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Influences of environmental factors on biomass of phytoplankton in the northern part of Tai Lake, China, from 2000 to 2012

Wenjing Guo · Yuanrong Zhu · Zhiyou Fu · Ning Qin · Hao Wang · Shasha Liu · Yan Hu · Fengchang Wu · John P. Giesy

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Abstract Long-term (2000 to 2012) monthly data on communities of phytoplankton, and environmental variables were measured in water collected from Meiliang Bay and Wuli Lake of Tai Lake, China. Redundancy analysis (RDA) was conducted to explore relationships between the phytoplankton communities and environmental variables. Change points for concentrations of nutrients, which serve as early warnings of state shifts in lacustrine ecosystems, were identified using the Threshold Indicator Taxa Analysis (TITAN). The biomass of phytoplankton was positively correlated with the concentrations of total phosphorus (TP), suspended solids (SS), water temperature (WT), and pH but negatively correlated with the N/P ratio (by mass) and Secchi disk depth (SD). Furthermore, TP, rather than other factors, was a controlling factor limiting the primary production of phytoplankton in most of this region. The change points for concentrations of TP controlling the occurrences of sensitive and tolerant taxa were 56.1 and 103.5 μg TP/L, respectively. These results imply that an abrupt change in this lacustrine ecosystem has occurred in most parts of the study area, and the turbid state of this lake can be altered by reducing TP loading. This study provides an alternative ecological method for exploring the production of algal blooms and could advance the understanding of HABs.

Keywords Eutrophication · Environmental parameters · Nutrients · Redundancy analysis · Threshold Indicator Taxa Analysis · Change point

Introduction

Eutrophication, which is one of the most severe ecological problems in freshwater ecosystems, results in increases in the primary production of phytoplankton and decreases in the abundance of macrophytes, in addition to changes of phytoplankton community structures and deleterious effects on communities of zooplankton and fishes in aquatic systems (Smith et al. 1999; Chen et al. 2003a). Harmful algal blooms (HABs), mainly caused by eutrophication, significantly decrease the quality of aquatic ecosystems, especially in lakes in developing countries, for example China (Smith and Schindler 2009; Heisler et al. 2008; Qin et al. 2010). These ecological and economic problems caused by HABs, including decreases in the abundance

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W. Guo · H. Wang · S. Liu
College of Water Sciences, Beijing Normal University,
Beijing 100875, China

W. Guo · Y. Zhu · Z. Fu · N. Qin · H. Wang · S. Liu ·
Y. Hu · F. Wu (✉) · J. P. Giesy
State Key Laboratory of Environment Criteria and Risk
Assessment, Chinese Research Academy of Environmental
Sciences, Beijing 100012, China
e-mail: wufengchang@vip.skleg.cn

J. P. Giesy
Department of Biomedical and Veterinary Biosciences and
Toxicology Centre, University of Saskatchewan, Saskatoon,
Saskatchewan, Canada

of prawns, fish, shellfish, and other aquatic organisms, may trigger the complete collapse of ecosystems and damage the functioning of lacustrine ecosystems (Jochimsen et al. 1998; Chen et al. 2007).

Aquatic parameters, including the concentrations of nitrogen (N), phosphorus (P), trace metals and total suspended solids as well as pH, temperature, and illumination, can influence the formation of algal blooms (Dokulil and Teubner 2000; Jacoby et al. 2000; Xu et al. 2014; Zhang et al. 2016; Shapiro 1990). Based on the relationships between aquatic parameters and algal blooms, various models have been established to simulate and predict the formation of HABs in eutrophic lakes (Ye et al. 2011; Ma et al. 2015; Lui et al. 2007). However, previous studies have mainly focused the responses of biomass of phytoplankton to various environmental factors over short periods (from several months to several years) (Wilhelm et al. 2011; Ke et al. 2008; Venkataramana et al. 2017). Only a few studies have addressed the long-term responses of phytoplankton communities to multiple factors (Chen et al. 2003b). In addition, several studies have focused on the effects of individual environmental parameters on the abundance and/or proliferation of algal biomass (Wu et al. 2015; Ma et al. 2015), whereas interactions among multiple factors under field conditions have been poorly studied.

Nutrients such as total nitrogen (TN) or TP are significant determinants of the total standing stocks and relative proportions of taxa in phytoplankton communities (Zimmer et al. 2009; Richardson et al. 2007; Ren et al. 2014; Xu et al. 2014). However, almost no accurate change points or thresholds for the concentrations of TN or TP in terms of the response of the phytoplankton community in eutrophic lakes, such as Tai Lake in China, have been investigated so far.

Multivariate statistical analyses, including redundancy analysis (RDA) and canonical correspondence analysis (CCA), have been used to explore the effects of environmental factors on biotic communities by analyzing patterns and relationships based on field observations and experiments. These multivariate statistical analyses are useful tools for understanding the relationships among assemblages of species and the chemical-physical properties of environments as well as for identifying the factors controlling the proliferation of phytoplankton (Niu et al. 2011; Wu et al. 2013a; Ziesche and Roth 2008; Grabowska and Mazurmarzec 2016). Threshold Indicator Taxa Analysis (TITAN) is an ecological method used to identify species and community change points that combines the analysis of indicator species with nonparametric change point analysis. This method can be used to calculate change points in frequencies and abundances of individual taxa and to examine whether multiple taxa exhibit synchronous responses over small changes in gradients of concentrations of nutrients (Baker and King 2010; King and Baker 2010; Cao et al. 2016; Smucker et al. 2013). Change points of nutrients can be applied to clarify the shift from a clear state to a turbid state related to the concentrations of nutrients. Thus, thresholds or change points affecting the response of phytoplankton communities are useful as early warning systems in lacustrine ecosystems (Smucker et al. 2013).

In this study, phytoplankton, a critical node in the food webs of lacustrine ecosystems, was selected to investigate the development of HABs in Tai Lake (Ch: *Taihu*), a large, shallow eutrophic lake in China. Monitoring data on the absolute and relative numbers of phytoplankton and chemical-physical properties were collected from 2000 to 2012 at eight locations in Meiliang Bay and Wuli Lake of Tai Lake. The primary objectives of the study were to (1) elucidate the variation in populations of phytoplankton and environmental parameters, (2) identify the synergistic effects of environmental conditions on the proliferation of phytoplankton, and (3) establish change points based on nutrient gradients and identify the relationships between changes in phytoplankton communities and nutrients. Together, the results will provide management guidelines to reduce the frequency and severity of algal blooms in Tai Lake.

Materials and methods

Study sites

Tai Lake (30° 90′ N~31° 54′ N, 119° 55.3′ E~120° 59.6′ E), the third largest freshwater lake in China, is located in the downstream portion of the Yangtze River Delta. It has a surface area of 2427 km^2 (water area 2338 km^2, island area 89 km^2), with an average depth of 2 m and a total volume of 4.76 km^3. The Basin of Tai Lake lies in the East Asia monsoon region with a mean annual precipitation of 1177 mm, which occurs mostly during the spring-summer period. According to the phenology in the East Asian monsoon region, four seasons in the Tai Lake have been defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

Tai Lake has shifted from an oligotrophic, diatom-dominated lake during the 1960s to a eutrophic, cyanobacteria-dominated lake during the 1990s (Chen et al. 2003a; Chen et al. 2003b). The frequencies of algal blooms have gradually increased since then. The most extraordinary case was in 2007, when a bloom of cyanobacteria occurred in the vicinity of the Gonghu Waterworks, which resulted in a drinking water emergency (Qin et al. 2010). Located in the northern part of Tai Lake, Meiliang Bay and Wuli Lake are the primary sources of drinking water and tourism for the city of Wuxi. This region has been hypereutrophic since the twentieth century, and blooms of *Microcystis* have been frequently observed in this region.

Sources of data and manipulations

The monitoring data used in this study were provided by the *Taihu* Laboratory for Lake Ecosystem Research (TLLER), Chinese Academy of Sciences. These data included aquatic parameters collected monthly during the period from 2000 to 2012 at eight locations in Meiliang Bay and Wuli Lake (Fig. 1). These parameters included Secchi disk depth (SD), pH, concentrations of nitrate nitrogen (NOx-N), ammonia nitrogen (NH_4-N), total nitrogen (TN), total phosphorus (TP), suspended solids (SS) chlorophyll-a (Chla) and water temperature (WT). The concentrations of Chla were measured spectrophotometrically after extraction with hot 90% ethanol (Lorenzen 1967). The phytoplankton communities were analyzed by use of previously described methods (Chen et al. 2003b). Other parameters were quantified by use of the Chinese standard methods for lake eutrophication survey (Jin and Tu 1990).

Statistical analyses

The monitoring data describing communities of phytoplankton were analyzed by conducting detrended correspondence analysis (DCA) to select an appropriate ordination procedure. The result of the length of the first gradient in the DCA was less than 3 suggested that the numerical analyses assumed unimodal species distributions, and that RDA was appropriate for the current datasets. When the length of the first gradient in the DCA was greater than 4, CCA could be applied for the analysis. All parameters except pH were transformed as $\ln(x + 1)$ before performing the analyses. The datasets were then centralized and standardized. Significance of effects of the environmental variables was tested using Monte Carlo simulations with 499 unrestricted permutations. Variance inflation factors (VIFs) were used to test the linear relationships between environmental variables (Ter Braak and Smilauer 2002). If a VIF was greater than 20, the variable was eliminated and the remaining variables were subjected to further analysis. Correlation analysis was performed using the SPSS software.

$\mathrm{Log}_{10}(x + 1)$ transformations of the relative abundances of species were performed to down-weight the influence of ubiquitous taxa with greater relative abundances on the indicator values. Five hundred bootstrap replicates for taxa were used to identify multiple candidate change points and calculate the change values for indicators. All sample units were split into two groups of declining (z−; tolerant) and increasing (z+; sensitive) taxa, which were used to identify community-level change points. Detailed explanations of the applied methods were provided in a previously published paper (Baker and King 2010). TITAN was conducted in R 3.2.4 using the TITAN2 package.

Results

Variation in phytoplankton and aquatic parameters from 2000 to 2012

Phytoplankton taxa, including cyanobacteria, green algae, diatom, euglenophyta and other groups of algae, were found in Meiliang Bay and Wuli Lake from 2000 to 2012. Among all taxa, cyanobacteria accounted for 95.7% of the total biomass of phytoplankton (according to the average values from eight sites) (Fig. S1). The contributions of other taxa were, in decreasing order, green algae, diatom, euglenophyta, and others. Cyanobacteria, especially *Microcystis*, dominated the phytoplankton community in Meiliang Bay during the 1990s (Chen et al. 2003b). In the period from 2000 to 2012, cyanobacteria were still the dominant phytoplankton taxa in the study region.

The concentrations of Chla varied from 1.2 mg/m^3 (April 2012) to 243.1 mg/m^3 (July 2009) (Fig. 2). The relative proportions of cyanobacteria ranged from 0.8% (March 2000) to 99.9% (August 2011). The greatest cyanobacteria biomass of 1.6×10^{10} ind./L was observed in June 2001, while at some locations, such as site 6 in March 2000 and site 5 in February 2010, no cyanobacteria were observed (not presented).

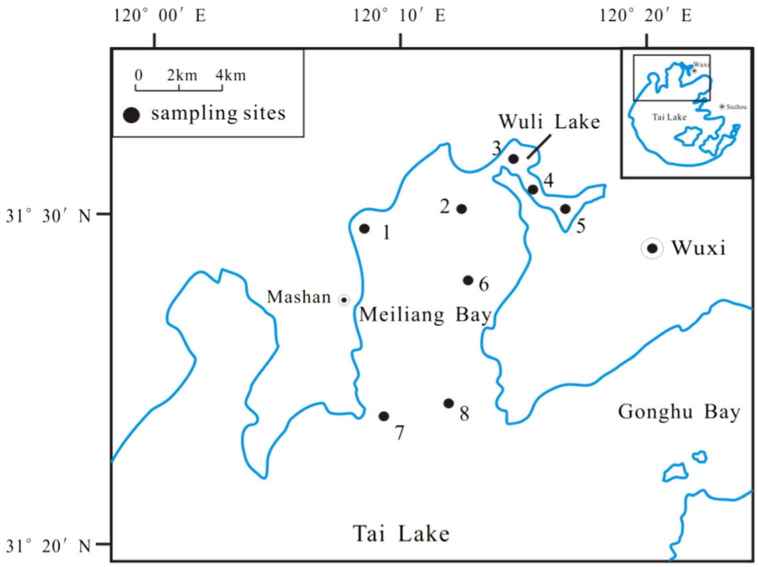

Fig. 1 Sampling sites in Meiliang Bay and Wuli Lake of Tai Lake

During the period from 2000 to 2012, the average monthly concentrations of Chla (Fig. 3a) and the mean monthly relative abundances of cyanobacteria (Fig.3b) increased and fluctuated in the study region. The highest concentrations of Chla peaked at 66.2 mg/m^3 in July (summer), while the lowest concentration was 9.0 mg/m^3 in January (winter). Another trend in the abundance of cyanobacteria was that greater percentages of cyanobacteria biomass appeared in summer, and the highest percentage of cyanobacteria (89.2%) peaked in July (Fig. 3b). Relatively lower percentages were observed in spring and winter, and the lowest percentage (41.7%) was measured in April. The variation in other parameters is described in Fig. S2 and Fig. S3 in the supplementary material.

Redundancy and correlation analyses

The DCA was conducted on ln(x + 1) transformed phytoplankton variables. The length of the first gradient in the DCA was 2.036 (not presented), which indicated that linear species distributions were assumed for the numerical analysis, and the RDA was more appropriate for the analysis of relationships between descriptors of populations of phytoplankton and environmental parameters (Lepš and Šmilauer 2003). After eliminating variables such as TN that had linear correlations with other parameters, total datasets for Meiliang Bay and Wuli Lake from 2000 to 2012 were analyzed by use of Canoco V4.5.

In the ordination plot from the RDA (Fig. 4), the environmental variables associated with the first ordination axis were N/P, NH_4-N/NO_X-N, NH_4-N, NO_X-N, and SS, while the variables associated with the second ordination axis were TP, WT, pH, and SD. According to the ordination plot of the RDA, the concentration of Chla was positively correlated with WT and pH and negatively correlated with SD. Axes 1 and 2, with eigenvalues of $\lambda_1 = 0.113$ and $\lambda_2 = 0.091$, explained 11.3 and 20.4% of the species variables, respectively. The two axes alone explained 85.6% of the cumulative variation of the phytoplankton-environment relationships, while the first four axes explained 97.4% of the cumulative variation (Table 1).

Correlation analyses between environmental parameters and concentration of Chla for Meiliang Bay and Wuli Lake from 2000 to 2012 were conducted (Table 2). The concentration of Chla was positively correlated with TP, WT, SS, and pH, but negatively correlated with N/P, NH_4-N, and SD. There was no significant correlation between Chla and TN, NH_4-N/NO_x-N.

Change points of concentrations of TP

The concentration of TP, which could be regulated by implementing measures to control inputs into Tai Lake, rather than TN, pH, WT or SD, was the key factor determining the total biomass of phytoplankton. Change points of the response of the phytoplankton community to TP were determined using the TITAN (Fig. 5). Sum

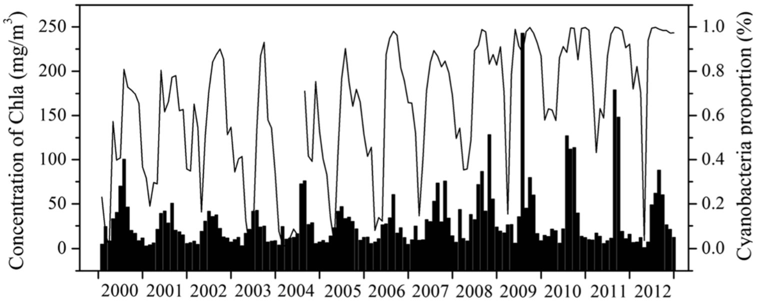

Fig. 2 Long-term variations of concentrations of Chla and relative proportions of cyanobacteria (monthly means). Bars represent concentrations of Chla; the solid line represents relative abundance of cyanobacteria

scores for sensitive (z−) taxa (cyanobacteria, green algae, and cryptophyceae) had a change point at 56.1 μg TP/L. The change point for sum (z+) taxa (tolerant taxa), including diatom and euglenophyta, was found at 103.5 μg TP/L. Quantiles (10, 50, 95, and 95%) corresponding to change points from 500 replicates are also reported (Table S1).

Discussion

Effects of nutrients

Previous studies have revealed that cyanobacteria prefer NH_4^+-N over other N sources like NO_3^--N (Liu et al. 2011; Alda et al. 1996). Nearly vertical directions of NH_4-N, NO_x-N and NH_4-N/NO_x-N in association with Chla were observed (Fig. 4), and relatively weak relationships between these variables and Chla were observed in the study area (Table 2) ($R = -0.120$, 0.084 and 0.061 respectively, $n = 833$). Additionally, a negative correlation between ratio of N/P and concentration of Chla (Fig. 4), and non-significant relationship between the concentration of TN and Chla in correlation analyses ($R = 0.058$, $p > 0.01$, $n = 833$) (Table 2) were also found. These results might indicate the concentration of TN was sufficient to satisfy the requirements of phytoplankton production in the study area. Thus, it is likely that the abundance of phytoplankton was limited by other factors rather than TN, which is consistent with the conclusions of previous studies (Chen et al. 2003a; Schindler et al. 2008). Furthermore, a TN concentration of 0.80 mg/L has been reported to be a threshold level under which the formation of algal blooms is limited in the northern part of Tai Lake (Xu et al. 2014; Xu et al. 2010). The mean annual concentrations of TN in Meiliang Bay and Wuli Lake, which ranged from 0.05 to 13.56 mg/L and had a mean concentration of 4.33 mg/L in the study period, exceeded the critical threshold level in this study area. Conclusively, it can be inferred that the concentration of TN was not the factor limiting the total biomass of phytoplankton in the northern part of Tai Lake from 2010 to 2012.

The results of both the RDA and correlation analysis showed that TP was significantly related to the concentrations of Chla (Fig. 4 and Table 2). In addition, the ratio of N/P averaged 32.6 (5.1–134.6) in northern Tai Lake and was mostly greater than the Redfield ratio of

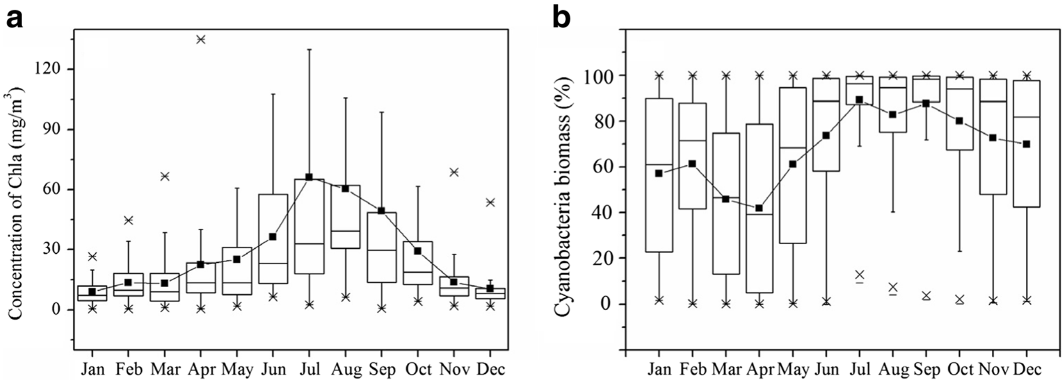

Fig. 3 Monthly variations (from 2000 to 2012) of concentrations of Chla (**a**) and relative abundances (%) of cyanobacteria (**b**) in Meiliang Bay and Wuli Lake of Tai Lake

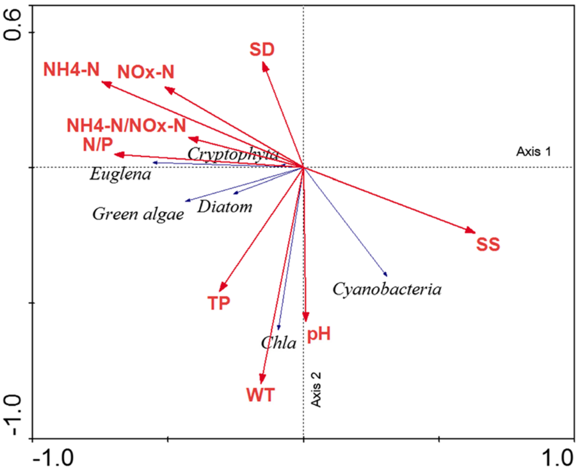

Fig. 4 Spatial ordination resulting from RDA of species parameters with respect to several environmental variables in the study region. In the ordination plot, projections of environmental variables reveal correlations with species; same direction indicates the positive correlation between environmental variables and species variables; opposite direction indicates the negative correlation

7.2 (mass ratio) (Redfield 1934). Previous studies have found that *Microcystis* tends to dominate in the north part of Tai Lake when the ratio of N/P is less than 30 (Liu et al. 2011) and that the formation of algal blooms is limited by TP when concentrations of TP are less than 0.20 mg/L (Xu et al. 2010). This concentration level is higher than the concentration of TP in the northern part of Tai Lake, which averaged 0.17 mg/L (0.03–4.4 mg/L). Therefore, it can be concluded that TP, rather than N or the N/P ratio, was the main factor limiting the proliferation of phytoplankton in most of this region from 2000 to 2012, which was consistent with previous research (Zhang et al. 2008). The restriction of TP in this region may be ascribed to the characteristics of pollution discharges in the surrounding area of Wuxi city. To effectively control algae blooms, limiting sources of TP and then reducing internal loadings of TP to the northern part of Tai Lake is currently preferable to controlling TN.

Effects of water temperature

Higher water temperatures were found to facilitate the proliferation of phytoplankton in this study. This result supports the conclusion in other aquatic ecosystems that the production of cyanobacteria is directly proportional to water temperature, as cyanobacteria has competitive advantages over other species of phytoplankton at higher temperatures (O'neil et al. 2012; Paerl and Huisman 2008; Gobler et al. 2007; LÜRLING et al. 2013). In the study area, the proportion of cyanobacteria was greater than 75% in summer and autumn, whereas in spring and winter, cyanobacteria accounted for only less than half of the total biomass of phytoplankton (Fig. 3b). This trend was also found in the results of the RDA (Fig. 4), in which a significant correlation ($R = 0.403$, $p < 0.01$, $n = 833$, Table 2) between the concentration of Chla and water temperature was observed. In addition, based on fitting a function to these two parameters, the concentration of Chla was significantly correlated with water temperature in the study region ($Y = 11.20 + 0.28 \times e^{0.18X}$, $R^2 = 0.28$, $p < 0.001$, $n = 833$) (Fig. S4).

Based on the result that higher water temperatures can promote the production of cyanobacteria, warmer water, caused by global warming, will favor the growth of cyanobacteria when concentrations of nutrients such as TN and TP exceed the thresholds. Given the prediction of continued warming, with an increase of 1.8 °C expected by the end of the twenty-first century (Meehl et al. 2007), algal blooms may be expected to be of longer duration and possibly greater severity (Stocker et al. 2013), and the compositions of phytoplankton communities will change with the increasing intensity of algae blooms due to the combination of nutrient

Table 1 Summary of RDA ordinations between phytoplankton variables and physicochemical indicators of aquatic environments

Axes	1	2	3	4	Total inertia
Eigen values	0.113	0.091	0.019	0.009	1.000
Species-environment correlations	0.645	0.627	0.351	0.275	
Cumulative percentage variance					
Of species data	11.3	20.4	22.4	23.2	
Of species-environment relation	47.4	85.6	93.7	97.4	
Sum of all eigenvalues					1.00
Sum of all canonical values					0.239

Table 2 Correlations between parameters describing the phytoplankton community and physical-chemical parameters describing the environment (n = 833)

	TP	TN	N/P	NH_4-N	NOx-N	NH_4-N/ NOx-N	WT	SS	SD	pH	Chla
TP	1.000	0.071*	− 0.232**	0.126**	0.005	0.102**	0.165**	0.037	− 0.107**	− 0.017	0.219**
TN		1.000	0.452**	0.878**	0.444**	0.565**	− 0.206**	0.067	0.066	− 0.176**	− 0.058
N/P			1.000	0.339**	0.579**	0.057	− 0.404**	− 0.299**	0.398**	− 0.057	− 0.250**
NH_4-N				1.000	0.228**	0.749**	− 0.267**	− 0.239**	0.117**	− 0.285**	− 0.120**
NOx-N					1.000	− 0.170**	− 0.184**	− 0.220**	0.166**	− 0.035	− 0.084*
NH_4-N/NO_x-N						1.000	− 0.127**	− 0.111**	0.022	− 0.235**	− 0.061
WT							1.000	0.139**	− 0.223**	0.250**	0.403**
SS								1.000	− 0.385**	0.086*	0.314**
SD									1.000	− 0.012	− 0.242**
pH										1.000	0.233**
Chla											1.000

**$p < 0.01$

*$p < 0.05$

loadings, primarily that of TN and TP, and climatic warming (Chen et al. 2003b).

Effects of other aquatic parameters

The pH of the water in Tai Lake was significantly correlated with biomass of phytoplankton (R = 0.233, p < 0.01, n = 833). The high pH was likely not a causative parameter but rather corresponded to the abundance of phytoplankton biomass. This result may have occurred because photosynthesis consumes CO_2 and HCO_3^- in the overlying water, thus increasing the pH in aquatic environments (Imhoff et al. 1979; Oliver and Ganf 2002).

A negative correlation between SD and the concentration of Chla (R = −0.242, p < 0.01, n = 833) and a positive correlation between SS and the concentration of Chla (R = 0.314, p < 0.01, n = 833) were observed in this study.

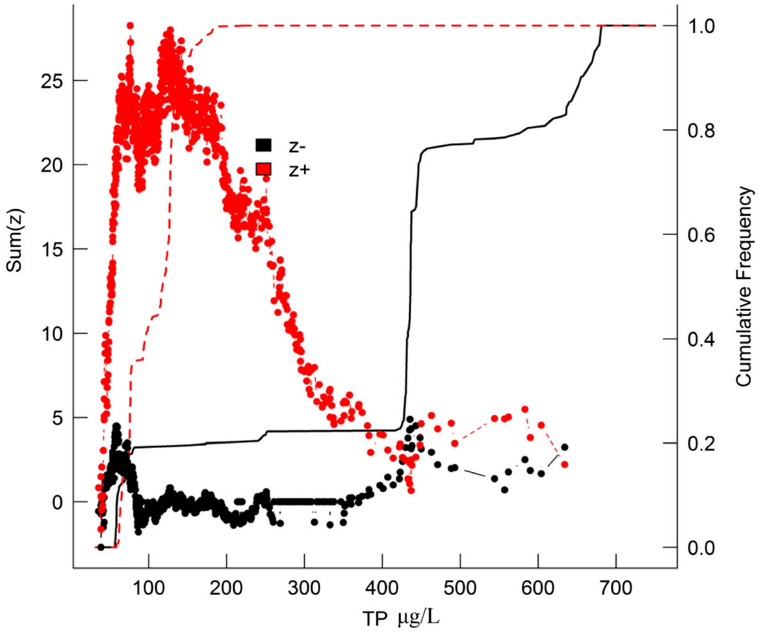

Fig. 5 Outcome of Threshold Indicator Taxa Analysis (TITAN) for significant indicator taxa (purity ≥ 0.95, reliability ≥ 0.95, $p \leq 0.05$) increasing (z+) or decreasing (z−) with the concentration of TP gradient are shown in increasing order of their change points. Black and vertical line in plot correspond to the cumulative frequency distribution of change points among 500 replicates for sum (z+) and sum (z −)

The results were also consistent with the results of previous study (Zhang et al. 2016). The high concentration of SS and low SD were likely the result of the proliferation of algae. Meanwhile, these relationships may have occurred because some species of cyanobacteria preferentially absorb certain wavelengths of light for proliferation at lower SDs (Mur et al. 1999), which result from high concentrations of suspended matter (SS) during algal blooms. In brief, further research needs to be conducted to explore these complex relationships.

Nutrient change points for the phytoplankton assemblage

The concentration of TP has a significant effect on the absolute and relative abundances of phytoplankton, and change points for nutrients have been reported in previous studies (Escaravage et al. 1996; Teubner et al. 1999). Change points were reported to be 27 μg/L for sensitive taxa and 51 μg/L for tolerant taxa in a stream located in the state of Connecticut in the USA (Smucker et al. 2013). For Lake Dianchi, China, change points for the concentration of TP were 131.5 and 151.5 μg/L for the z− and z+ taxa, respectively (Cao et al. 2016). In this study, concentrations of TP of 56.1 μg/L (z−) and 103.5 μg/L (z+) produced peak frequencies and abundances of phytoplankton taxa in response to the gradient of nutrient enrichment. The concentrations of change points were twice the values reported for Connecticut but much lower than the values reported for Lake Dianchi. Distinct change points for communities of phytoplankton might be ascribed to differences in the efficiencies of uptake and utilization among phytoplankton taxa with different rates of growth and competitive advantages.

The change points determined in this study provide accurate predictors of the stable clear-water regime in Tai Lake. This result was consistent with the shallow lake theory, which states that the stability of clear and turbid regimes in lacustrine ecosystems can be influenced by nutrient concentrations (Scheffer 1998). When shallow lacustrine ecosystems are destabilized by external drivers, such as artificial disturbance or wind (Davis et al. 2010), abrupt change from a clear to a turbid state could occur as a result of the release of TP from sediments or the input of TP from the watershed. This conclusion is supported by previous studies that revealed that the regeneration of TP in sediments and strong wind on the water are potential causes of algal blooms (Wu et al. 2013b, 2001).

During the study period, the mean concentration of TP (0.17 mg/L, ranging from 0.03 to 4.4 mg/L) in the northern part of Tai Lake was greater than those for the change points of tolerant and sensitive taxa. Therefore, it can be concluded that an abrupt change has occurred, and the lacustrine ecosystem has entered a turbid state in most of the study area. As a consequence, HABs have been frequently observed in this region.

Combined with the significant positive relationship between concentrations of TP and the biomass of phytoplankton, the change points of TP should arouse more attention in this deteriorated lacustrine ecosystem. To improve the resilience of the clear regime and facilitate a return of the phytoplankton community to a more desirable stable point, implementing the control of TP loading would be an effective method in Tai Lake.

Conclusion

In this study, significant correlations between phytoplankton variables and environmental parameters, such as TP, N/P ratio, WT, pH, SD and SS, were found using RDA and correlation analysis. The results indicate that the concentration of TP can currently limit the total standing stock of phytoplankton in most of this region. Based on long-term monitoring data, the change points of the phytoplankton community were 56.1 μg/L (sensitive taxa) and 103.5 μg/L (tolerant taxa) along with concentration of TP gradient based on the use of TITAN. This result implies that a regime shift has occurred in most of the study area.

Overall, identifying thresholds for various assemblages of phytoplankton in response to nutrient enrichment gradients can advance the understanding of the mechanisms underlying HABs. This research can provide useful information for pollution control strategies and lacustrine management.

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Supplementary Material

Influences of environmental factors on biomass of phytoplankton in the northern part of Tai Lake, China, from 2000 to 2012

Wenjing Guo [a, b], Yuanrong Zhu [b], Zhiyou Fu [b], Ning Qin [b], Hao Wang [a, b], Shasha Liu [a ,b], Yan Hu [b], Fengchang Wu [b *], John P. Giesy [b c]

[a] *College of Water Sciences, Beijing Normal University, Beijing 100875, China*

[b] *State Key Laboratory of Environment Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*

[c] *Department of Biomedical and Veterinary Biosciences and Toxicology Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*

** Corresponding author: Fengchang Wu, wufengchang@vip.skleg.cn. +86-10-84915312*

This supplementary material contains 1 table and 4 figures. This document contains 9 pages including this cover page.

Table S1

Declining(z-) and increasing(z+) taxa change points of community identified in TITAN along with concentration of TP in northern part of Tai Lake. Indicators scores (IndVal), all taxa satisfied purity⩾0.95, reliability⩾0.95 and p⩽0.05

Taxa	10%	50%	90%	95%	IndVal	*p*	z+/-
Cyanobacteria	246.5	383	431.5	435.0	59.3	0.004	-
Green algae	56.0	128	446.5	576.0	55.1	0.004	-
Diatom	63.0	72	94.1	166.0	57.8	0.004	+
Euglenophyta	75.7	97	128.0	130.0	83.0	0.004	+
Cryptophyceae	58.5	166	252.0	277.5	56.7	0.004	-

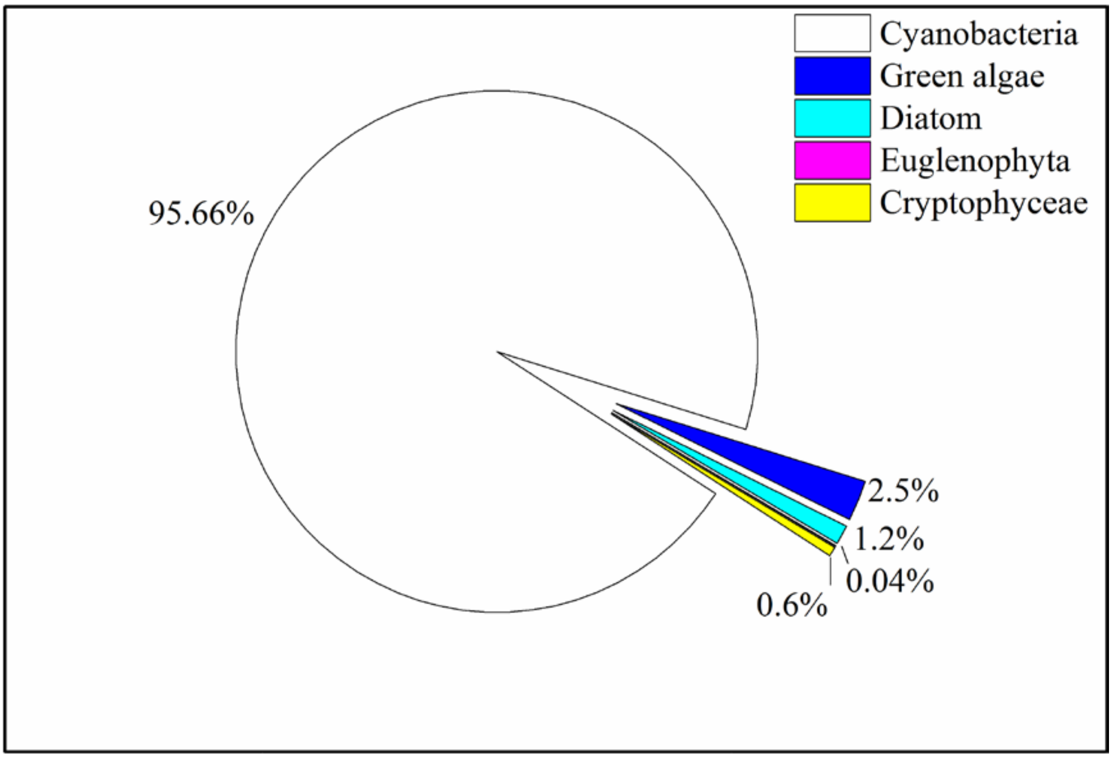
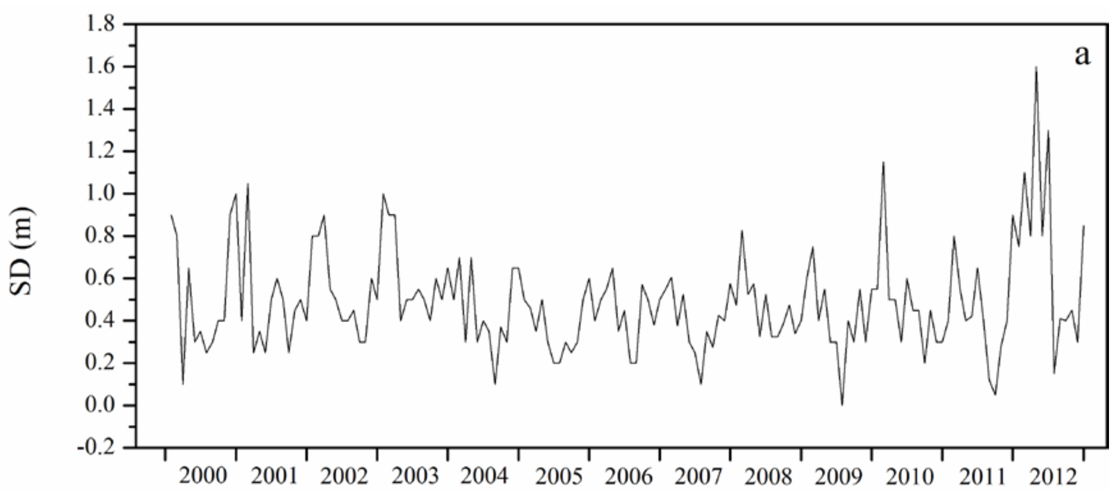
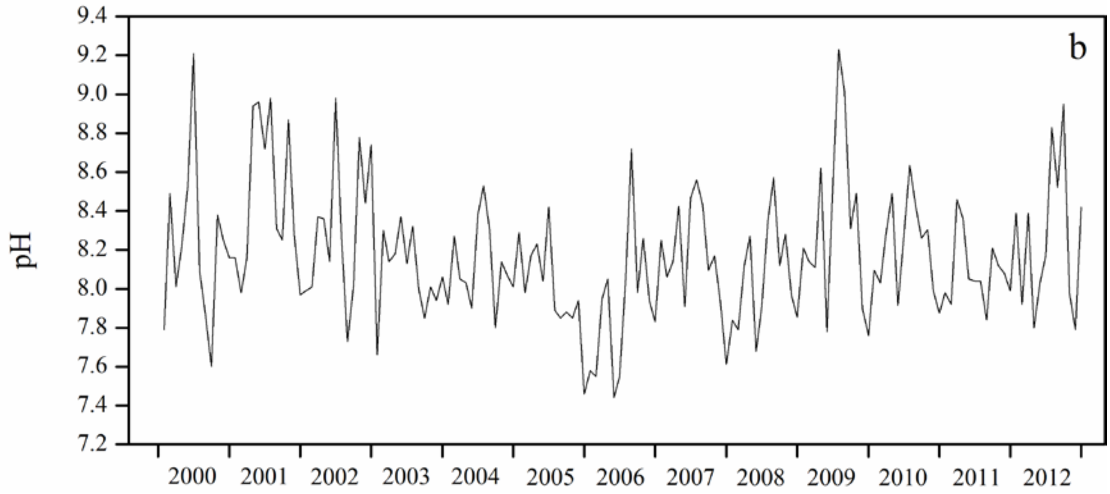
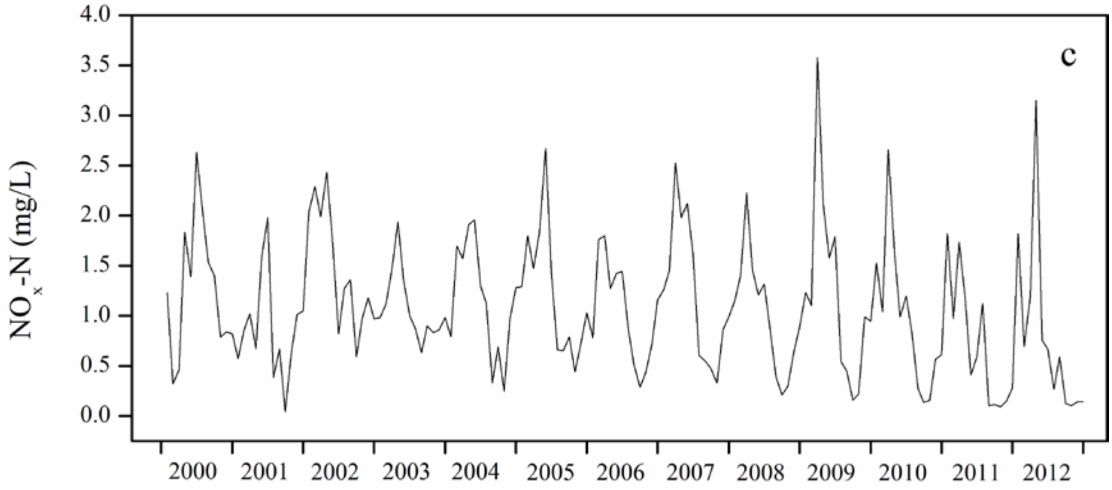
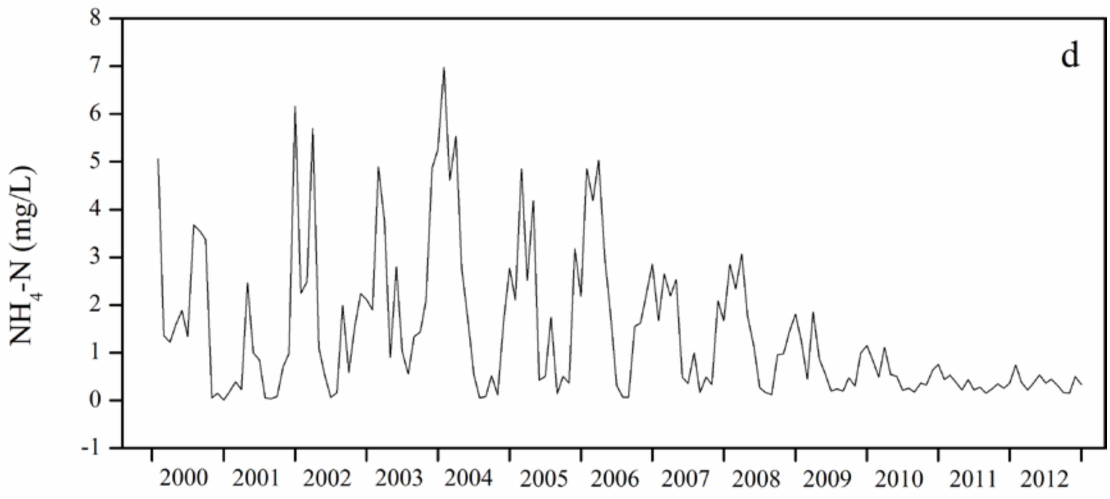


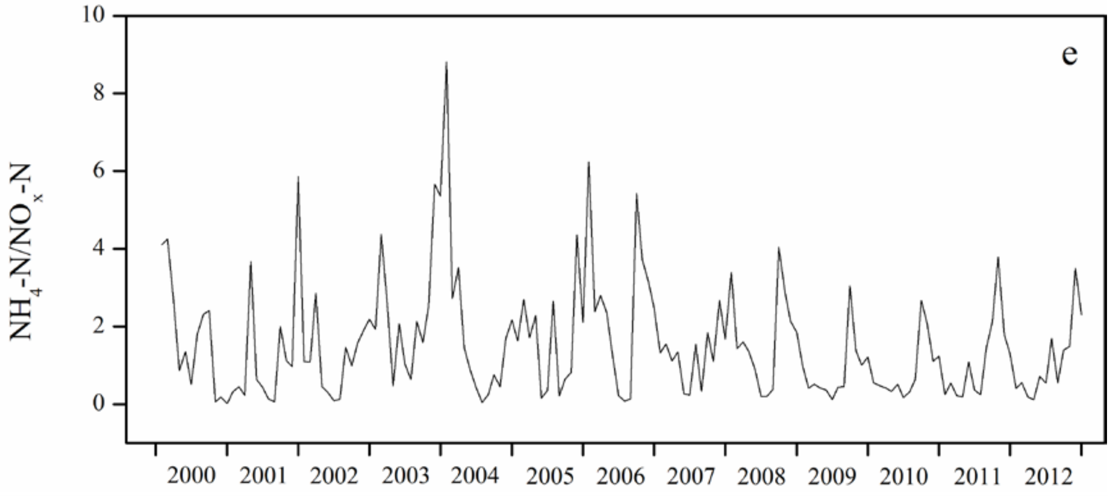
Fig. S1 The composition of algae taxa in the study area (based on the monthly average of the eight stations)

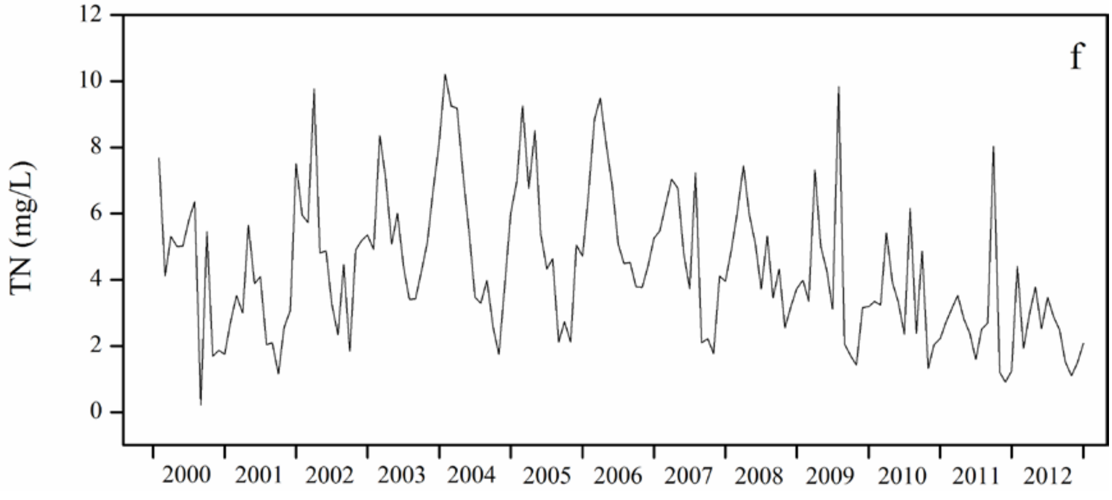

a
SD (m)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


b
pH
9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


c
NO_x-N (mg/L)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


d
NH4-N (mg/L)
8
7
6
5
4
3
2
1
0
-1
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


e
NH4-N/NOx-N
10
8
6
4
2
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


f
TN (mg/L)
12
10
8
6
4
2
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

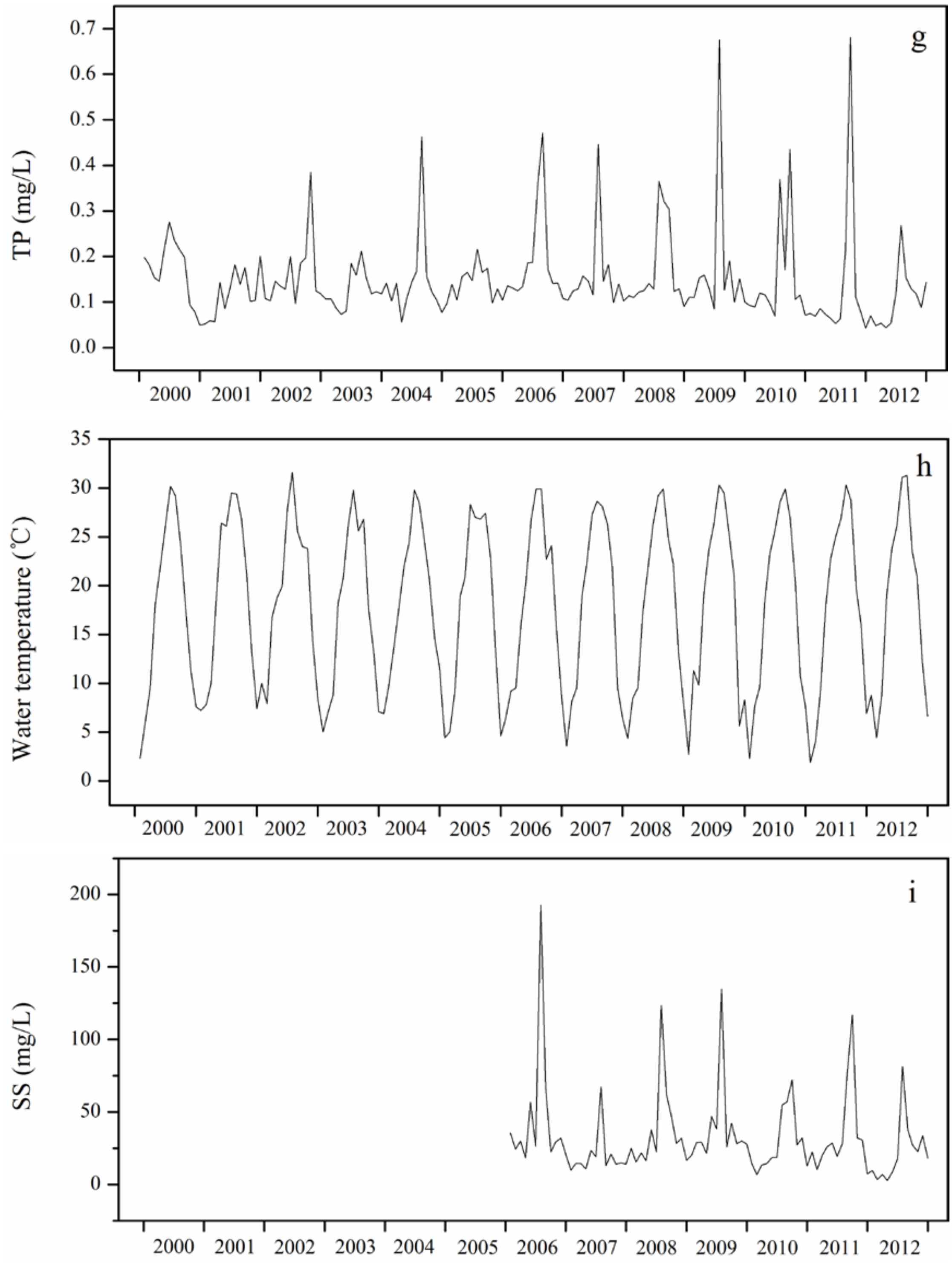
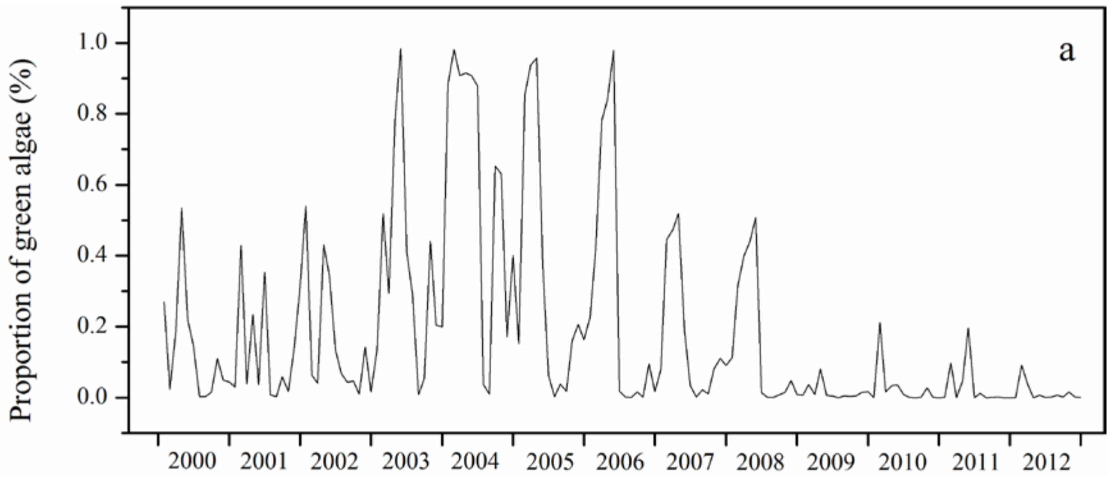
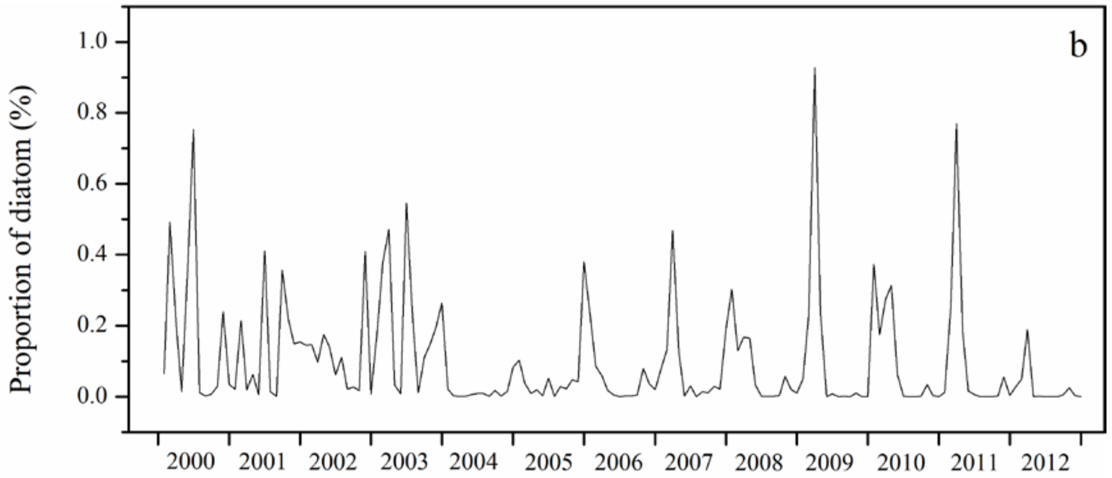
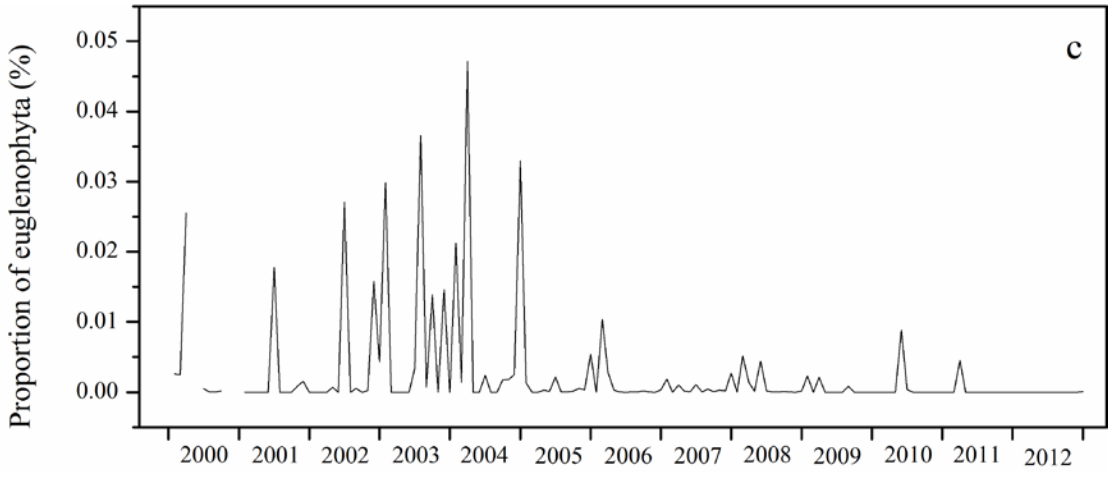


Fig. S2 The variation of several aquatic parameters in the study area from 2000 to 2012 (a-Secchi disk depth (SD), b-pH, c-concentration of nitrate nitrogen (NOx-N), d-ammonia nitrogen (NH_4-N), e-ratio of ammonia nitrogen to nitrate nitrogen (NH_4-N/NOx-N), f-total nitrogen (TN), g-total phosphorus (TP), h-water temperature (WT), i-suspended solids (SS)), some of that data like suspended solids were not collected


a
Proportion of green algae (%)
1.0
0.8
0.6
0.4
0.2
0.0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


b
Proportion of diatom (%)
1.0
0.8
0.6
0.4
0.2
0.0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012


c
Proportion of euglenophyta (%)
0.05
0.04
0.03
0.02
0.01
0.00
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

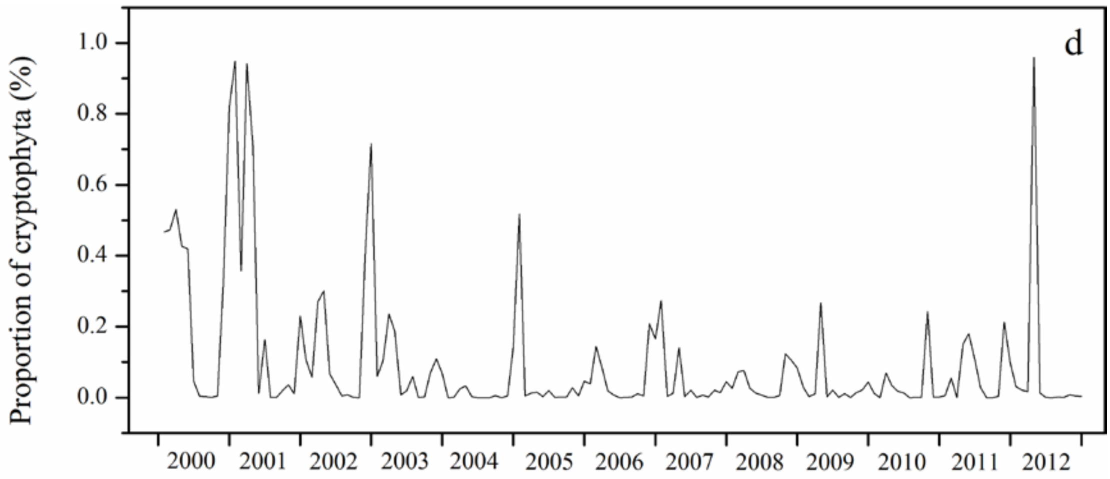


Fig. S3 The variation of several proportions of algae taxa in study area from 2000 to 2012 (a-green algae, b-diatom, c-euglenophyta, d-cryptophyta), some of that data like proportion of euglenophyta were not collected

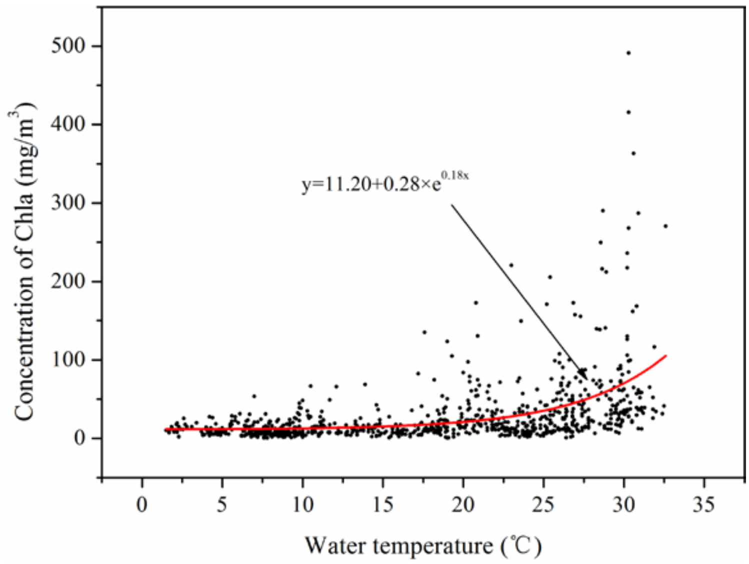


Fig. S4 Scatter plot showing association between Chla and water temperature in the study area, the best fit regression was represented by the exponential function