplankton

This research also investigated temporal patterns of the zooplankton community densities at the phylum level in order to

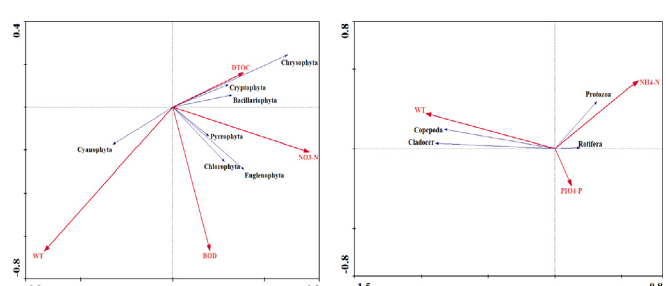

Fig. 6. Redundancy Analysis of phytoplankton and zooplankton communities and their relation to water quality parameters. (The vectors represent the most correlating water quality parameters ($p < 0.05$).

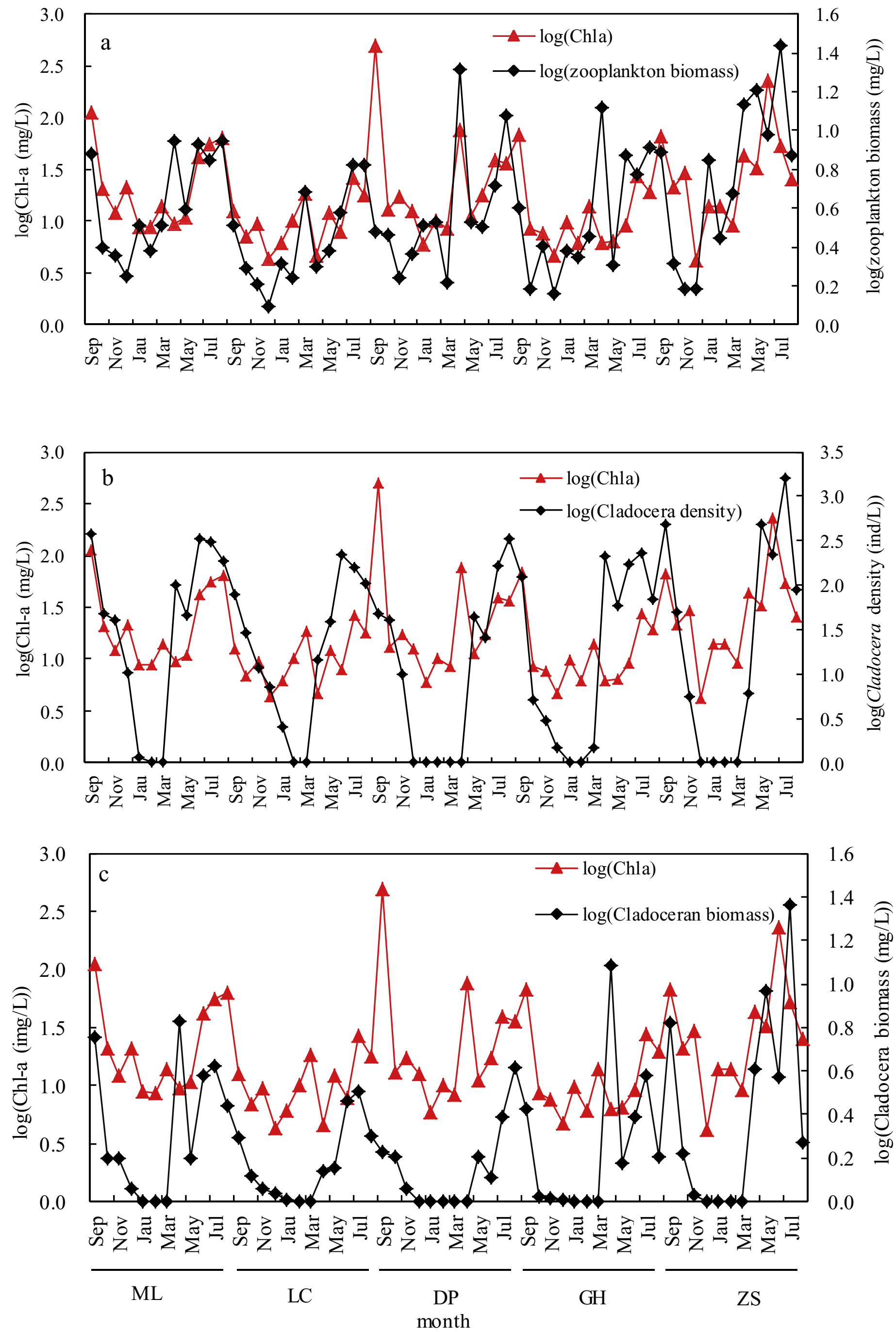

Fig. 7. Synchronous variation of log Chl-*a* and (a) log zooplankton biomass (b) log *cladoceran* density (c) log *cladoceran* biomass.

reveal their reactions to environmental changes in Lake Taihu. A lot of overlap was observed in 50.0% ellipses and centroids (Fig. 4), which suggests that Spring and Autumn groups are not that different. However, when compared with Summer and Winter, significant variation was observed among these seasons. Also, zooplankton communities were undergoing a directional change, which indicated that they were unstable. Some explanations are as follows. On the one hand, water temperature is an extremely important environmental factor that affects growth, development, community composition, quantity change and the horizontal distribution of zooplankton (Sarma et al., 2005). *Prozoa* dominated more than 90.0% of total zooplankton, which is positively related with $NH4^{+}$–N, PO_4^{3-}-P and negatively related with water temperature. As surface-water temperature increases and nutrient decreases from May to July 2012, *Prozoa* decreased dramatically. Furthermore, *Cladocera* and *Copedoda* species positively related with water temperature and negatively related with $NH4^{+}$–N, PO_4^{3-}-P. The appearance of *Cladocera* and *Copedoda* species in this period are related to high temperature and decreased concentrations of nutrients. Alternatively, the community of zooplankton might be influenced by variations in the phytoplankton community. According to Sommer et al. (1986), productivity of phytoplankton accelerates in spring with increased concentrations of nutrients and increased light and benefits growth of *Cladoceran* populations. It has been reported that physicochemical factors in ecosystems do not directly change the *Cladocerans* populations structure, instead through reining in the phytoplankton growth at first and then influence the dynamics of *Cladocerans* afterwards. Moreover, dominance of *Cyanobacteria* might result in a decrease in numbers of some zooplankton, for *Cyanobacteria* pose an influence in filtration, they are hard to be digested and also for the reason of that they release toxins, leading to changes in biodiversity (Yang., 2012).

4.3. Respondence of zooplankton to variation in dynamic structures of phytoplankton community

Apart from the effect of water temperature and nutrients in variation on communities, there were other explanations that may account for the temporal dynamics of phytoplankton and zooplankton in Lake Taihu. Alternatively, zooplankton communities might react to variations in environmental indicators for their interaction with the lower trophic level communities of the food web. In this study, mean TSI values ranged from 53.69 ± 3.7 (GongHu Bay) to 69.32 ± 7.4 (Dapu Kou) in Lake Taihu (Table 2), which indicated that the stations sampled were lightly to moderately eutrophic, which might be responsible for an increase in biomass of phytoplankton. There was significant synchrony between zooplankton biomass and phytoplankton biomass (represented by Chl-a concentration) (Fig. 7). During warmer months, zooplankton biomass peaked with Chl-a reaching a maximum, while both of them decreased to the least value during colder months. Additionally, *Cladocerans* (mainly composed of *Daphnia*) made the greatest contribution to the variation of total biomass of the zooplankton when they appeared in early Summer and early Autumn (Fig. 3). Both biomass and numbers of *Cladoceran* exhibited a close relationship ($p < 0.0001$) with phytoplankton biomass (represented by Chl-a concentration). These observations suggested that the respondence of zooplankton to variations in phytoplankton composition along with structures of communities can vary along the trophic web (Anas, 1998). Alternatively, zooplankton can initiate a decrease in phytoplankton biomass through grazing and change compositions of phytoplankton communities through selective feeding that can result in accumulation of some inedible algae (Balseiro, 1977). However, in Fig. 7a, from the overall synchrony between zooplankton biomass and phytoplankton biomass, it seems that zooplankton can initiate a decrease in phytoplankton biomass through grazing in a few months, for example, in April, August to November, June to July, there exits a wane and wax relationship between them. However, these wane and wax relationships between them happens in different stations and different months in Lake Taihu, so to gain a definite conclusion of whether zooplankton can control the biomass of phytoplankton biomass in Lake Taihu, it's necessary to implement some more detailed scientific experiment to address this problem.

4.4. Temperature shaping the structure and function of phytoplankton and zooplankton community

Partial environmental parameters can have direct and indirect impact on temporal variation of phytoplankton and zooplankton in freshwaters (Hong et al., 2014). Nevertheless, little is understood about which water quality parameters contributed most to the dynamics of the phytoplankton and zooplankton communities. Results of this research revealed that water temperature accounted for the most variance of phytoplankton communities. As indicated in previous studies, temperature is an essential indicator affecting phytoplankton growth (Sun et al., 2017). *Cyanobacteria* reach the fastest growth rate when water temperatures are greater than 20 °C, resulting in frequent cyanobacterial blooms in warmer seasons. Cyanobacteria had an advantage over other communities when water temperature elevated. However, temperature is not the determining factor that result in the presence or absence of cyanobacterial blooms in Lake Taihu for blooms can take place even if the temperature is very low (Ma et al., 2016). What's more, NO_3-N can also significantly influence the temporal changes in phytoplankton. Although it made a much smaller contribution compared with what water temperature did (Liu et al., 2015). The reality that nitrogen can limit the growth of phytoplankton is likely to explain this results. Lesser concentrations of nitrogen over the period with high temperature might account for a greater populations of phytoplankton for nitrogen was consumed due to their proliferation. Additionally, some other cyanobacterial communities that do not fix nitrogen themselves can only rely on external input of N to maintain their production. Therefore, taking measures to control nitrogen inputs may be an useful way to diminish frequency of algae blooms. What's more, results of this research also showed that ammonium nitrogen and nitrate nitrogen were significant indicators affecting zooplankton communities. In actual fact, it's more complex to determine which environmental factors really impact the zooplankton communities, so lacking of scientific experimental data, it's hard to make clear the relationships between zooplankton communities and water quality indicators. Temperature constrained the quantities and diversity of zooplankton communities in Lake Taihu. Different kinds of species have different optimal temperatures. Suitable temperature accelerates the production and predating rates of some filter-feeding zooplankton communities like *Daphnia* and this could result in

Table 2
Physicochemical environmental parameters in five sampling sites of Lake Taihu from September 2011 to August 2012. (calculated as average value and standard deviation).

Parameters	ML	LC	DP	GH	ZS	p
SIO_3^{2-} (mg/L)	2.34 ± 0.70	2.13 ± 0.80	1.97 ± 0.50	2.00 ± 0.90	2.55 ± 0.60	0.223
PO_4^{3-}P (mg/L)	0.02 ± 0.01	0.013 ± 0.01	0.10 ± 0.05	0.01 ± 0.01	0.05 ± 0.03	<**0.001**[a]
NO_2^--N (μg/L)	42.03 ± 18.00	12.06 ± 8.70	128.29 ± 85.20	18.88 ± 12.30	102.83 ± 51.80	< **0.001** [a]
NO_3^--N (mg/L)	0.69 ± 0.50	0.74 ± 0.60	0.97 ± 0.60	0.66 ± 0.40	1.20 ± 0.70	0.2207
$NH^+{}_4$-N (mg/L)	0.55 ± 0.20	0.49 ± 0.40	1.48 ± 0.80	0.32 ± 0.10	1.31 ± 1.20	<**0.001** [a]
SO_4^{2-} (mg/L)	71.73 ± 20.20	62.73 ± 17.00	58.86 ± 18.90	68.83 ± 22.90	72.05 ± 19.30	0.4817
DTOC (mg/L)	23.71 ± 2.80	22.13 ± 3.00	27.07 ± 4.50	22.09 ± 2.90	27.04 ± 3.80	**0.0027** [a]
COD (mg/L)	5.73 ± 1.80	4.24 ± 0.70	7.55 ± 4.90	3.8 0 ± 0.90	6.85 ± 2.60	<**0.001** [a]
BOD (mg/L)	3.03 ± 1.20	1.69 ± 0.90	5.21 ± 2.20	1.96 ± 0.80	4.44 ± 2.10	<**0.001** [a]
TP (mg/L)	0.15 ± 0.09	0.13 ± 0.13	0.37 ± 0.23	0.07 ± 0.02	0.24 ± 0.13	<**0.001** [a]
TN (mg/L)	3.13 ± 0.76	2.48 ± 1.31	5.07 ± 2.09	2.04 ± 0.78	5.04 ± 1.71	<**0.001** [a]
SS (mg/L)	36.80 ± 26.70	52.83 ± 26.80	93.61 ± 67.30	29.99 ± 18.30	44.05 ± 25.00	**0.015** [a]
TSI	60.77 ± 7.00	56.80 ± 4.90	69.32 ± 7.40	53.69 ± 3.70	66.00 ± 7.10	**0.0011** [a]
Chl-a (mg/m3)	36.36 ± 40.70	12.10 ± 9.60	61.36 ± 132.80	14.60 ± 17.20	48.35 ± 58.60	**0.0200** [a]
SD (m)	0.49 ± 0.27	0.31 ± 0.19	0.21 ± 0.11	0.47 ± 0.20	0.40 ± 0.30	**0.0087** [a]

[a] $p < 0.05$.

the over exploitation of alga food and extinction of some phytoplankton. What's more, under proper warmer conditions, biomass of large *Cladocerans* (N.Abrabtes et al., 2006) and *Copepods* surpassed those of smaller sized species (Fig. 3). Zooplankton communities may regenerate nutrients in most of the natural water bodies (Barlow and Bishop, 1965). The input of nitrogen nutrients can impact the zooplankton community through direct or indirect influences. Besides, there exists some other factors which may affect the temporal variation of phytoplankton and zooplankton, like external inputs, interaction with each other, bacterioplankton and so on. These factors go beyond the range of this research, as a result, we must be cautious to make the conclusions. However, this research offers fresh point of views into comprehension of reaction of phytoplankton and zooplankton to variation of freshwater environment, especially in large, shallow lakes.

In conclusion, results of this research proved that the variations of phytoplankton and zooplankton showed a directional change in heavily polluted northern areas of Lake Taihu. In addition, water temperature and nitrogen contributed most to variations of phytoplankton and zooplankton communities. These conclusions confirmed that temperature along with nutrient accumulations are the foremost environmental indicators shaping the structure and function of phytoplankton and zooplankton communities. As the temperature rises in the future, we can regulate the discharge of nutrient into Lake Taihu in order to improve water quality environment and this can help mitigate the negative effect of temperature rise to water quality environment in Taihu Lake. So, reducing of nitrogen inputs may be effective in diminishing the cyanobacterial blooms in Lake Taihu.

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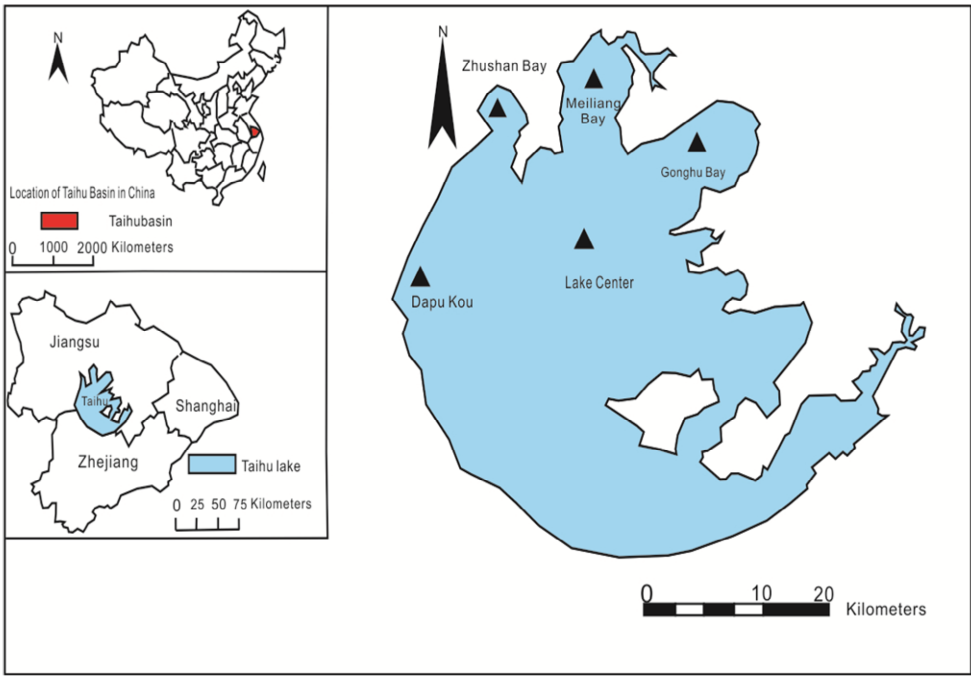
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.11.007.

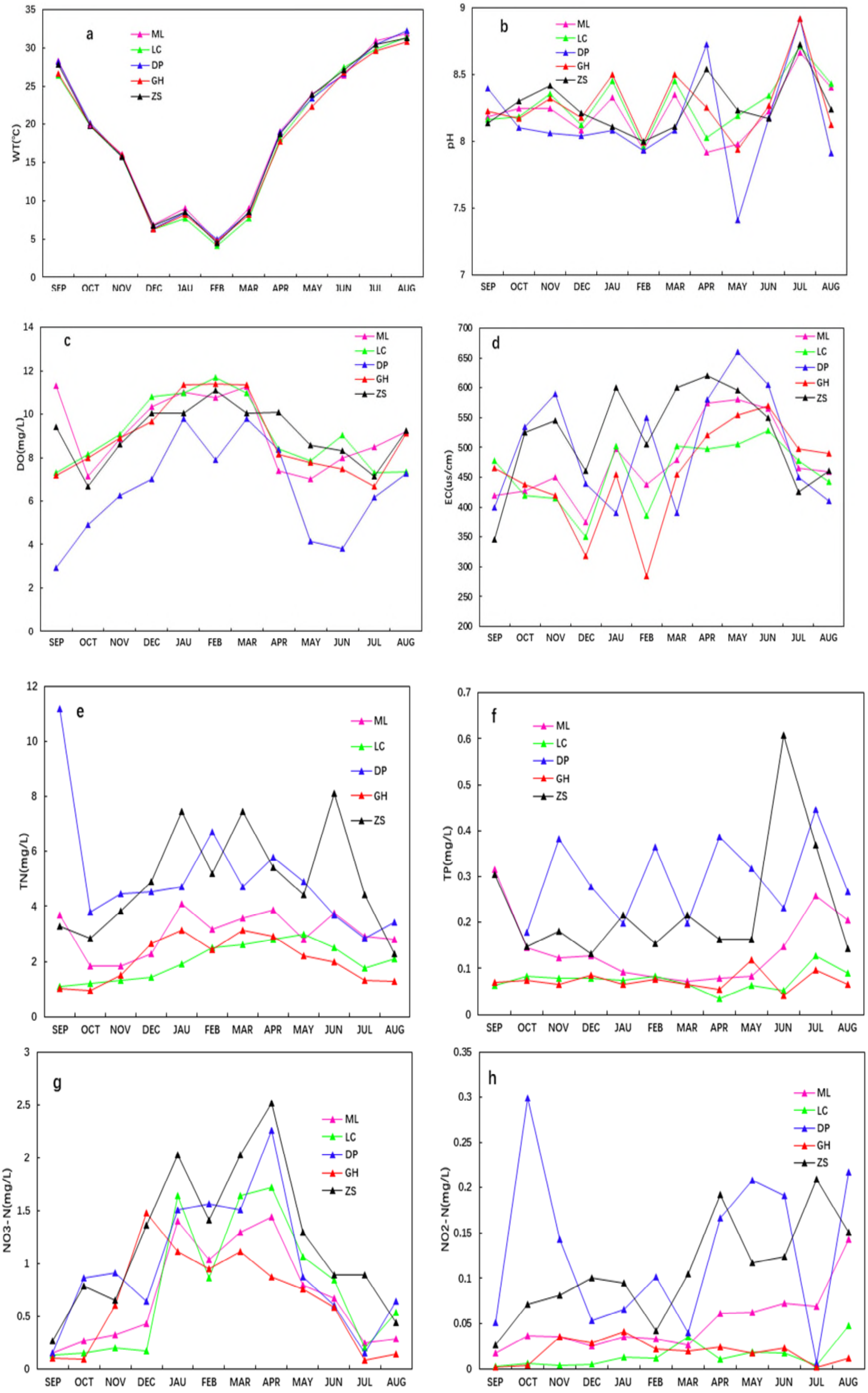
References

Altshuler, I., Demiri, B., et al., 2011. An integrated multi-disciplinary approach for studying multiple stressors in freshwater ecosystems: *Daphnia* as a model organism. Integr. Comp. Biol. 51, 623–633.
Anas, G., Bernadette, P.A., 1998. Relationships between zooplankton community structure and phytoplankton in two lime-treated eutrophic hardwater lakes. Freshw. Biol. 39, 775–790.
Balseiro, E.G., Modenutti, B.E., et al., 1997. Nutrient recycling and shifts in N:P ratio by different zooplankton structures in a south Andes lake. J. Plankton Res. 19, 805–817.
Barlow, J.P., Bishop, J.W., 1965. Phosphate regeneration by zooplankton in Cayuga Lake. Limnol. Oceanogr. 10, 15–24.
Benjamin, A., Jean-philippe, J., et al., 2013. Local forcings affect lake zooplankton vulnerability and response to climate warming. Ecology 94, 2767–2780.
Bonecker, C.C., Simões, N.R., et al., 2013. Temporal changes in zooplankton species diversity in response to environmental changes in an alluvial valley. Limnologica 43, 114–121.
Carlson, R.E., 1977. A trophic state index for lakes. Limnol. Oceanogr. 22, 361–369.
Carmichael, W.W., 1989. Cyanobacteria secondary metabolites—the cyanotoxins. J. Appl. Microbiol. 72, 203–205.
Collins, S.L., Micheli, F., et al., 2000. A method to determine rates and patterns of variability in ecological communities. Oikos 91, 285–293.
Davis, T.W., Bullerjahn, G.S., et al., 2015. Effects of increasing nitrogen and phosphorus concentrations on phytoplankton community growth and toxicity during Planktothrix blooms in Sandusky bay, Lake Erie. Environ. Sci. Technol. 49, 7197–7207.
Dudgeon, D., Arthington, A.H., et al., 2006. Fresh water biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.
Foley, J.A., Defries, R., et al., 2005. Global consequences of land use. Science 309, 570–744.
George, D.G., Harris, G.P., 1985. The effect of climate on long-term changes in the crustacean zooplankton biomass of Lake Windjammers. Nature 316, 536–539.
Haberman, J., Haldna, M., 2017. How are spring zooplankton and autumn zooplankton influenced by water temperature in a polymictic lake? P EST ACAD SCI 66, 264–278.
Hong, Y.G., Xu, X.R., et al., 2014. Linking seasonal inorganic nitrogen shift to the dynamics of microbial communities in the Chesapeake Bay. Appl. Microbiol. Biotechnol. 98, 3219–3229.
Hutchinson, G.E., 1967. A Treatise on Limnology. Volume II: Introduction to Lake Biology and the Limnoplankton. John Wiley and Sons Inc., New York.
Kosten, S., Huszar, V.L.M., et al., 2012. Warmer climates boost cyanobacterial dominance in shallow lakes. Global Change Biol. 18, 118–126.
Li, W., Yang, Q., et al., 1994. Algal bloom in lake Taihu and its control. In: Sund, H., Yu, X., Stabel, H., Yuan, K., Geller, W., She, F. (Eds.), Environmental Protection and Lake Ecosystem. China Science and Technology Press, Beijing, pp. 243–261.
Liu, L., Yang, J., et al., 2015. Phytoplankton communities exhibit a stronger response to environmental changes than bacterioplankton in three subtropical reservoirs. Environ. Sci. Technol. 49, 10850–10858.
Ma, J.R., Qin, B.Q., Hans, W.P., et al., 2016. The persistence of cyanobacterial (Microcystis spp.) blooms throughout winter in Lake Taihu, China. Limnol. Oceanogr. 61, 711–722.
N.Abrabtes, S.C., Antunes, M.J., et al., 2006. Seasonal succession of cladocerans and phytoplankton and their interactions in a shallow eutrophic lake (Lake-Vela,Portugal). Acta Oecol. 29, 54–64.
Natalie, Loick-Wilde, Sarah, C., et al., 2016. Nitrogen sources and net growth efficiency of zooplankton in three Amazon River plume food webs. Limnol. Oceanogr. 61, 460–481.
O'Neil, J.M., Davis, T.W., et al., 2012. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. Harmful Algae 14, 313–334.
Paerl, H.W., Dyble, J., et al., 2003. Microbial indicators of aquatic ecosystem change: current applications to eutrophication studies. FEMS Microbiol. Ecol. 46, 233–246.
Pilkaityte, R., Razinkovas, A., 2007. Seasonal changes in phytoplankton composition and nutrient limitation in a shallow Baltic lagoon. Boreal Environ. Res. 12, 551–559.
Qin, B.Q., Xu, P., et al., 2007. Environmental issues of lake Taihu, China. Hydrobiologia 581, 3–14.
Qin, B.Q., Zhu, G.W., et al., 2010. A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management. Environ. Man 45 (1), 105–112.
Sarma, S.S.S., Nandini, S., et al., 2005. Life history strategies of *cladocerans*: comparisons of tropical and temperature taxa. Hydrobiologia 542, 315–334.
Segers, H., 2008. Global diversity of rotifers (Rotifera) in freshwater. Hydrobiologia 595, 49–59.
Shakira, S.E., Azan, Shelley E., et al., 2015. A review of the effects of Bythotrephes longimanus and calcium decline on zooplankton communities— can interactive effects be predicted? Environ. Rev. 23, 395–413.
Shayestehfar, A., Noori, M., et al., 2010. Environmental factor effects on the seasonally changes density in Parishan lake (Khajoo spring site). Iran. Asian J Exp Biol SCI 1, 840–844.
Silva, L.H.S., Huszar, V.L.M., et al., 2014. Drivers of phytoplankton, bacterioplankton, and zooplankton carbon biomass in tropical hydroelectric reservoirs. Limnologica 48, 1–10.
Sommer, U., Gliwicz, M., et al., 1986. The PEG model of seasonal succession of planktonic events in freshwaters. Arch. Hydrobiol. 106, 433–471.
Strayer, D.L., Dudgeon, D., 2010. Freshwater biodiversity conservation: recent progress and future challenges. J. North Am. Benthol. Soc. 29, 344–358.
Sun, X.M., Alan, D.S., et al., 2017. Temporal patterns of phyto- and bacterioplankton and their relationships with environmental factors in Lake Taihu, China. Chemosphere 184, 299–308.
Watanabe, M.M., Kaya, K., et al., 1992. Fate of the toxic heptapeptides, the microcystins, from blooms of *Microcystis* (Cyanobacteria) in hypertrophic lake. J. Phycol. 28, 761–767.
Xu, S., Wang, Y., et al., 2015. Nitrogen and phosphorus limitation of phytoplankton growth in different areas of Lake Taihu, China. J. Freshw. Ecol. 30, 113–127.
Yang, G.J., Qin, B.Q., et al., 2012. Contrasting zooplankton communities of two bays of the large, shallow, eutrophic Lake Taihu, China: their relationship to environmental factors. J. Great Lake. Res. 2, 299–308.
Yang, J., Hong, L., et al., 2016. Decline in water level boosts cyanobacteria dominance in subtropical reservoirs. Sci. Total Environ. 557–558, 445–452.
Yang, K., Yu, Z.Y., et al., 2017a. Spatial and temporal variations in the relationship between lake water surface temperatures and water quality - a case study of Dianchi Lake. Sci. Total Environ. 624, 859–871.
Yang, J.R., Lv, H., et al., 2017b. Disturbance induced phytoplankton regime shifts and recovery of cyanobacteria dominance in two subtropical reservoirs. Water Res. 120, 52–63.
Yu, T., Zhang, Y., et al., 2013. Six-decade change in water chemistry of large freshwater Lake Taihu, China. Environ. Sci. Technol. 47, 9093–9101.

Support Information



S.I. 1. Location of the five sampling stations in Tai Lake.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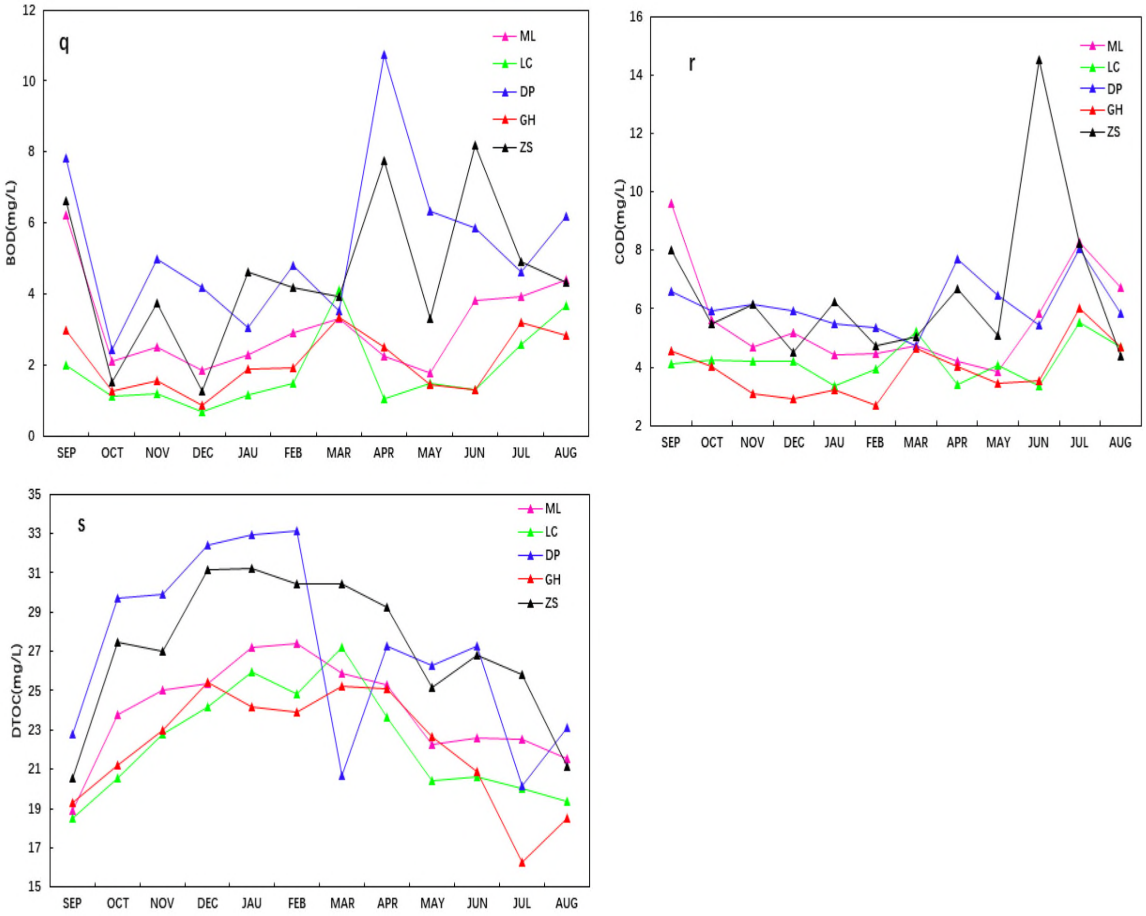

S.I. 2. Environmental parameters of five sampling stations in Tai Lake, from September 2011 to August 2012.