

Original Research

Differentiated Responses of Plankton and Zoobenthos to Water Quality Based on Annual and Seasonal Analysis in a Freshwater Lake

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Abstract

In order to reveal the differentiated responses of plankton and zoobenthos to water quality on both annual and seasonal time scales, an ecological study on plankton and zoobenthos community was conducted during 2011 to 2015 in Nansi Lake in northern China. Different dynamics were found among phytoplankton, zooplankton, and zoobenthos in terms of density, biomass, and biodiversity. On an annual time scale and with deterioration of water quality, density and biomass of plankton and zoobenthos showed different variations, while phytoplankton (density, biomass, and biodiversity) changed significantly when water quality improved. On a seasonal time scale, density and biomass of phytoplankton showed significant differences between spring and summer. Results of Pearson's correlation analysis revealed that phytoplankton, zooplankton, and zoobenthos were significantly affected by different environmental factors. Our study demonstrated that phytoplankton was more sensitive to water quality changes than zooplankton and zoobenthos. These results suggest that density and biomass of phytoplankton could rapidly reflect water quality, whereas biodiversity of phytoplankton could indicate long-term status of water quality combined with the physico-chemical parameters of water. The results could contribute to predicting the dynamics of plankton and zoobenthos in freshwater lakes and to selecting effective bio-indicators for ecosystem health assessment of freshwater lakes.

Keywords: biodiversity, community, plankton, water quality, zoobenthos

Introduction

Biodiversity conservation in aquatic ecosystems has become a hotspot due to the sharp decline of biodiversity caused by human activities [1]. Biodiversity, which is one of the fundamental elements of ecosystem functioning [2], has been considered an important indicator that could be applied in biological restoration as well as assessing ecosystem health of a lake [3]. Previous studies of biodiversity in aquatic ecosystems, which refer to phytoplankton, zooplankton, and zoobenthos, focus mainly on the relationships between biological characteristics and environmental variables [4-5], spatio-temporal patterns [6-8], and biological restoration [9-11]. Yet studies on differentiated response patterns of biodiversity in freshwater lakes on water quality based on annual and seasonal analysis, as an essential work for the biological recovery and management of a lake ecosystem, are few and should be paid more attention.

Generally, phytoplankton, zooplankton, and zoobenthos were used to assess the ecosystem health of a lake [12-13]. On one hand, they reflected water quality directly because their density and biomass were affected by physico-chemical factors [14-15]. For instance, as the primary producer in aquatic ecosystems, phytoplankton grows fast in eutrophic lakes, therefore its density and biomass could reflect the trophic status of a lake. On the other hand, certain species of phytoplankton, zooplankton, and zoobenthos were indicators of polluted lakes [12-13]. For instance, the dominant species of *Microcystis* indicated eutrophication of lakes [16].

Nansi Lake is the largest freshwater lake in northern China, with a total water area of 1,266 km² and average water depth of 1.4 m. Since Nansi Lake is an important storage lake in the eastern route of the South-to-North Water Diversion Project of China, its water quality should meet the requirements of national water quality standards of grade III. Nansi Lake used to be a polluted lake in the 1980s, but its water quality has improved greatly since 2002. The main indexes of water quality reduced and water purification made great progress in 2010 and 2011 [17]. The significant change of water quality in Nansi Lake provides good material to study the differentiated response of plankton and zoobenthos to water quality in a large freshwater lake.

We collected plankton, zoobenthos, and water samples in Nansi Lake from 2011 to 2015 and measured them in a laboratory. This research aims to study the differentiated response of plankton and zoobenthos to water quality on both annual and seasonal time scales in terms of density, biomass, and biodiversity. Furthermore, we attempted to reveal the mechanism of differentiated response of different taxa in a lake to find effective and credible indexes for assessment of water quality. This work would contribute to predicting the dynamics of plankton and zoobenthos in freshwater lakes and to selecting effective bio-indicators for the ecosystem health assessment of freshwater lakes.

Materials and Methods

Study Area and Sampling Sites

Nansi Lake (34°27'N~35°20'N, 116°34'E~117°21'E) is located in southwestern Shandong Province in northern China. With a total area of 1,266 km², Nansi Lake is the largest freshwater lake in northern China. The climate of the lake is temperate continental monsoon. A total of 10 sampling sites were set in Nansi Lake (Fig. 1).

Sampling Methods

Biodiversity Sampling

Biodiversity samples were collected in spring and summer respectively during 2011-2015. Plankton samples were collected with plankton nets. The qualitative samples, which were collected by 13# plankton net (macroplankton samples) and 25# plankton net (microplankton samples) respectively, were classified with a light microscope. The quantitative samples were collected in different ways. Microplankton samples, which were collected with a 1 L plankton sampler, were kept in brown bottles and fixed with Lugol's iodine solution for microscopic enumeration. Macroplankton samples, which were collected with 40 L water samples concentrated to 30 mL through a 13# plankton net, were fixed with formaldehyde solution for microscopic enumeration. Zoobenthos samples were collected with a grab sampler. Each sample was washed and sieved through a 40-mesh nylon-membrane. The retained materials were preserved in 75% alcohol and then transferred to a laboratory to be enumerated. The biomass of plankton and zoobenthos were calculated according to the Handbook of fishery natural resource investigation in inside water area [18].

Water Sampling

Water samples were collected once a year during 2011 to 2014 and twice a year (in spring and summer, respectively) in 2015. Water samples were collected at a

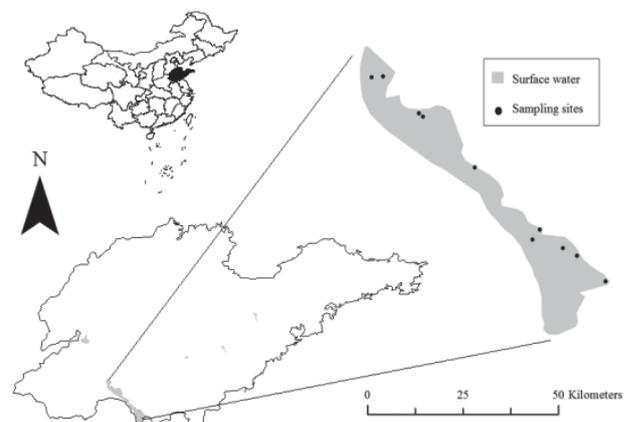


Fig. 1 Location and sampling sites of Nansi Lake, China.

depth of 0.5 m below the surface using a 1 L Ruttner water sampler. Samples were carried back to the laboratory as soon as possible in low temperature conditions for total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD_{Cr}), NH₃-N, and permanganate index (COD_{Mn}) measure. Water temperature (WT), water depth, transparency (SD), pH, chlorophyll a, and dissolved oxygen (DO) were measured in the field using a thermometer (WT, Beijing Purity Instrument Co., Ltd, China), Secchi disk (SD-20, Beijing Purity Instrument Co., Ltd, China), a portable pH meter (CT-6021A, Shenzhen Kedida Electronics Co. Ltd, China), a portable chlorophyll a meter (Hydrolab DS5X, HACH, USA), and a portable dissolved oxygen meter (HI9829, HANNA, Italy).

Calculation of Biodiversity

Shannon-Wiener index (H) [19] and Simpson's diversity index (D) [20] were calculated by the following equations:

$$H = -\sum_{i=1}^S P_i \ln P_i \quad (1)$$

$$D = 1 - \sum (N_i / N)^2 \quad (2)$$

...where N_i is abundance of species i , N is total abundance, S is species richness, and P_i is the abundance proportion of species i .

Statistical Analysis

Statistical analysis were performed with SPSS (Version 19.0). Two-way ANOVA was used to analyze the effects of year and season on the phytoplankton, zooplankton, and zoobenthos. We use a Duncan test to analyze the significant differences of phytoplankton, zooplankton, and zoobenthos over five years. Pearson's correlation analysis was conducted to explore the correlations between phytoplankton, zooplankton, zoobenthos, and environmental factors.

Results

Environmental Variations

Nine indexes of water quality in Nansi Lake were measured in this study (Table 1). Water quality of Nansi Lake in 2011 was relatively good, with only TP and COD_{Cr} showing high concentrations and exceeding the national water quality standards of grade III (TP ≤ 0.05 mg·L⁻¹; TN ≤ 1 mg·L⁻¹; NH₃-N ≤ 1 mg·L⁻¹; COD_{Cr} ≤ 20 mg·L⁻¹; COD_{Mn} ≤ 6 mg·L⁻¹). The water quality remained good in 2012 and became better in 2013 when the concentrations of TP, chlorophyll a, COD_{Cr}, COD_{Mn}, and NH₃-N decreased. However, water quality of Nansi

Table 1. Water quality of Nansi Lake from 2011 to 2015.

| Mean | 2011 | 2012 | 2013 | 2014 | 2015 |
|--|-------|-------|-------|-------|-------|
| TP/(mg·L ⁻¹) | 0.086 | 0.091 | 0.081 | 0.14 | 0.07 |
| TN/(mg·L ⁻¹) | 0.97 | 1.04 | 1.01 | 1.36 | 2.40 |
| Chlorophyll a/ (mg·L ⁻¹) | 10.87 | 8.58 | 7.17 | 6.14 | 17.93 |
| SD/m | 0.50 | 0.63 | 0.69 | 0.29 | 0.36 |
| Water depth/m | 3.1 | 2.9 | 2.7 | 1.4 | 1.2 |
| pH | 7.63 | 7.58 | 7.95 | 8.26 | 8.18 |
| COD _{Cr} /(mg·L ⁻¹) | 21.6 | 25.7 | 21.5 | 23.46 | 26.41 |
| COD _{Mn} /(mg·L ⁻¹) | 5.59 | 5.67 | 5.23 | 5.46 | 5.38 |
| NH ₃ -N/(mg·L ⁻¹) | 0.28 | 0.25 | 0.11 | 1.10 | 0.56 |

TP: total phosphorus; TN: total nitrogen; SD: transparency; COD_{Cr}: chemical oxygen demand; COD_{Mn}: permanganate index

Lake became worse in 2014, showing higher concentrations of TP, TN, COD_{Cr}, and NH₃-N – probably due to the dry weather in 2014. This trend continued to 2015, causing high concentrations of TN, chlorophyll a, and COD_{Cr} in Nansi Lake. However, compared with 2014, water quality of Nansi Lake in 2015 showed slight improvement.

Phytoplankton

A total of 92, 117, 119, 124, and 132 species of phytoplankton belonging to seven phyla were identified during 2011 to 2015 in Nansi Lake. During the whole survey period, phytoplankton density ranged from 2.699×10⁵ cells·L⁻¹ to 6.959×10⁶ cells·L⁻¹, and phytoplankton biomass ranged from 0.225 mg·L⁻¹ to 5.459 mg·L⁻¹ (Fig. 2). Density and biomass of phytoplankton decreased during 2011-13 and then increased in 2014. But finally they dropped in 2015, approaching the lowest value. In addition, the density and biomass of phytoplankton in summer were larger than those in spring. The Shannon-Wiener index of phytoplankton ranged between 2.30 and 3.54 and Simpson's diversity index of phytoplankton ranged between 0.66 and 0.96 in Nansi Lake. Biodiversity (Shannon-Wiener index and Simpson's diversity index) of phytoplankton in summer was higher than that in spring during 2011-15. Both Shannon-Wiener index and Simpson's diversity index of phytoplankton in Nansi Lake were roughly unchanged during 2011-14 and decreased in 2015 significantly.

Zooplankton

A total of 58 and 62 species of zooplankton were observed in Nansi Lake in 2011 and 2012, respectively, while 67 species were observed in 2013-14. In 2015, 65 species of zooplankton were identified in Nansi Lake. Zooplankton density ranged from 2,926.36 ind·L⁻¹ to

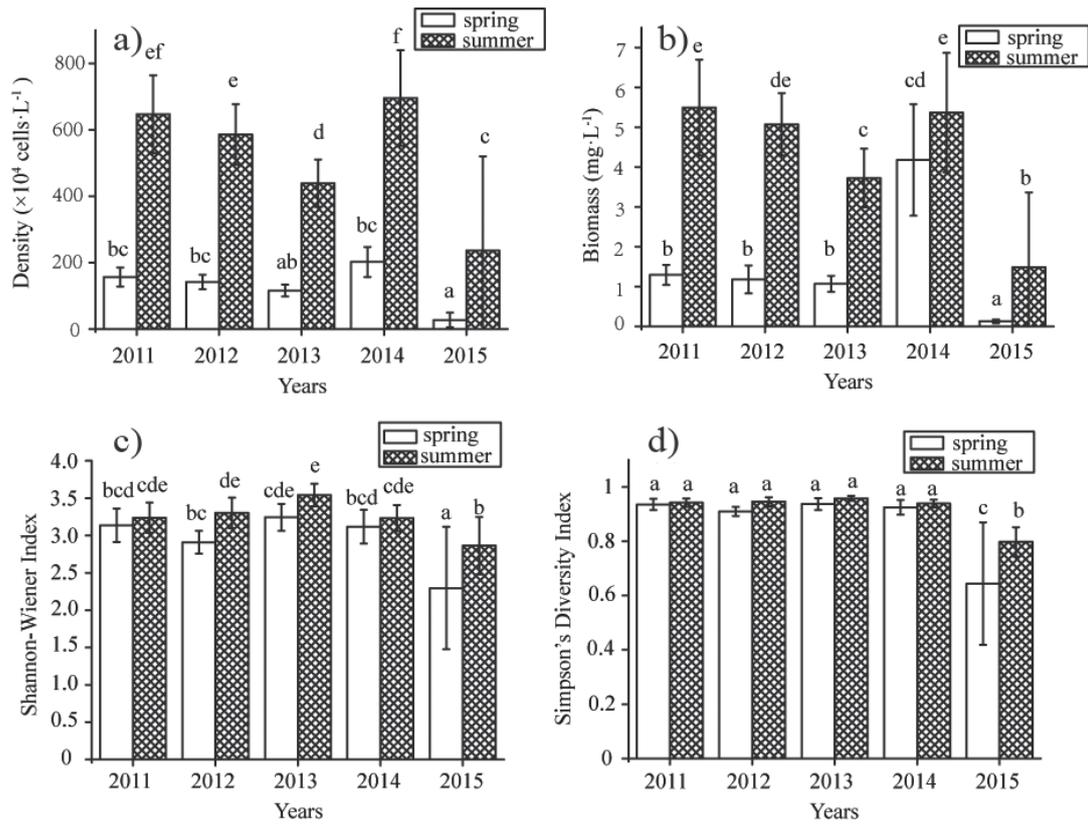


Fig. 2 Density, biomass, biodiversity of phytoplankton in Nansi Lake during 2011 to 2015 (a) density; b) biomass; c) Shannon-Wiener index; d) Simpson's diversity index).

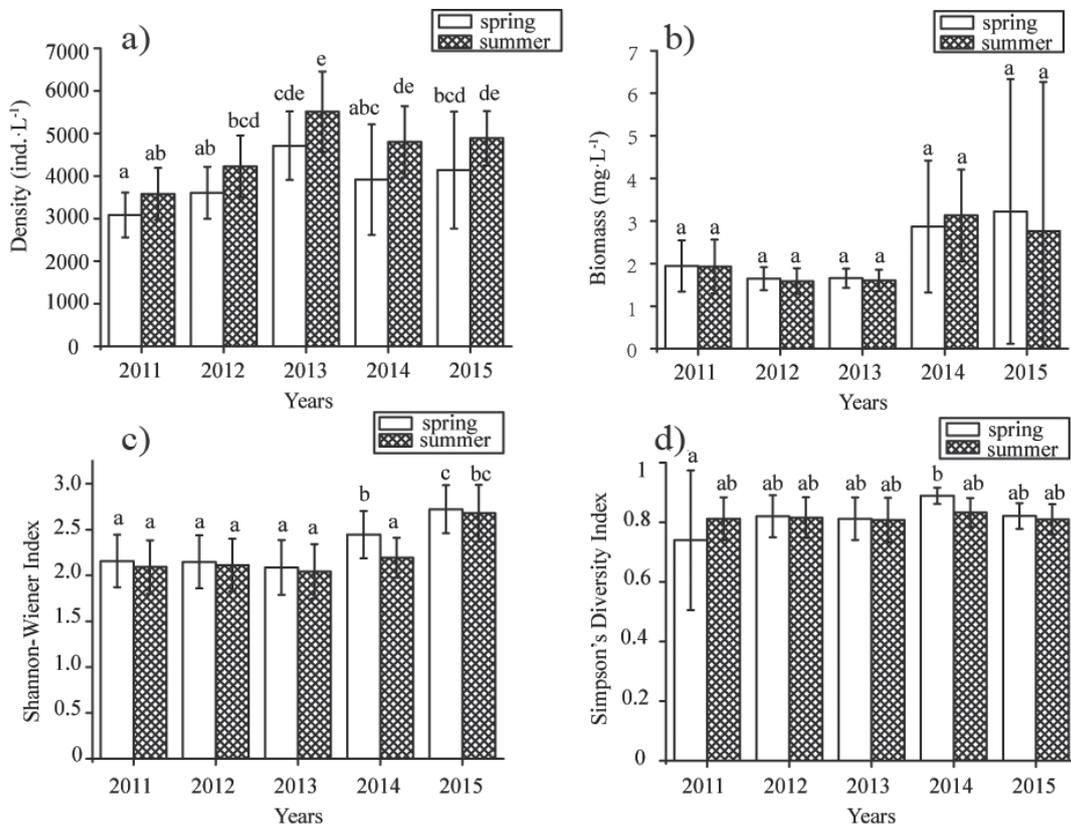


Fig. 3 Density, biomass, biodiversity of zooplankton in Nansi Lake during 2011 to 2015 (a) density; b) biomass; c) Shannon-Wiener index; d) Simpson's diversity index).

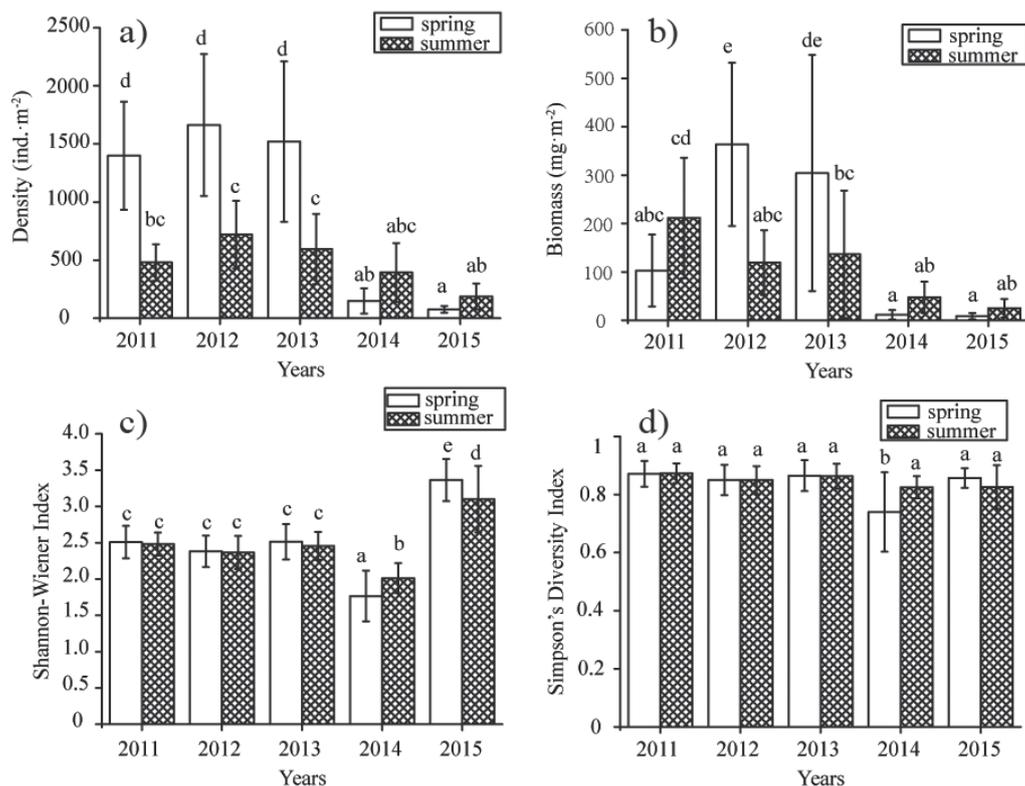


Fig. 4 Density, biomass, biodiversity of zoobenthos in Nansi Lake during 2011 to 2015 (a) density; b) biomass; c) Shannon-Wiener index; d) Simpson's diversity index).

5,226.58 ind.·L⁻¹, and biomass ranged from 1.48 mg·L⁻¹ to 3.55 mg·L⁻¹ (Fig. 3). Zooplankton density increased during 2011-13 and then decreased in 2014. It finally increased in 2015. Moreover, the density of zooplankton in summer was larger than that in spring. Biomass of zooplankton decreased in 2011-13 and then increased in 2014. Finally, it decreased in 2015. The Shannon-Wiener index of zooplankton ranged between 2.04 and 2.72 and Simpson's diversity index of zooplankton ranged between 0.74 and 0.89 in Nansi Lake. The Shannon-Wiener index of zooplankton remained steady during 2011-13 and increased in 2014-15, whereas Simpson's diversity index was steady during the whole survey period.

Zoobenthos

Fifty-two species of zoobenthos were identified in 2014-15 in Nansi Lake, while 35, 49, and 51 species were found during 2011 to 2013. Zoobenthos density ranged from 76.40 ind.·m⁻² to 1,644.92 ind.·m⁻², and biomass ranged from 7.83 g·m⁻² to 353.61 g·m⁻² in Nansi Lake (Fig. 4). Average density and biomass of zoobenthos showed a tendency to ascend during 2011-13 and decreased significantly in spring 2014. The declined trend continued to 2015. The Shannon-Wiener index of zoobenthos ranged between 1.77 and 3.36, and Simpson's diversity index ranged between 0.70 and 0.86 in the lake. Shannon-Wiener index of zoobenthos in Nansi Lake decreased significantly in 2014 and recovered in 2015 (whether in

spring or summer), while Simpson's diversity index of that decreased significantly in spring 2014.

Correlations between Phytoplankton, Zooplankton, Zoobenthos and Environmental Factors

Pearson's correlation analysis was conducted to reveal the relationships between plankton, zoobenthos, and environmental factors in Nansi Lake in 2015 (Table 2). Pearson's correlation analysis indicated that phytoplankton density and biomass had significantly positive correlations with WT and TP. The results also showed a positive correlation between phytoplankton diversity (Shannon-Wiener index and Simpson's diversity index) and WT, and negative correlations between phytoplankton diversity, transparency and NH₃-N concentration. Moreover, Pearson's correlation analysis showed that zooplankton density was significantly correlated with TN (positively) and pH (negatively) in Nansi Lake. There were no significant correlations between zooplankton biomass and environmental factors. Biodiversity of zooplankton was positively correlated with WT and negatively correlated with transparency and DO. Moreover, significantly positive correlations existed between zoobenthos density, COD_{Cr}, chlorophyll a, WT, and TP in Nansi Lake. Zoobenthos biomass was positively correlated with WT and TP. No significant correlations were found between environmental factors and zoobenthos diversity.

Table 2. Pearson correlation analysis (n = 20) between phytoplankton, zooplankton, zoobenthos, and environmental factors of Nansi Lake in 2015.

| Item | WT | pH | DO | SD | COD _{Cr} | COD _{Mn} | Chlorophyll a | TP | TN | NH ₃ -N |
|--|----------------|----------------|----------------|-----------------|-------------------|-------------------|---------------|----------------|----------------|--------------------|
| Phytoplankton density | 0.531* | 0 | -0.271 | -0.328 | 0.306 | 0.166 | 0.326 | 0.547* | 0.012 | -0.242 |
| Phytoplankton biomass | 0.525* | -0.022 | -0.276 | -0.329 | 0.293 | 0.165 | 0.301 | 0.555* | 0.015 | -0.256 |
| Shannon-Wiener index of phytoplankton | 0.487* | -0.344 | -0.403 | -0.592** | 0.158 | -0.01 | 0.32 | 0.437 | 0.161 | -0.500* |
| Simpson's diversity index of phytoplankton | 0.502* | -0.416 | -0.434 | -0.642** | 0.177 | -0.019 | 0.388 | 0.441 | 0.154 | -0.444* |
| Zooplankton density | 0.366 | -0.477* | -0.176 | -0.433 | 0.036 | 0.015 | 0.07 | 0.301 | 0.640** | -0.295 |
| Zooplankton biomass | -0.071 | -0.406 | -0.025 | -0.108 | -0.312 | -0.124 | -0.217 | -0.183 | 0.1 | -0.153 |
| Shannon-Wiener index of zooplankton | 0.721** | -0.275 | -0.513* | -0.553* | 0.318 | 0.074 | 0.409 | 0.495* | 0.091 | -0.336 |
| Simpson's diversity index of zooplankton | 0.642** | -0.289 | -0.479* | -0.541* | 0.204 | -0.021 | 0.34 | 0.444 | 0.108 | -0.296 |
| Zoobenthos density | 0.645** | 0.119 | -0.282 | -0.339 | 0.479* | 0.232 | 0.454* | 0.699** | 0.051 | -0.309 |
| Zoobenthos biomass | 0.572** | 0.233 | -0.188 | -0.27 | 0.425 | 0.23 | 0.4 | 0.626** | 0.012 | -0.205 |
| Shannon-Wiener index of zoobenthos | -0.326 | -0.112 | 0.149 | 0.003 | -0.016 | -0.149 | -0.052 | -0.147 | -0.077 | 0.186 |
| Simpson's diversity index of zoobenthos | -0.253 | -0.147 | 0.066 | -0.127 | -0.038 | -0.196 | -0.015 | -0.106 | -0.069 | 0.202 |

** : Significant correlations with $\alpha = 0.01$, * : Significant correlations with $\alpha = 0.05$

WT: water temperature; DO: dissolved oxygen; TP: total phosphorus; TN: total nitrogen; SD: transparency; COD_{Cr}: chemical oxygen demand; COD_{Mn}: permanganate index

Discussions

Annual Dynamics of Plankton and Zoobenthos

Different annual dynamics were found among phytoplankton, zooplankton and zoobenthos in Nansi Lake in terms of density, biomass and biodiversity. With the increase of nutrient concentration, the density of phytoplankton in Nansi Lake increased significantly in summer in 2014 and biomass of that increased significantly in 2014 in spring and summer, which indicated that nutrients had important influence on the growth of phytoplankton, and similar results were reported in previous studies [21-22], while the decrease of TP, density, and biomass of phytoplankton in Nansi Lake decreased significantly in 2015. Moreover, in our study, density and biomass of phytoplankton were significantly and positively correlated with TP in 2015. This implied

that TP is the main limiting factor of phytoplankton in Nansi Lake. Our study found that zooplankton density decreased in 2014 and then increased in 2015. One study showed a negative correlation between zooplankton density and TP [23]. Similarly, in our study, with the increase of TP concentration in 2014, density of zooplankton decreased. In addition, zooplankton biomass increased in 2014-15 with the increase of nutrient concentration in Nansi Lake. Especially noteworthy was the report that zooplankton biomass increased with the increase of NH₃-N concentration [24]. In our study, density and biomass of zoobenthos declined in 2014 and 2015, corresponding to the deterioration of water quality (higher COD_{Cr}, TP, TN, and NH₃-N). A 50-year study in Nansi Lake also pointed out that water reduction and pollution can result in a decrease of zoobenthos density [25]. Moreover, zoobenthos was affected by sediments [26]. The lower water depth and water pollution in 2014-15 may change the properties of sediments, leading to a

Table 3. Water quality of Nansi Lake in 2015 in different seasons.

| Season | WT (°C) | pH | SD (m) | DO (mg·L ⁻¹) | Chlorophyll a (mg·L ⁻¹) | TP (mg·L ⁻¹) | COD _{Mn} (mg·L ⁻¹) | COD _{Cr} (mg·L ⁻¹) | NH ₃ -N (mg·L ⁻¹) | TN (mg·L ⁻¹) |
|--------|---------|------|--------|--------------------------|-------------------------------------|--------------------------|---|---|--|--------------------------|
| Spring | 19.90 | 8.29 | 0.54 | 10.57 | 12.23 | 0.04 | 5.17 | 20.25 | 0.75 | 1.99 |
| Summer | 30.86 | 8.16 | 0.19 | 5.96 | 23.63 | 0.10 | 5.59 | 32.51 | 0.17 | 2.81 |

WT: water temperature; SD: transparency DO: dissolved oxygen; TP: total phosphorus; TN: total nitrogen; COD_{Cr}: chemical oxygen demand; COD_{Mn}: permanganate index

decrease of zoobenthos. Compared with zooplankton and zoobenthos, phytoplankton was more sensitive to water quality change in our study. Density and biomass of phytoplankton changed with water quality significantly during the period of 2014-15, whereas those of zooplankton and zoobenthos had no significant changes when water quality improved in 2015.

In this research, the biodiversity (Shannon-Wiener index and Simpson's diversity index) of plankton and zoobenthos remained steady during 2011-13 and changed with variation of water quality in 2014 and 2015. However, the responses were different. The biodiversity of phytoplankton in Nansi Lake remained steady in 2014, which indicated that worse water quality had little influence on the biodiversity of phytoplankton in a short time. But in 2015, biodiversity of phytoplankton in Nansi Lake decreased significantly, which may due to the increase in eutrophication [27-28]. Worse water quality resulted in lower zooplankton density of some species, while richness of zooplankton did not change in our study. So the Shannon-Wiener index of zooplankton showed that zooplankton diversity increased during 2014-15 in Nansi Lake. Our study found that zoobenthos diversity changed obviously with water quality, especially the Shannon-Wiener index. When water quality became worse, the Shannon-Wiener index of zoobenthos decreased significantly in 2014. In 2015, when water

quality improved slightly, the Shannon-Wiener index of zoobenthos increased.

Seasonal Variations of Plankton and Zoobenthos in 2015

In our study, density and biomass of phytoplankton displayed significant differences between spring and summer in 2015. The higher density and biomass of phytoplankton in summer could be attributed to the higher water temperature and the deterioration of water quality (Table 3), and a similar result was obtained in Lake Chaohu [29]. This indicated that the density and biomass of phytoplankton made a rapid response to the variation of water quality. In addition, we found that the community composition of phytoplankton varied with seasons, which was also found in other lakes [30-31]. In our study, Cryptophyta was the dominant species in spring, whereas Bacillariophyta was the dominant species in summer. However, a study of spring-summer successions of phytoplankton in Lake Taihu found that the dominant species changed from Chlorophyta to Cyanobacteria [31]. The difference of dominant species between the two lakes was probably because Lake Taihu was a eutrophic lake while Nansi Lake was not. However, unlike phytoplankton, zooplankton in Nansi Lake had no significant difference between spring and summer

Table 4. Shannon-Wiener index (*H*) of plankton and zoobenthos and the pollution degree of Nansi Lake in different seasons during 2011 to 2015.

| Season | Year | Phytoplankton | | Zooplankton | | Zoobenthos | |
|--------|------|---------------|------------------|-------------|------------------|------------|--------------------|
| | | <i>H</i> | Pollution degree | <i>H</i> | Pollution degree | <i>H</i> | Pollution degree |
| Spring | 2011 | 3.14 | Clean | 2.16 | Slight pollution | 2.51 | Slight pollution |
| | 2012 | 2.91 | Slight pollution | 2.15 | Slight pollution | 2.38 | Slight pollution |
| | 2013 | 3.24 | Clean | 2.09 | Slight pollution | 2.51 | Slight pollution |
| | 2014 | 3.12 | Clean | 2.45 | Slight pollution | 1.77 | Moderate pollution |
| | 2015 | 2.30 | Slight pollution | 2.72 | Slight pollution | 3.36 | Clean |
| Summer | 2011 | 3.24 | Clean | 2.09 | Slight pollution | 2.48 | Slight pollution |
| | 2012 | 3.30 | Clean | 2.11 | Slight pollution | 2.37 | Slight pollution |
| | 2013 | 3.54 | Clean | 2.04 | Slight pollution | 2.46 | Slight pollution |
| | 2014 | 3.23 | Clean | 2.19 | Slight pollution | 2.01 | Slight pollution |
| | 2015 | 2.86 | Slight pollution | 2.68 | Slight pollution | 3.10 | Clean |

in terms of density and biomass in 2015. Density of zooplankton in summer was higher than that in spring, whereas biomass of zooplankton was lower in summer. This was because density and biomass of Cladocera and Copepoda decreased in summer in our study, which probably resulted from high predation pressure by fish [32]. In our study, density and biomass of zoobenthos in summer were higher than those in spring in 2015, corresponding to the higher water temperature and nutrient concentration in summer. Moreover, our research revealed that both density and biomass of zoobenthos were positively correlated with WT and TP. It could be concluded that water temperature and TP had an important influence on zoobenthos in terms of density and biomass, which was similar to previous studies [15, 33].

Biodiversity (Shannon-Wiener index and Simpson's diversity index) of plankton and zoobenthos showed little difference between spring and summer in Nansi Lake in 2015. Therefore, it is suitable for the long-term assessment of water quality. The pollution status of Nansi Lake was assessed using the Shannon-Wiener index (Table 4). The results were different when we use different bio-indicators, which indicated that the combination of Shannon-Wiener index and physico-chemical parameters could give an overall and credible assessment of water quality in Nansi Lake.

Influencing Factors of Plankton and Zoobenthos

Different influencing factors of plankton and zoobenthos in Nansi Lake were found in this study. Pearson's correlation analysis showed that density and biomass of phytoplankton had positive correlations with WT and TP, which indicated that WT and TP are important factors driving phytoplankton growth in Nansi Lake. A similar result was observed in previous study [34]. Increased water temperature promotes photosynthesis [35] and phytoplankton growth [36]. Nutrients, especially nitrogen and phosphorus, are essential for phytoplankton growth [37]. A study in Taihu Lake found that TP and TN are limiting factors of phytoplankton biomass [38]. Elliott et al. [39] pointed out that the increase of water temperature and nutrient concentration could result in the increase of phytoplankton biomass in a temperate freshwater lake. Nowrouzi and Valavi [40] found that phytoplankton density was affected by water temperature and nutrients in a freshwater lake. It could be concluded that water temperature and nutrients are important factors for determining density and biomass of phytoplankton in freshwater lakes. In addition, our study found that zooplankton density was positively correlated with TN. The increase of TN concentration accelerates phytoplankton growth [37], and therefore zooplankton density increases in abundant food conditions [41]. There were significantly positive correlations between zoobenthos (density and biomass), WT, and TP in our study. The results indicated that water temperature and nutrients had great influence on density and biomass of zoobenthos, which was also

obtained in Daya Bay [15, 33]. However, previous research revealed that TP was negatively correlated with zoobenthos [42]. The different correlation between TP and zoobenthos in our study is probably because the properties of sediments in Nansi Lake make a complex influence on zoobenthos.

Conclusions

Our study confirmed that plankton and zoobenthos had different responses to variations in water quality in Nansi Lake. Based on annual analysis, when water quality became worse, the density of phytoplankton increased while those of zooplankton and zoobenthos decreased. Meanwhile, biomass of plankton increased while that of zoobenthos decreased. In addition, zoobenthos diversity (Shannon-Wiener index and Simpson's diversity index) decreased and Shannon-Wiener index of zooplankton increased, whereas biodiversity of phytoplankton had no obvious changes with the deterioration of water quality. When water quality improved, density and biomass of phytoplankton decreased significantly. Moreover, biodiversity of phytoplankton decreased while the Shannon-Wiener index of zooplankton and zoobenthos increased. Based on seasonal analysis, phytoplankton density and biomass showed significant differences between spring and summer in Nansi Lake. In addition, different influencing factors of plankton and zoobenthos were found in the lake. Phytoplankton was more sensitive to water quality change than zooplankton and zoobenthos. Furthermore, compared with biodiversity, density and biomass of phytoplankton were more sensitive to variations of water quality in a short time. Therefore, density and biomass of phytoplankton could reflect water quality rapidly, whereas biodiversity of phytoplankton could indicate the long-term status of water quality. This study contributes to predicting dynamics of plankton and zoobenthos in freshwater lakes and to selecting effective bio-indicators for assessing the ecosystem health of freshwater lakes.

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