### **ORIGINAL PAPER**



# Phytoplankton community structure and water quality assessment in an ecological restoration area of Baiyangdian Lake, China

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### Abstract

Shihoudian Lake is one of the ecological restoration engineering pilot sites of Baiyangdian Lake, China. To evaluate the phytoplankton characteristics and eutrophication status in Shihoudian Lake, we investigated the community structure of phytoplankton, including the species composition, density, biomass dominance, biodiversity and water quality parameters, in autumn 2018 and spring and summer 2019. The relationships between the community structure and the main environmental factors were analysed using a multivariate statistical method. A total of 143 species of phytoplankton were identified, belonging to 53 genera and eight phyla, and *Cyanophyta* and *Prochlorophyta* were the most dominant phyla. Both the density and the biomass were the highest in the summer. A redundancy analysis showed that total phosphorus and chemical oxygen demand were the primary influencing factors of the community distribution of *Cyanophyta*. Evaluation of the comprehensive diversity index and water quality index revealed that the water of Shihoudian Lake was lightly to moderately polluted, providing scientific evidence for eco-environmental protection and remediation.

Keywords Algae · Freshwater ecosystems · Redundancy analysis · Total phosphorus · Trophic status

### Introduction

Freshwater ecosystems provide important benefits for humans, including providing drinking water, aquatic products and entertainment venues (Strayer and Dudgeon 2010). In recent decades, many lakes have become eutrophic, and some, such as lake Taihu (China's third largest lake) (Li et al. 2014b) and lake Erie (USA) (Michalak et al. 2013), have even suffered cyanobacterial blooms. Such blooms cause a variety of environmental problems, including reductions in fish yields, deterioration of water quality (Chen et al. 2019), loss of submerged macrophytes (Li et al. 2014b) and an overall decline in biological diversity.

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Phytoplankton are essential primary producers (Becker et al. 2010) in water bodies, and changes in phytoplankton species and numbers could directly influence water ecosystem structure and function (Lepistö et al. 2004). Thus, phytoplankton not only represent the basis of mass cycling and energy flow in the whole aquatic ecosystem (Wang et al. 2014a; Wang and Wang 2014) but are also an important indicator of the eutrophic status of water (Kolar et al. 2005). A study of the community structure of phytoplankton in Taiping Lake, Anhui, by Xiong et al. (2016) provided scientific evidence for water eco-environmental protection in this water body. In addition, eutrophication in the Chagan Lake Wetland was evaluated through a multivariate analysis of the relationship between phytoplankton and environmental factors (Li et al. 2014a). Similarly, the status of living organisms in lakes and other water bodies has been evaluated according to the phytoplankton community structure (Jun et al. 2019). Therefore, it is important to research the phytoplankton community, environmental factors and their role in the ecosystems to provide a theoretical basis for lake ecological restoration and management.

Development of phytoplankton populations is dependent on the concentration of nutrients and other ecological factors such as light, temperature, composition and quantity of





organic matter, currents and grazing. Outbreaks of cyanobacterial blooms occur when eutrophic water bodies are exposed to the appropriate water temperature, air temperature, flow rate, radiation and other external conditions (Heisler et al. 2008). Thus, it is important to identify the changes in phytoplankton communities and the key environmental factors impacting changes in the Baiyangdian Lake.

With the construction of the Xiongan New Area, the eutrophication of Baiyangdian Lake has drawn great attention from researchers (Tang et al. 2019; Yang et al. 2020). A demonstration project for phytoplankton resource investigation and water ecological remediation was launched in 2018. Shihoudian Lake was one of five engineering pilot sites used in this project, wherein fishing and the construction of habitats were the primary ecological remediation technologies. Thus, the first step in conducting ecological remediation was to evaluate the phytoplankton characteristics and pollution status.

The aims of this work were to determine the relationships between environmental factors and phytoplankton communities and to identify predominant environmental factors of phytoplankton communities. The density, biomass and dominant species of phytoplankton at multiple sites in Shihoudian Lake were investigated in autumn 2018 and spring and summer 2019. The physicochemical factors of the water were also monitored. The community structure characteristics and trophic level of phytoplankton were systematically analysed to provide basic data for the further development of ecological environment remediation and fish breeding in Shihoudian Lake. These factors will also be helpful for scientific management and protection of lakes in North China.

**Fig. 1** The sampling distribution map of Shihoudian Lake

# 38°50' N 115°59' E A \* Shihoudian E Lake \* B \* C 0 150 300 m \* Sampling sites

### Materials and methods

### Study site

Baiyangdian Lake is a large natural lake on the North China Plain and is located at 38° 44′–38° 59′ N and 115° 45′–116° 26′ E, with an average water depth of 2–3 m and an approximate area of 366 km² (Wang et al. 2014b). It is a well-known water body in North China and named "A pearl of North China". For years, the ecological system of Baiyangdian Lake has become increasingly fragile due to human activities, and severe destruction of its biological resources has occurred. According to a study conducted by Li et al. (2018), Baiyangdian Lake has been in a state of eutrophication since 1999.

Five sampling sites, labelled A, B, C, D and E, were established in Shihoudian Lake (Fig. 1). Sampling was carried out six times, including in the autumn of 2018 (October and November), the spring of 2019 (April and May) and the summer of 2019 (June and July). No sampling was performed in winter due to the presence of ice on the lake surface up to a depth of 0.5 m.

### Sample collection and treatment

In total, five water samples of 1 L were collected for phytoplankton analyses by mixing water from the surface, a depth of 0.5 m, a depth of 1 m and 0.5 m above the bottom in open waters. Samples were preserved with 1% Lugol's iodine solution and concentrated to 30 mL after

sedimentation for 48 h. An Olympus CX31 optical microscope (Olympus, Tokyo, Japan) was used for plankton species identification. For each taxon, a minimum of 20 cells were detected, and the geometric shape closest to the cell shape was used to calculate the mean biovolume, which was then transformed into the biomass (expressed as mg/L wet weight) based on an assumed density of 1 g/cm<sup>3</sup> (Zhang and Huang 1991; Hillebrand et al. 1999).

The data of eight physicochemical environmental factors in water were also measured and collected at the five sampling sites. Dissolved oxygen (DO) and the pH were determined using a portable multimeter (YSI Pro Plus; YSI Incorporated, USA). Water samples were collected in 5-L polypropylene buckets and preserved in the field and the laboratory until analysis. Ammonia nitrogen (NH<sub>3</sub>-N), total nitrogen (TN), nitrite nitrogen (NO<sub>2</sub>-N), nitrate nitrogen (NO<sub>3</sub>-N), total phosphorus (TP) and chemical oxygen demand (COD<sub>Mn</sub>) were determined using the Nessler test method, alkaline potassium persulfate digestion–UV spectrophotometric method, N-(1-naphthalene)-diaminoethane spectrophotometry, UV spectrophotometry method, ammonium molybdate tetrahydrate spectrophotometry method and potassium dichromate method, respectively (Jiang et al. 2014; Amri et al. 2017).

### Index calculation

The dominant species of phytoplankton were identified by calculating the dominance index (*Y*) for each species.

$$Y = Ni/N \times fi \tag{1}$$

where Ni is the abundance of the ith species, N is the abundance of all species and fi is the frequency of occurrence of the ith species.

The dominant species had a value of Y > 0.02 (Lin et al. 2011).

The indices of the diversity of plankton and fish included the following (Shannon 1948; Margalef 1958).

The Margalef abundance index (D) was calculated according to the following equation:

$$D = (S - 1) / \ln N. \tag{2}$$

D values of 0–1, 1–2, 2–4, 4–6 and > 6 corresponded to heavy, severe, moderate, light and no pollution.

The Shannon–Weaver diversity index was calculated with the following equation:

$$H' = -\sum (Ni/N) \ln (Ni/N). \tag{3}$$

H' values of 0–1, 1–2, 2–3 and > 3 corresponded to heavy, moderate, light and no pollution.

Simpson's diversity index (D') was calculated according to the following equation:

$$D' = 1 - \sum (Ni/N)^2. {4}$$

Pielou's evenness index was calculated with the following equation:

$$J = H' / \ln S \tag{5}$$

where *Ni* is the abundance of the *i*th species, *N* is the abundance of all species and *S* is the species.

J values of 0–0.3, 0.3–0.5 and > 0.5 corresponded to heavy, moderate and light or no pollution.

### **Data analysis**

The statistical analysis and data plotting were conducted with Excel and SPSS 13.0.

Redundancy analysis (RDA) was carried out to analyse the relationship between phytoplankton and environmental factors using Canoco 5.0 software. The length of the first axis was used to identify the analysis category as follows: > 4: canonical correspondence analysis (CCA), < 3: RDA and 3–4: either of the two (Muylaert et al. 2000; Beyene et al. 2009).

### **Results and discussion**

### Physicochemical factors of the water

The phytoplankton community changed greatly in Shihoudian Lake due to natural and man-made interference. In 2018, 250 acres of cage net and fishing facilities were cleared in Shihoudian Lake, which led to an improvement in water quality. However, due to the enclosed aquaculture for many years, a large amount of residual diet and manure was deposited, which influenced the water quality of the lake. The physicochemical index values for Shihoudian Lake across the five sampling sites and six sampling dates are provided in Fig. 2. The following values were observed: COD<sub>Mn</sub> of the water, 2.60-9.4 mg/L; NH<sub>3</sub>-N, 0.15-1.24 mg/L; TP, 0.01-0.08 mg/L; TN, 0.44-2.35 mg/L; NO<sub>3</sub>-N, 0.11-0.35 mg/L; NO<sub>2</sub>-N, 0.0003-0.014 mg/L; DO, 6.93-11.43 mg/L; pH 8.2-9.1. According to the water quality evaluation standards for groundwater (GB 3838-2002), the overall, the status of Shihoudian Lake was between categories IV and V.

### Phytoplankton community composition

A total of 143 phytoplankton species were collected across the three seasons (Table 1), representing eight phyla.



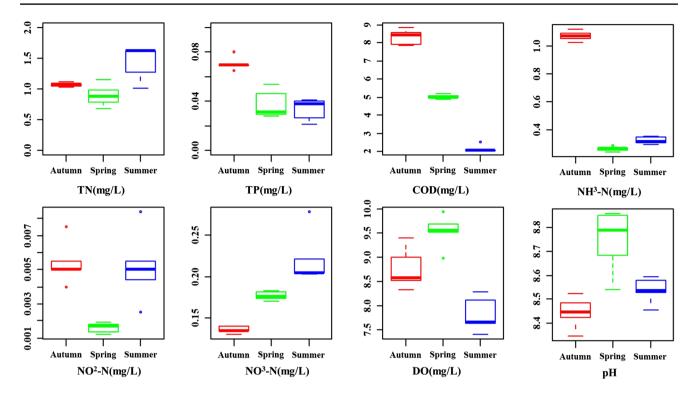


Fig. 2 Physicochemical characteristics associated with ecological remediation in Shihoudian Lake

Table 1 The community structure of phytoplankton in Shihoudian Lake

	Species number	Ratio
Cyanophyta	17	0.12
Prochlorophyta	66	0.46
Bacillariophyta	28	0.20
Cryptophyta	5	0.03
Euglenophyta	12	0.08
Xanthophyta	8	0.06
Chrysophyta	6	0.04
Pyrrophyta	1	0.01
Total	143	1

Chlorophyta had the highest species richness of the total phytoplankton (66 species; 46.2%), followed by Bacillariophyta (28 species; 19.6%). With the gradual increase in water temperature, a simultaneous increase occurred in light intensity and duration during the summer. In addition, with the gradual increase in nutritional salt, a concurrent increase in phytoplankton number occurred (Lehman 2000; Chuai et al. 2012). The number of phytoplankton species in different seasons exhibited an order of summer > autumn > spring, with numbers of 102 and 72 in the summer and spring, respectively. Green algae dominated in all three seasons, with the highest percentage in autumn (56.0%). The phytoplankton community was

**Table 2** Species and code in the dominant species sequencing graph of phytoplankton in Shihoudian Lake

Dominant species (Latin name)	Dominance index	Code
Oscillatoria sp.	0.55	OSS
Westella botryoides	0.02	WBO
Merismopedia sinica	0.02	MSI
Anabaena sp.	0.43	ANS
Coelosphaerium kuetzingiarum	0.02	CKU
Microcystis sp.	0.03	MSP
Merismopedia tenuissima	0.03	ETE
Anabaena circinalis	0.03	ACI
Synedra sp.	0.20	SYS
Phormidium sp.	0.63	PHS
Chlorella sp.	0.07	CHS
Chroomonas acuta	0.07	CAC
Merismopedia sp.	0.02	MES

dominated by blue algae-green algae throughout the year in Shihoudian Lake.

Dominant species had a dominance index value of Y > 0.02. According to the phytoplankton density and distribution (Table 2), 13 dominant species belonging to three phyla were identified in this study. The dominant species were members of Cyanophyta, with the highest dominance observed for Phormidium and Oscillatoria. Dominance of Oscillatoria, Phormidium, Anabaena and Microcystis





**Table 3** The average density of phytoplankton in Shihoudian Lake ( $\times 10^4$  ind./L)

Sampling time	Average biodensity × 10 <sup>4</sup> ind./L								
	Cyanophyta	Prochloro- phyta	Cryptophyta	Xanthophyta	Euglenophyta	Bacillari- ophyta	Chrysophyta	Pyrrophyta	Total
Autumn	314.24	23.01	1.71	1.88	0.40	0.47	0.03	0	341.75
Spring	500.12	55.89	36.55	3.24	2.59	83.37	3.61	2.74	688.12
Summer	1304.33	207.81	28.44	6.55	7.28	187.57	7.34	3.29	1752.61

Table 4 The average biomass of phytoplankton in Shihoudian Lake (mg/L)

Sampling time	Average biomass (mg/L)								
	Cyanophyta	Prochloro- phyta	Bacillari- ophyta	Cryptophyta	Euglenophyta	Xanthophyta	Chrysophyta	Pyrrophyta	Total
Autumn	1.567	0.039	0.004	0.068	0.023	0.039	0.002	0	1.742
Spring	1.05912	0.08342	0.49418	0.19648	0.11712	0.00168	0.04564	0.149	2.14664
Summer	3.681	0.351	1.737	0.27	0.307	0.08	0.068	0.237	6.731

species indicates water eutrophication. *Xanthophyta* species indicate clean water and were found occasionally, but they were not the dominant species. In all three seasons, *Cyanophyta* were dominant species, while *Prochlorophyta* were dominant species in spring and autumn. *Cryptophyta* and *Bacillariophyta* were dominant in the spring. This proportion of dominant taxa to total phytoplankton abundance was similar to that of Taihu Lake during a summer cyanobacteria bloom. Although no algal blooms were previously recorded for the study lake, the high proportion of *Cyanophyta* was also similar to that of another eutrophic lake (Jiang et al. 2014). Wang et al. (2013) showed that dominant taxa of *Chlorophyta* and *Cyanophyta* indicate that a lake is eutrophic to some extent.

### The density and biomass of phytoplankton

The average density and the biomass level of phytoplankton in the three seasons are shown in Tables 3 and 4. The seasonal variation in the average density of phytoplankton was in the range of  $341.75 \times 10^4$  to  $1752.61 \times 10^4$  ind./L with a medium value of  $927.49 \times 10^4$  ind./L. The average density in different seasons exhibited the following order: summer > spring > autumn. The density composition of Cyanophyta was highest, followed by that of Bacillariophyta and Prochlorophyta. The seasonal variation in the average biomass of phytoplankton was in the range of 1.74-6.73 mg/L with a medium value of 3.54 mg/L. The average biomass in different seasons exhibited the following order: summer > spring > autumn. The biomass composition of Cyanophyta was highest, followed by that of Bacillariophyta and Prochlorophyta. Among them, both the density and the biomass of *Cyanophyta* were highest in all seasons,

Table 5 The diversity index of phytoplankton in Shihoudian Lake

Shannon–Wie- Simpson Pielou Margal ner diversity abundance evenness abunda	ef
index index index index	nce
Autumn 1.310 0.595 0.316 4.093	
Spring 2.194 0.777 0.504 4.155	
Summer 2.092 0.771 0.456 4.959	

indicating eutrophication of the water (Ke et al. 2009; Zhang and Zang 2015).

### The diversity index of phytoplankton

The seasonal variation of the determined biodiversity index of phytoplankton is presented in Table 5. The Shannon-Wiener diversity index in the three seasons was in the range of 1.31–2.194 with an annual average of 1.865. The highest and lowest index values occurred in spring and autumn, respectively. The Simpson abundance index in the three seasons was in the range of 0.595–0.777 with an annual average of 0.714. The highest and lowest index values occurred in spring and autumn, respectively. The Pielou evenness index in the three seasons was in the range of 0.316-0.504 with an annual average of 0.425. The highest and lowest index values occurred in spring and autumn, respectively. Finally, the Margalef abundance index in the three seasons was in the range of 4.093-4.959 with an annual average of 4.402. The highest and lowest values occurred in summer and autumn, respectively. In a normal environment, the diversity index is high. When the environment is polluted, the density index decreases (Gao et al. 2019). Shihoudian Lake is a typical



lake in the Baiyangdian Lake region, around which there is a large population, with well-developed tourism. Thus, the water was polluted due to the gradual acceptance of wastewater in the river basin, and aquatic living resources were severely damaged. Judging from the relationship between the diversity index and the level of water pollution (Negro et al. 2000), the lake exhibited a state of light to moderate pollution.

## The relationship between the phytoplankton community and environmental factors

The evolution of the phytoplankton community was comprehensively influenced by the environmental factors of this water body. In addition to the effect of water temperature on phytoplankton, nutritional salt was also a dominant factor that influenced the phytoplankton community (Muylaert et al. 2000) because nutrition is the most basic factor that affects the growth of phytoplankton (Nydick et al. 2004). RDA preliminarily demonstrated a correlation between phytoplankton in the ecological remediation area and the main environmental factors (Fig. 3, Table 2). The length of the first axis was 2.0 (<4). Thus, it was appropriate to choose the linear model of RDA, which showed that the former two axes of RDA1 and RDA2 were significantly different (P < 0.01). The characteristic values of these two axes were 0.164 and 0.09936, respectively. The explanation degree reached 62.15%, indicating that the two sequencing axes could efficiently demonstrate the mutual relationship between phytoplankton in Shihoudian Lake and different environmental factors. The abbreviations of environmental factors and the codes for phytoplankton are listed in Tables 2 and Fig. 2. Oscillatoria positively correlated with NO<sub>2</sub>-N and DO. Kruskopf and Plessis (2006) proposed that nitrogen had the greatest influence on Oscillatoria growth, followed by ferric iron and phosphorus, which was similar to the present study. Low and high pH values would inhibit the

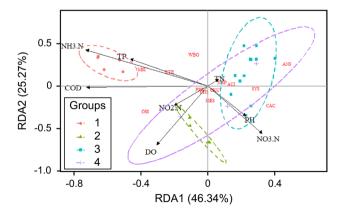


Fig. 3 RDA between phytoplankton and environmental factors





enzyme activity in algal cells, influencing algal metabolism, leading to a decrease in growth and proliferation (Melack 1981). In this study, Chroomonas acuta Uterm correlated positively with NO<sub>3</sub>-N. Reynolds (2006) proposed an optimum N-to-P ratio of 16:1 for the growth of phytoplankton. When the ratio was larger than 16:1, phytoplankton growth was limited mainly by P, while when the ratio was smaller than 16:1, it was limited mainly by N. In this work, Raphidiopsis sinensia and Microschizophyllum correlated positively with TP, NH<sub>3</sub>-N and COD<sub>Mn</sub>, with N and P ratios greater than 16. Thus, the growth of blue algae was mainly limited by P in Shihoudian Lake. The environmental factors that dramatically affected the phytoplankton in Baiyangdian Lake were different in various areas in the water body and during different periods (Shen and Liu 2008; Zhang et al. 2010; Jin et al. 2017). In total, the environmental factors that mainly affected blue algae in Shihoudian Lake were in descending order: total P and  $COD_{Mn} > molecular$  nitrogen, pH and DO.

The phytoplankton community structure of various types of lakes exhibits significant differences (Lepistö et al. 2004; Lv et al. 2013; Devab et al. 2019). Baiyangdian Lake is a typical aquatic macrophyte-dominated lake in northern China (Yang et al. 2020) that is distinguished from other lakes. The dominant species of cyanobacteria in this survey were Oscillatoria sp. and Phormidium sp., with dominance indexes of 0.55 and 0.63, respectively. This study provides a reference for the monitoring and evaluation of water quality of lakes in northern China and similar lakes worldwide at the same latitude, as well as a basis for the formulation of specific measures for ecological remediation of Baiyangdian Lake. Although the water quality of Baiyangdian Lake has been improved, changes in the dominant species require a long time (Zhao et al. 2019). Therefore, both short-term remediation and long-term maintenance are key factors to ensure the remediation target.

### **Conclusion**

This study analysed the trophic states, species numbers, community structures and biodiversity of phytoplankton in Baiyangdian Lake. The species richness, abundance, diversity index and evenness index of phytoplankton showed the lake exhibited a state of light to moderate pollution. The phytoplankton abundance was highest in summer, *Cyanophyta* were the dominant tax of plankton. TP and COD<sub>Mn</sub> were the main environment factors influencing the species number and diversity of phytoplankton based on the redundancy analysis (RDA) results. It provides a reference for the formulation of specific measures for ecological remediation of Baiyangdian Lake.

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**Authors' contributions** HZ designed the study; HZ and XL performed the experiments; and HZ and SC analysed the data and wrote the manuscript.

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### **Compliance with ethical standards**

**Conflict of interest** The authors declare that there is no conflict of interest regarding the publication of this article.

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