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Seasonal pattern of cyanobacteria community and its relationship with environmental factors: a case study in Luoma Lake, East China

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ABSTRACT

Luoma Lake is located on the east route of the South-to-North Water Diversion Project, and it is a potential source of drinking water. From March 2011 to May 2013, the spatio-temporal distribution variation of cyanobacteria community associated with environmental factors was comprehensively investigated based on a monthly sampling. A total of 27 cyanobacteria species belonging to 14 genera were identified, and the most predominant cyanobacteria genus was *Pseudanabaena*, not the usual bloom-forming genera such as *Microcystis* and *Anabaena*. The cyanobacteria abundance at all the sampling sites exhibited similar spatio-temporal distribution variation, and the cyanobacteria abundance ranged over seven orders of magnitude from the undetectable level to 3.9×10^7 cells/L. Redundancy analysis and Pearson correlation analysis were applied to analyze the relationship between species and environment variables. The results suggested there was a positive correlation between cyanobacteria abundance and water temperature and ammonium concentration, while that between cyanobacteria abundance and dissolved oxygen concentration was negative. In addition, other environmental factors like precipitation and water turbulence could affect the cyanobacteria community distribution. Cyanobacterial blooms might not occur in Luoma Lake, with the predominant cyanobacteria genus being *Pseudanabaena* and water quality improved owing to the implementation of the water diversion project.

Keywords: Cyanobacteria community; Seasonal pattern; Dominant species; Environmental factors; Water diversion project; Luoma Lake

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1. Introduction

In recent years, eutrophication has become a worldwide ecological problem in freshwater and coastal ecosystems [1–3]. Serious eutrophication in freshwater lakes can cause the increasing occurrence of cyanobacteria population and even harmful algal blooms (HABs) under certain conditions [4,5]. The cyanobacterial dominance and HABs create environmental issues such as bad odor and surface scum. Some cyanobacteria species even produce toxins, which are threats to aquatic life and the safety of water resources [6–8]. At present, HABs are increasingly frequent in some eutrophic freshwater lakes of China, such as Taihu Lake, Chaohu Lake, and Dianchi Lake [9–13]. HABs are a major public concern to drinking water utilities, and more and more scientific research has been carried out to determine the factors contributing to water blooms.

Luoma Lake is the fourth largest freshwater lake in Jiangsu province, China [14,15]. It is a typical shallow lake and covers an area of 320 km^2, which is now in meso-eutrophic level [15,16]. It is located on the east route of the South-to-North Water Diversion Project (SNWDP), which is designed to ease water challenges in Northern China and thus contribute to socio-economic development [17]. Therefore, Luoma Lake becomes a potential drinking water source for the residents along this water diversion project, on account of its function of water channel and water resource regulating.

Therefore, it is necessary to determine the occurrence possibility of cyanobacterial blooms during the implementation of this water diversion project, due to the fact that HABs would greatly affect the water quality and threaten the safety of drinking water. There have been many studies concerning to the spatio-temporal distribution of cyanobacteria population and their relationship with environmental factors. These studies provided an effective way to understand the development pattern of cyanobacteria community and the formation mechanism of cyanobacterial blooms [18–20]. Cyanobacteria populations are sensitive to water environment changes and some cyanobacteria species have specific growth rhythms [21,22]. Many environmental factors have been found related to the formation of HABs. There is a consensus so far that HABs are often not caused by one single environmental factor, but rather multiple factors occurring simultaneously or consecutively [23,24]. Two studies have indicated that an increase of water temperature (WT) in warm seasons plays an important role in the mass proliferation of cyanobacteria species [25,26], but different cyanobacteria species usually have distinct optimum temperatures for growth. Besides, different cyanobacteria species usually show preferences for nutrient element selection. The effects of nutrient concentration on the growth and toxicity of cyanobacteria species are various, and the influences of the nutrient composition on HABs are quite complex in some cases [27,28].

Up to now, little research has been carried out with respect to the composition and spatio-temporal distribution of cyanobacteria community in Luoma Lake. It was recorded that the frequency and intensity of cyanobacterial blooms had been far less than other large freshwater lakes, such as Taihu Lake and Dianchi Lake. Moreover, when the SNWDP is brought into operation, Luoma Lake will receive the water from Hongze Lake which has already received the water from Yangtze River in the first place. Therefore, the aquatic environment in Luoma Lake would change to some extent, due to the mixed water column and nutrient elements. In this context, what changes will take place to the cyanobacteria community and the occurrence possibility of HABs are not yet determined, so it is necessary to record these background data before the implementation of the project. Accordingly, the main purposes of this study were to: (i) monitor the cyanobacteria community variation over long term during the implementation of the water diversion project from March 2011 to May 2013; (ii) analyze the dynamic of the cyanobacteria community and investigate the relationship between cyanobacteria population and various environmental factors. This study could provide a theoretical basis for preventing the occurrence of cyanobacterial blooms and protecting the aquatic environment in Luoma Lake.

2. Materials and methods

2.1. Study area

Luoma Lake (34°00′–34°11′N, 118°06′–118°18′E), located in the north of Jiangsu province, mainly has three inflowing rivers (Yi River, Zhongyun River, and Fangting River) and three outflowing rivers (The Grand Canal, Xinyi River, and Liutang River). The water level variation of Luoma Lake ranges from 1.9 to 5.7 m, which usually undergo obvious seasonal fluctuation. It receives inflows of local catchment and the water body can generally be renewed ten times in one year [15,29]. The average annual rainfall in the study area is 779 mm [16]. Besides, the annual rainfall shows a common pattern that the rain season contributes nearly 70% of the total rainfall and the annual rainfall shows the variation over different years [30].

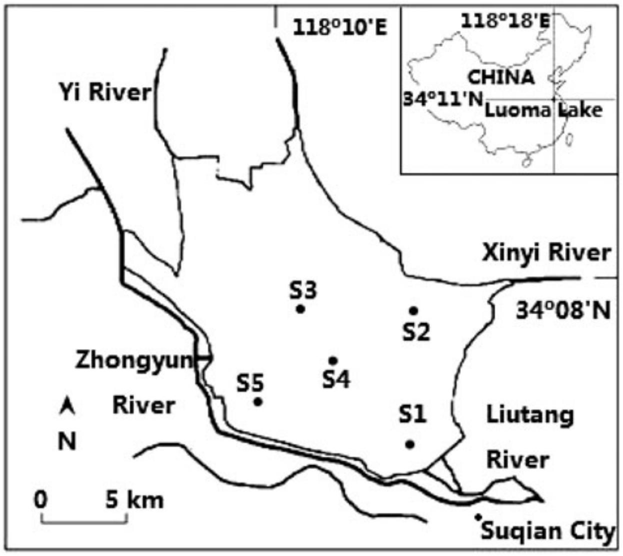

Fig. 1. Locations of the sampling sites in Luoma Lake [31].

2.2. Site and sampling

From March 2011 to May 2013, sampling was conducted monthly at five sampling sites (S1–S5) (Fig. 1). Water samples were collected with a Ruttner water sampler (Hydrobios, Germany, 1,000 mL) at a depth of 0.5 m below water surface. One litter water sample was preserved using 1% Lugol's iodine solution and kept in a cool environment, and then carried to the laboratory for the identification and investigation of cyanobacteria population.

2.3. Analysis methods

The physicochemical parameters such as WT, dissolved oxygen (DO), transparency (Trans), and pH were measured using on-site instruments, respectively: thermometer (TES1316, Shanghai Precision Instruments Co., China), portable DO meter (YSI59, YSI Corporation in China, USA), Secchi disk (20 cm), and portable pH meter (PH-HJ90, Aerospace Computer Company, China). Total nitrogen (TN), total phosphorus (TP), ammonium (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N), and orthophosphate (PO_4-P) were determined according to the Chinese national standards for water quality [32]. Chemical oxygen demand (COD) was determined by acidic potassium permanganate method [32]. The water sample kept using Lugol's iodine solution was concentrated to 10 mL after a 48-h-sedimentation process, and then a 0.1 mL concentrated water sample was counted under 400× magnification with a compound microscope (CX31, OLYMPUS, Japan). Cyanobacteria species were identified according to the phytoplankton morphological criteria, as described by Hu and Wei [33].

2.4. Statistical analysis

The computer program CANOCO v.4.5 was used to conduct all of the multivariate and ordination analyses [34]. In the data matrix of cyanobacteria species, only those taxa that occurred more than three times and accounted for greater than 1% of the total biomass were chosen for analysis. Before the analysis was done, all the environmental and species data were log $(x+1)$ transformed except for pH variables, and detrended correspondence analysis was conducted to select the appropriate model for subsequent analysis (to decide whether unimodal or linear ordination was suitable for the data-set in this case) according to the length of first gradient. Finally, redundancy analysis (RDA), which indicated that the numerical analyses assumed linear species distributions, was applied to find out the correlation between the environmental factor variables and cyanobacteria species data. A Monte Carlo permutation test was utilized to determine the environmental variables best related to the cyanobacteria dynamics [35]. In the ordination diagram, species are represented as triangles while environmental factors are represented as arrows. Pearson correlation analysis between environmental variables and cyanobacteria species was also performed using the SPSS 18.0 software, and in the meantime a *t*-test was used to check the significance of parameters.

3. Results

3.1. Physical and chemical parameters

The means and ranges of environmental parameters at the five sampling sites are shown in Table 1. From March 2011 to May 2013, WT of Luoma Lake showed a seasonal variation tendency (Fig. 2(a)). It is obvious that the average temperature in summer and autumn was much higher than that in spring and winter (Fig. 2(a)). COD_{Mn} exhibited a similar variation pattern as temperature except for a few months, and the COD_{Mn} value in summer was relatively higher than in other seasons (Fig. 2(a)).

Water Transparency and water depth in Luoma Lake displayed similar variation tendencies during the whole monitoring period (Fig. 2(b)). The water depth in Luoma Lake was usually much lower in summer than in other seasons, probably associated with water drawdown by farmers for irrigation (Fig. 2(b)). The TN and TP values were both dynamic, but they

Table 1
Environmental parameters of the sampling sites in Luoma Lake from March 2011 to May 2013 (means and ranges at each sampling site)

Variable	S1	S2	S3	S4	S5
WD (m)	3.5 (1.5–5.8)	3.8 (1.7–4.9)	3.5 (1.2–6.5)	3.8 (1.7–4.9)	3.0 (1.1–4.1)
Trans (m)	0.78 (0.40–1.60)	0.95 (0.40–2.70)	0.83 (0.32–2.10)	0.84 (0.42–1.80)	1.06 (0.32–2.10)
WT (℃)	16.5 (3.0–30.0)	16.5 (3.0–30.1)	16.7 (3.2–29.7)	16.6 (3.0–29.7)	16.7 (3.2–30.3)
pH	8.25 (7.97–8.54)	8.22 (7.89–8.50)	8.18 (7.74–8.54)	8.20 (7.76–8.56)	8.21 (7.31–8.50)
DO (mg/L)	10.16 (7.24–15.00)	10.37 (7.00–15.20)	10.27 (7.16–15.60)	10.18 (7.16–15.50)	10.22 (6.20–15.20)
COD_{Mn} (mg/L)	3.44 (2.30–5.00)	3.64 (2.10–4.90)	3.36 (2.20–4.60)	3.33 (2.30–5.10)	3.44 (2.30–4.90)
TN (mg/L)	3.39 (0.58–5.82)	2.92 (0.50–6.32)	3.19 (0.50–6.68)	2.70 (0.51–6.20)	2.23 (0.51–4.62)
TP (mg/L)	0.025 (0.009–0.050)	0.032 (0.008–0.065)	0.030 (0.106–0.065)	0.023 (0.007–0.042)	0.024 (0.008–0.050)
NH_4-N (μg/L)	138.05 (25.42–507.87)	171.23 (29.54–722.44)	157.73 (36.45–694.98)	130.41 (28.24–353.43)	175.11 (28.24–1303.83)
NO_2-N (μg/L)	30.85 (3.00–115.13)	57.22 (0–222.21)	71.61 (4.00–368.20)	48.39 (4.00–143.10)	24.82 (1.25–167.87)
NO_3-N (mg/L)	1.66 (0.02–4.96)	2.09 (0.06–5.48)	2.19 (0.04–5.27)	2.05 (0.05–4.94)	1.45 (0.03–4.02)
PO_4-P (μg/L)	8.83 (0–32.61)	9.25 (0–27.96)	13.40 (0–41.18)	9.49 (0–32.61)	8.17 (0–23.50)
N/P	128.89 (19.06–627.02)	126.44 (12.02–595.78)	127.10 (21.25–381.63)	155.18 (21.51–623.79)	114.11 (22.54–289.56)

WD: water depth; Trans: transparency; WT: water temperature; DO: dissolved oxygen; COD: chemical oxygen demand; TN: total nitrogen; TP: total phosphorus; and N/P: total nitrogen/total phosphorus.

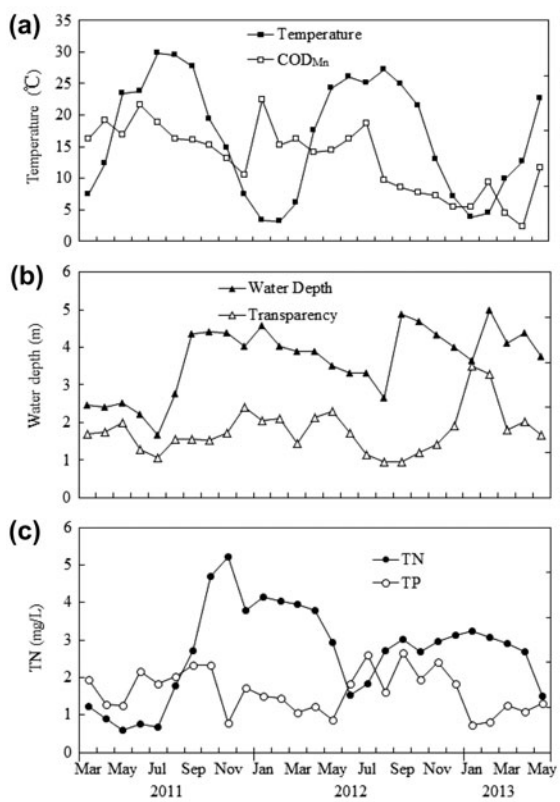

Fig. 2. Seasonal variations of (a) WT, COD_{Mn}, (b) water depth and Trans, and (c) TN and TP in Luoma Lake from March 2011 to May 2013.

showed different seasonal variation trends (Fig. 2(c)). The maximum value of TN occurred in November 2011 and that of TP occurred in September 2012.

3.2. Cyanobacteria community composition

A total of 27 cyanobacteria species belonging to 14 genera were morphologically identified in Luoma Lake (Table 2). At the five sampling sites, a similar occurrence in composition of cyanobacteria species was observed. There were more species detected in summer and autumn (18 species in total) than in winter (seven species) and spring (12 species). *Microcystis, Merismopedia,* and *Oscillatoria* all had more than three species observed, but they were not as dominant as *Pseudanabaena*. During the whole period, the only identified *Pseudanabaena* species, *Pseudanabaena limnetica* occurred most frequently among all the cyanobacteria species. The average proportion of *Pseudanabaena* to total cyanobacteria population was 65.14%, followed by *Microcystis* 7.66%, *Oscillatoria* 7.62%, *Chroococcus* 7.18%, *Merismopedia* 4.69%, *Pleurocapsa* 1.85%, *Rhabdoderma* 1.84%, *Cylindrospermum* 1.76%, *Aphanizomenon* 0.89%, and the others 1.38%.

3.3. Variation in cyanobacteria abundance

As shown in Fig. 3, the cyanobacteria abundance in Luoma Lake exhibited distinct temporal variation. A

Table 2
Cyanobacteria species identified in Luoma Lake from March 2011 to May 2013

Genera	Species
Microcystis	*M. aeruginosa; M. incerta; M. wesenbergii*
Merismopedia	*M. elegans; M. glauca; M. punctata; M. tenuissima*
Oscillatoria	*O. princeps; O. amphibian; O. agardhii; O. tenuis*
Chroococcus	*C. tenax; C. minor; C. minutus*
Dactyloccocopsis	*D. rhaphidioides; D. acicularis*
Anabaena	*A. circinalis; A. azotica*
Phormidium	*P. tenus; P. corium*
Pseudanabaena	*P. limnetica*
Pleurocapsa	*P. fuliginosa*
Cylindrospermum	*C. stagnale*
Aphanizomenon	*A. issatschenkoi*
Gloeocapsa	*G. magma*
Raphidiopsis	*R. curvata*
Rhabdoderma	*R. lineare*

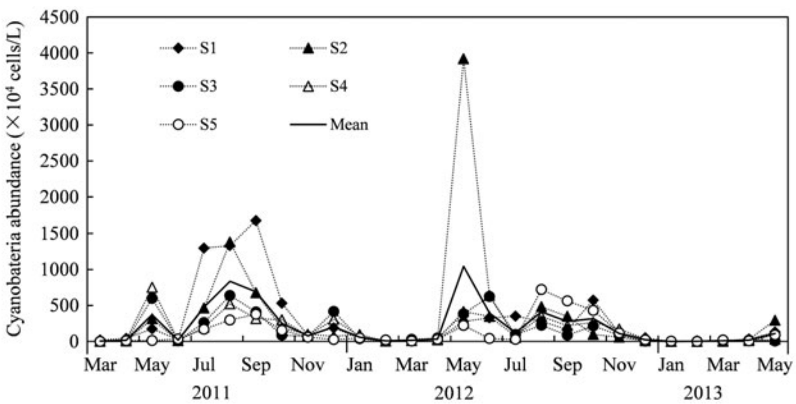

Fig. 3. Seasonal variation of the total cyanobacteria abundance in Luoma Lake from March 2011 to May 2013.

similar seasonal pattern was observed at all the five sampling sites, namely that the cyanobacteria abundance in summer and autumn was much higher than in other seasons. Besides, the cyanobacteria abundance in summer 2011 was higher than in 2012. The cyanobacteria abundance ranged over seven orders of magnitude from the undetectable level to 3.9×10^7 cells/L. The cyanobacteria abundance reached the peak (3.9×10^7 cells/L) at S2 in May 2012, which was much higher than the other monitoring values. The increase of cyanobacteria abundance often occurred in May, followed by a decrease in June or July, and then the cyanobacteria abundance displayed another increase in August. The relatively high cyanobacteria abundances usually lasted three months until the end of October, followed by the continuous decrease started in December, and finally the lowest cyanobacteria abundance was usually observed in January or February.

3.4. Succession of cyanobacteria community

The seasonal succession of cyanobacteria community in Luoma Lake is shown in Fig. 4. In general, the cyanobacteria genera exhibited a seasonal variation trend similar to that of the total cyanobacteria abundance. The abundance of each genus usually began to increase in late spring, while the peak value occurred in warm months.

As shown in Fig. 4, *Pseudanabaena*, *Microcystis*, *Oscillatoria*, and *Chroococcus* were four cyanobacteria genera which had a relatively higher occurrence frequency and cell abundance, accounting for 87.6% of the total cyanobacteria population. Fig. 5 displays the comparison between seasonal variations of the total cyanobacteria population and *Pseudanabaena*. It is obvious that *Pseudanabaena* was the most predominant cyanobacterial genus during the study period. The seasonal distribution patterns

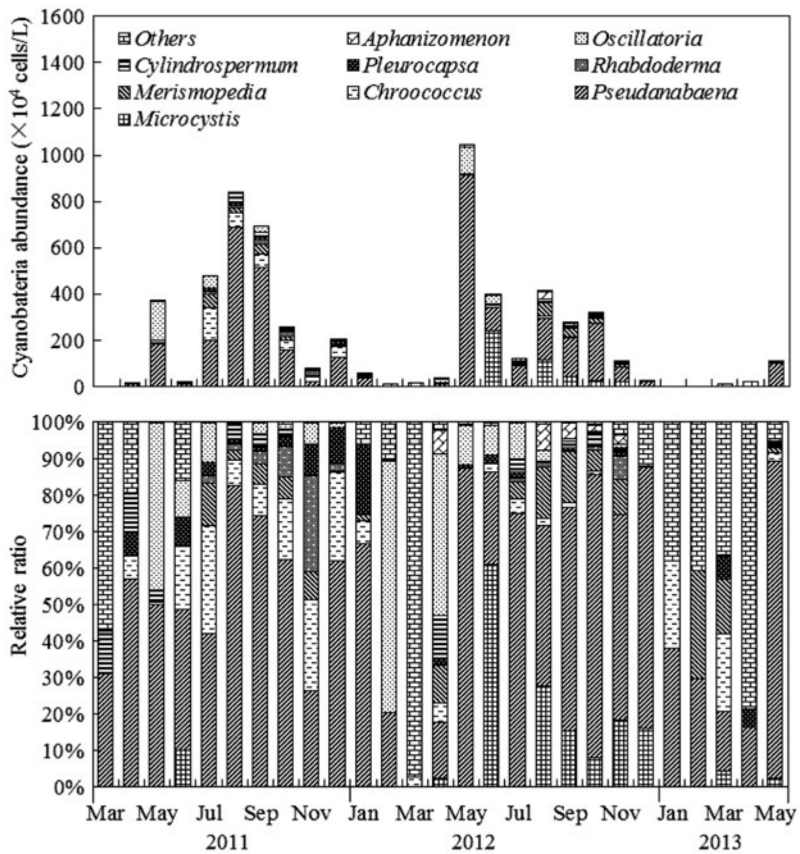

Fig. 4. Seasonal succession of cyanobacteria community in Luoma Lake from March 2011 to May 2013.

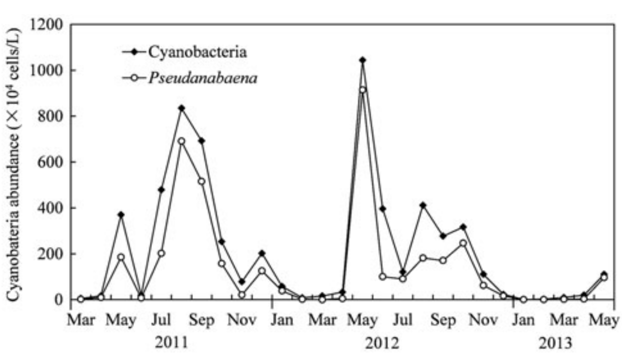

Fig. 5. Comparison between the seasonal variations of cyanobacteria community and *Pseudanabaena* in Luoma Lake from March 2011 to May 2013.

of the total cyanobacteria community and *P. limnetica* were basically the same. In some months during the cold season, cyanobacteria species including *P. limnetica* in Luoma Lake were even barely detected.

3.5. Correlation analysis

Based on the environmental and species data, RDA was conducted to explore the potential correlation between them (Fig. 6). In the RDA ordination diagram, the projection of a taxon on this axis indicates the level of the physicochemical factor where the

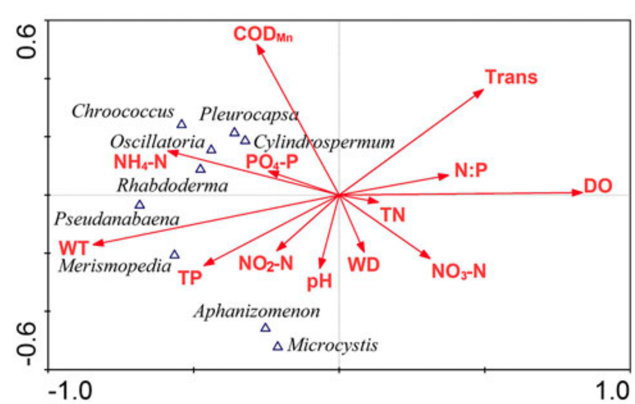

Fig. 6. RDA ordination diagram of cyanobacteria genera with environmental variables in Luoma Lake from March 2011 to May 2013.

Table 3
Summary of RDA between environmental factors and cyanobacteria abundance in Luoma Lake from March 2011 to May 2013

Axes	1	2	3	4
Eigenvalues	0.264	0.063	0.039	0.025
Species–environment correlations	0.787	0.652	0.544	0.511
Cumulative percentage variance of species data	26.4	32.6	36.6	39.0
Cumulative percentage variance of species–environment relation	63.5	78.6	88.0	93.9
Sum of all eigenvalues	1.000			
Sum of all canonical eigenvalues	0.415			

Table 4
Pearson correlation coefficients between environmental parameters and cyanobacteria abundance in Luoma Lake from March 2011 to May 2013

	PSE	MER	MIC	RHA	OSC	CHR	PLE	CYL	APH
WD	−0.009	−0.011	0.044	0.117	−0.186*	−0.173*	0.008	−0.120	0.008
Trans	−0.288**	−0.490**	−0.267**	−0.292**	−0.150	−0.213*	−0.148	0.028	−0.268**
WT	0.578**	0.475**	0.310**	0.291**	0.426**	0.426**	0.218*	0.329**	0.293**
pH	0.118	0.007	0.143	−0.043	−0.005	−0.091	−0.126	0.124	0.113
DO	−0.589**	−0.444**	−0.201*	−0.319**	−0.400**	−0.438**	−0.253**	−0.339**	−0.174*
COD_{Mn}	0.223**	−0.064	−0.166	0.044	0.256**	0.274**	0.251**	0.146	−0.179*
TN	−0.158	0.097	−0.080	0.189*	−0.165	−0.046	0.038	−0.286**	−0.042
TP	0.324**	0.377**	0.212*	0.200*	0.053	0.246**	0.119	0.092	0.156
NH_4-N	0.366**	0.349**	0.012	0.298**	0.271**	0.411**	0.264**	0.127	0.195*
NO_2-N	0.074	0.302**	0.123	0.345**	−0.023	0.138	0.230**	−0.326**	0.102
NO_3-N	−0.251**	−0.025	0.002	0.033	−0.153	−0.238**	−0.066	−0.443**	−0.004
PO_4-P	0.195*	0.077	0.053	0.076	0.027	0.151	0.157	0.225**	−0.076
N:P	−0.301**	−0.146	−0.155	0.020	−0.180*	−0.193*	−0.046	−0.283**	−0.100

WD: water depth; Trans: transparency; WT: water temperature; DO: dissolved oxygen; COD: chemical oxygen demand; TN: total nitrogen; TP: total phosphorus; N/P: total nitrogen/total phosphorus; PSE: *Pseudanabaena*; MER: *Merismopedia*; MIC: *Microcystis*; RHA: *Rhabdoderma*; OSC: *Oscillatoria*; CHR: *Chroococcus*; PLE: *Pleurocapsa*; CYL: *Cylindrospermum*; and APH: *Aphanizomenon*.
$^{*}p < 0.05$; $^{**}p < 0.01$.

taxon is most abundant. The observed variance of cyanobacteria abundance data that can be explained by the axis is shown in Table 3. The axis 1 and axis 2 explained 32.6% of the cumulative percentage variance of cyanobacteria abundance.

As shown in Fig. 6, environmental variables such as WT (−0.6644), DO (0.6567) and NH_4-N (−0.4627) strongly correlated with axis 1, while COD_{Mn} (0.3371) and Trans (0.2362) were associated with axis 2. Many environmental factors, including WT, DO, NH_4-N, Trans, and COD_{Mn}, were found closely related to the variation of cyanobacteria community. It is obvious that WT was the most important factor controlling the succession of cyanobacteria community. The temporal variation of *Pseudanabaena* was mainly correlated with environmental variables such as WT, DO, and NH_4-N. Other cyanobacteria genera like *Microcystis*, *Oscillatoria*, and *Chroococcus* were also strongly associated with WT. *Oscillatoria*, *Chroococcus*, and *Rhabdoderma* all preferred high NH_4-N concentration. Table 4 shows the results of Pearson correlation analysis. There is clear evidence that the seasonal variations of most cyanobacteria genera were strongly related to WT, DO, and NH_4-N during our study period, which was confirmed by RDA analysis.

4. Discussion

4.1. Seasonal variation of cyanobacteria species in Luoma Lake

In the study period, the cyanobacteria community composition experienced distinct seasonal variations with more types of cyanobacteria species observed in summer and autumn than in winter and spring. The same occurrence was also discovered in other regulating lakes of the SNWDP, such as Hongze Lake [36], Nansi Lake [13], and Dongping Lake [37]. The first increase of cyanobacteria abundance occurred in May, followed by a decrease in June or July, and then it showed another increase in August. This distinctive pattern in Luoma Lake was not common but similar to that found in a few research studies [13,38]. We believe the rising temperature was the main reason for the increase of cyanobacteria abundance. Besides, the species richness could be influenced by water velocity and fluctuating water level [39,40]. The water level in Luoma Lake experienced conspicuous fluctuation in warm months, which was unfavorable for nutrient accumulation and the maintenance of a stable water column. It may be one reason why a decrease of cyanobacteria abundance occurred in June or July.

During the monitoring period, the most dominant cyanobacteria genus was *Pseudanabaena,* and it accounted for nearly seventy percent of the total cyanobacteria population (Fig. 5). Unlike other large eutrophic lakes in China, such as Taihu Lake, Chaohu Lake, and Dianchi Lake [3,41–43] where the most dominant cyanobacteria genus was *Microcystis*, the proportion of bloom-forming *Microcystis* to total cyanobacteria population was only 7.66% in Luoma Lake. During our study period, no *Microcystis* blooms were noticed in Luoma Lake. Takamura found that heavy blooms of *Microcystis* occurred in the hypertrophic Lake Kasumingaura before 1986, when the TN:TP mass ratios were usually less than 10 [44]. Liu et al. [3] found out the *Microcystis* species tended to dominate at low TN:TP (<30) in warm temperatures in Taihu Lake. The ratios TN to TP in warm temperatures in Luoma Lake were mostly over 30, which might be one reason why *Microcystis* was not the dominant cyanobacteria genus in Luoma Lake. Besides, *Microcystis* species tend to dominate at low NH_4-N:NO_x-N (<1) in warm temperatures [3,45], whereas the average of this ratio in Luoma Lake was 2.3, which might be another reason why *Microcystis* was not dominanted.

P. limnetica, the most dominant cyanobacteria species in Luoma Lake, is a common dominant species in many shallow lakes, and it has a low requirement for light and can survive in turbulent water environments [46,47]. Up to now, there is little report concerning cyanobacterial blooms caused by *P. limnetica*. However, it has been proved that *P. limnetica* could potentially produce neurotoxic amino acids [48]. At the concentration of 10 μmol/L, the neurotoxic amino acids were able to induce neuronal injury in mixed cortical cell cultures of neurons and astrocytes [49]. The monitoring for dominated cyanobacteria species should pay more attention to their ability of cyanotoxins production.

4.2. Environmental factors controlling seasonal variation of cyanobacteria species

There is a consensus that phytoplankton community variation is associated with many environment changes. The featured spatio-temporal distribution pattern is determined by the combined effect of multiple environmental factors [50]. According to the correlation analysis, the cyanobacteria community variation in Luoma Lake was mainly related to WT, DO, and NH_4-N (Fig. 6).

WT is usually the most important environmental factor that greatly influences the phytoplankton distribution and succession. Compared with other phytoplankton assemblages, cyanobacteria species usually have higher optimal temperature for cell growth and recruitment. They choose to turn into a dormant phase when the WT is not suitable, and gradually recover to normal growth rates as the temperature becomes higher [51]. Generally, cyanobacteria dominance takes place at higher WTs (>20°C) [52]. The rising WT is in favor of cyanobacteria species, because many physical characteristics of the water environment will be changed. For instance, the intensified vertical density stratification, the increase of nutrient diffusion [25], and the decrease of surface water viscosity conform with the buoyancy regulation mechanism of some cyanobacteria species [53–55]. When WTs exceed 20°C, the growth rates of cyanobacteria species begin to increase obviously while eukaryotic phytoplankton species often decrease or stabilize [25,54], which enhance the competitive ability of cyanobacteria species. In this study, the first increase of cyanobacteria abundance often occurred in May when the mean temperature was above 20°C (Fig. 7). The cyanobacteria abundance in Luoma Lake was at a relatively high level from May to October in each year, with the WT ranging from 19.1 to 30.3°C. The mean WT in the cold season was below 10°C, which was too severe for cyanobacteria growth. Consequently, from December to the following February, the cyanobacteria abundance maintained at a very low level. It can be concluded that temperature was a very important environmental factor affecting cyanobacteria abundance in Luoma Lake. The variation of WT had a strong and positive effect on the growth and proliferation of cyanobacteria population.

Among all the potential environmental factors attributed to HABs, anthropogenic nutrient pollution has been given the most attention [23,56]. Paerl et al. [57] observed that increasing nitrogen nutrients could

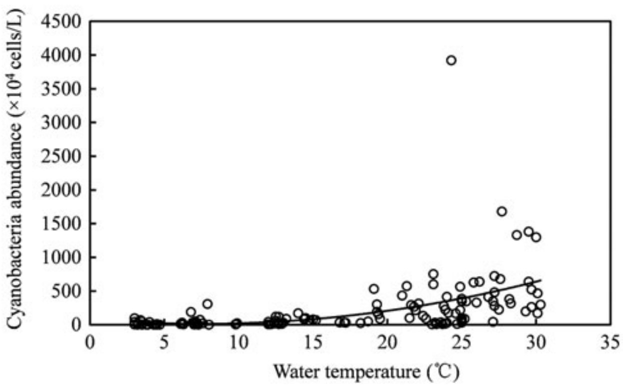

Fig. 7. The correlation between WT and cyanobacteria abundance in Luoma Lake.

accelerate the growth of *Microcystis* in summer and might determine the duration and magnitude of cyanobacteria blooms in Meiliang Bay, China. In our study, NH_4-N was positively related with the variation of cyanobacteria abundance. Zhang et al. [58] identified NH_4-N as the key driving factor for mass development of cyanobacteria population in summer and autumn in Taihu Lake. Yang et al. [59] found out that NH_4-N exhaustion was coincident with the removal of the cyanobacterial bloom. Sheng et al. [43] also suggested NH_4-N was one of the important driving forces for cyanobacterial blooms, even though it was not as significant as WT. According to the correlation analysis, the dominant genus *Pseudanabaena* was positively associated with TP. In freshwater lakes or reservoirs, the availability of phosphorus is often an important factor which limits the multiplication of cyanobacteria species [60], and the phosphorus availability increase is beneficial to the dominance of cyanobacteria species [61].

During the study period, the peak value of cyanobacteria abundance (3.9×10^7 cells/L) occurred at S2 in May 2012 (Fig. 3), which was much higher than all the other monitoring values. This peak value was attributed to the mass proliferation of *Pseudanabaena*. In order to seek the reason, two important environmental factors WT and NH_4-N were taken into consideration. The WT at S2 was 24.3℃ in May 2012, which was favor for cyanobacteria cell growth, but there were no obvious differences with other sampling sites. It is noteworthy that of all the physicochemical variables in May 2012, only the NH_4-N concentration at S2 differed greatly comparing with other sampling sites (722.4 μg/L, the other NH_4-N values at S1, S3, S4, and S5 were 56.5, 38.6, 38.6, and 124.9 μg/L, respectively). Thus, we carried out a comparison between the variation of *Pseudanabaena* and NH_4-N (Fig. 8). As shown in the figure, there was a positive correlation between *Pseudanabaena* abundance and NH_4-N concentration on the whole. However, the high value of NH_4-N concentration in August 2012 did not correspond to the high value of *Pseudanabaena* abundance. We believed there must have been other reasons for this special occurrence in May 2012.

It has been reported that precipitation can potentially affect the phytoplankton growth in lakes, rivers, and estuaries [62]. Sometimes after heavy precipitation, the water environment changed a lot. It was no longer suitable for the growth of a dominant species as a result of the mixing of the water body. In addition, the precipitation variation would influence the hydraulic condition. For instance, flood discharge can greatly affect nutrient accumulation and maintenance

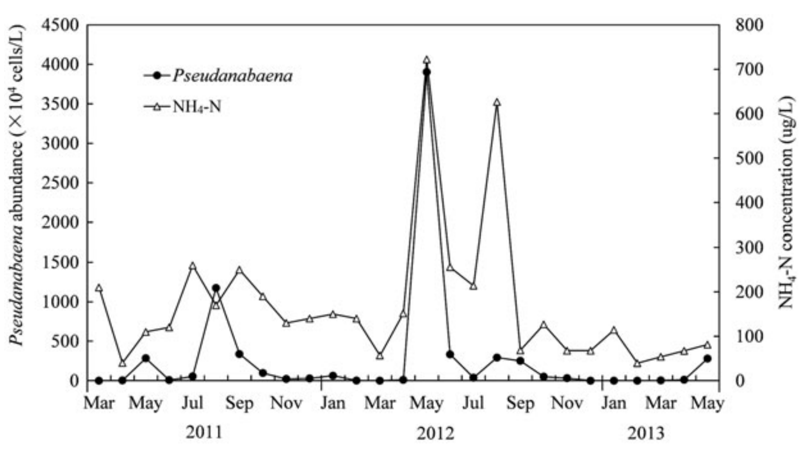

Fig. 8. Seasonal variation of *Pseudanabaena* abundance and NH_4-N concentration at sampling site S2 in Luoma Lake from March 2011 to May 2013.

Table 5
The precipitation of warm months (from May to September) in 2011 and 2012 in Luoma Lake

	Year									
	2011					2012				
Month	May	Jun.	Jul.	Aug.	Sep.	May	Jun.	Jul.	Aug.	Sep.
Total (mm)	64.2	58.8	179.2	284.6	47.2	12.0	74.6	181.6	158.0	308.8
Days	8	8	10	16	12	2	7	9	12	8
Maximum (mm)	28.4	34.4	49.0	78.4	15.8	7.8	20.0	96.8	42.2	161.8

of the water column. Sometimes, it is the main factor affecting phytoplankton population rather than physical factors and nutrient elements [63]. In this case, the precipitation information for warm months (from May to September) around Luoma Lake in 2011 and 2012 was collected (Table 5). As is shown in Table 5, the total precipitation and number of rainy days in May 2012 was very limited, leading to less water turbulence, which may be one crucial factor contributed to the mass proliferation of *Pseudanabaena*. However, the combined influence of various environmental factors is still complex. There may be other factors affecting the variation of cyanobacteria community, such as microbial predation.

At present, the occurrence of HABs in Luoma Lake is rare, unlike other typical eutrophic lakes in China. One convincing explanation is probably that the water body in Luoma Lake can be renewed ten times in one year [15,29], decreasing the accumulation of cyanobacteria species. On the other hand, the TP concentration was much lower and the TN:TP mass ratio was much higher, which is not good for the growth of bloom-forming genus *Microcystis* [3]. Therefore, cyanobacterial blooms might not occur with the improvement of water quality when the water diversion project is in operation. The long-term monitoring for cyanobacteria community and relevant environmental factors is still required in Luoma Lake. Besides, further and specific research should be introduced in future studies, with a focus on such factors as microbial predation and cyanotoxins production.

5. Conclusion

Based on a monthly sampling, a total of 27 cyanobacteria species was identified in Luoma Lake from March 2011 to May 2013. The cyanobacteria abundance ranged over seven orders of magnitude from the undetectable level to 3.9×10^7 cells/L. *Pseudanabaena* was the most predominant cyanobacteria genus while the abundance of the common bloom-forming genus *Microcystis* was low. The results of correlation analysis showed that WT, DO, and NH_4-N concentration were correlated with cyanobacteria abundance. Besides, other environmental factors such as precipitation and water turbulence could affect the cyanobacteria community distribution. The cyanobacterial blooms might not occur in Luoma Lake, with the predominant cyanobacteria genus being *Pseudanabaena* and the water quality improved.

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