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Seasonal Dynamics of Phytoplankton in Relation to Key Aquatic Habitat Factors in a Polluted Urban Small Water Body in Tianjin, China

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Abstract To evaluate the seasonal dynamics of phytoplankton and its relationships with aquatic habitat factors in polluted urban landscape lakes, annual investigations have been carried out in the West zone of Xinkai Lake. The results showed that the lake belongs to the eutrophic–supertrophic type in terms of key habitat factors measurement. The seasonal succession of phytoplankton community was determined. The dominant cyanobacterial species *Oscillatoria tenuis* Ag. bloomed in autumn, although the other species with higher degrees of dominance never bloomed in the year investigated. Significant correlations between some habitat factors and phytoplankton biomass were observed.

Keywords Seasonal dynamic · Phytoplankton community · Urban small lake · Algal blooms

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Eutrophications of large shallow lakes, such as Taihu Lake in Jiangsu Province, Chaohu Lake in Anhui Province and Donghu Lake in Wuhan city of China, have long been investigated. Trophic status, composition and succession of phytoplankton species in these lakes were recognized basically (Dokulil and Teubner 2000; Xie et al. 2003; Li et al. 2006). Small shallow forest lakes in Finland were examined to show seasonal succession, vertical distribution and variation of phytoplankton communities (Salonen et al. 1984; Holopainen et al. 2003). In contrast to large shallow lakes, a few attentions were paid to the eutrophication and the phytoplankton succession in urban small water bodies (Wang et al. 2004).

With economic and social progress, small water bodies were constructed or reconstructed to improve urban ecological environmental qualities such as landscape effects and microclimate adjustments. These water bodies are characterized by small surface area, shallow depth, stable hydrodynamic and city location. Investigations have demonstrated that phytoplankton biomass and primary production were relatively high in some of these water bodies owing to non-point sources pollution (Liu et al. 2004). The questions with these lakes, how phytoplankton succession progresses and trophic status processes, are worthy of further research. In this paper the seasonal dynamics of phytoplankton were presented and were related to the key aquatic habitat factors in an urban small eutrophic lake.

Materials and Methods

The Xinkai Lake, which locates in the southwestern part of Tianjin city (latitude 39°06′N, longitude 117°10′E) and is used for landscape purposes, was selected for the study. It covers a surface area of 26,000 m^2. The maximum depth of the lake is 2.8 m and the mean is 2.0 m. The lake was reconstructed in 1995. Since then, the aquatic ecosystem had adjusted to a stable phase. Blooms dominated by cyanobacteria have occurred in summer and autumn year after year since 2002.

Water samples were weekly taken below the surface (20 cm) on two sites of the lake from June 2005 to May 2006 at 9:30–10:00 a.m. The major aquatic habitat parameters, such as pH value, concentrations of ammonia nitrogen (AMN, mg L^{-1}), nitrate nitrogen (NAN, mg L^{-1}), nitrite nitrogen (NIN, μg L^{-1}), dissolved total nitrogen (DTN, mg L^{-1}), total nitrogen (TN, mg L^{-1}), soluble reactive phosphate (SRP, μg L^{-1}), dissolved total phosphorus (DTP, μg L^{-1}), total phosphorus (TP, μg L^{-1}) and chlorophyll a (Chl-a, μg L^{-1}) were determined, respectively, as soon as possible according to APHA (1995). Illumination (Ill, $\mu\,Em^{-2}\,s^{-1}$) and water temperature (TEM, °C) were detected in situ.

The phytoplankton samples were preserved with 4% formalin solution and were concentrated to 10 mL after sedimentation for 48 h. After mixing, 0.1 mL concentrated samples were counted directly using an Olympus optical microscope at 400×. Classification and identification of phytoplankton species and genera were based on Hu et al. (1980). The phytoplankton biomass was estimated from the approximate geometric volume of each taxon, assuming that the biomass per μm^3 equals to 10^{-6} μg fresh weight. The geometric dimensions were measured on 10–30 individuals of each phytoplankton species in each sample. The cell numbers of individual species were quantified. Phytoplankton abundance was expressed as the number of cells or the total algal biomass per liter sample.

Statistical analysis was performed with SPSS 14.0 for Windows (SPSS Inc., Chicago, Illinois) and Origin 6.0 Professional (Microcal Software Inc., Northampton, MA). The results were expressed as means and standard deviations (±SD).

Results and Discussion

Nutrients, especially nitrogen and phosphorus, are essential for healthy growth of phytoplankton in freshwater. Plant can absorb nitrogen both as nitrate and ammonia. Chlorophyll a is easily measured. It can be used to estimate phytoplankton productivity. Main data (Table 1) were extracted from the investigation results to evaluate the trophic status of the water body studied. The concentrations of ammonia nitrogen, total nitrogen and total phosphorus went beyond class V requirements of Environmental Quality Standards for Surface Water (National standards of the People's Republic of China) (GB3838-2002). Approximate 95% concentration data of total nitrogen and total phosphorus exceeded the limit values of eutrophication indicators proposed by OECD. It was considered that the West zone of Xinkai Lake was in the eutrophic–supertrophic state in terms of the chlorophyll a concentrations in spring, summer and autumn. Blooms have occurred since 2002 year after year, in which the dominant species was always the cyanobacterium *Oscillatoria tenuis* Ag.

A total of 150 taxa of phytoplankton belonging to eight phyla and 74 genera were identified from annual water sampling, the details of phytoplankton composition were shown in Table 2.

The dominant phyla were Chlorophyta, Cyanophyta, Bacillariophyta and Euglenophyta. It was determined from the total phylum biomass in each sample. Monthly data of these phyla were plotted in Fig. 1 to describe the temporal dynamics. The RPT symbol signified the ratio of the phylum biomass to the total. According to the climate of Tianjin, from March to May, June to August, September to November and December to February are generally considered as period spring, summer, autumn and winter, respectively. It was indicated that RPT of the dominant phylum (or co-dominant phyla) differed significantly from those of non-dominant phyla in given months. The dominant phyla were Euglenophyta in early-to-mid spring, Chlorophyta in mid-to-late winter and mid-to-late summer,

Table 1 Main water quality data related to the lake trophic state

Items	Spring		Summer		Autumn		Winter	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
AMN (mg L^{-1})	0.58–2.91	1.06	0.03–4.40	1.65	0.67–1.93	1.32	0.43–5.48	1.48
NAN (mg L^{-1})	0.24–1.45	0.79	0.13–2.00	0.57	0.28–0.77	0.57	0.48–1.41	0.87
TN (mg L^{-1})	3.04–5.29	3.85	2.34–6.51	3.81	2.64–63.20	10.60	0.97–7.40	2.88
TP (μg L^{-1})	189–1,146	450	94–501	202	114–4,366	627	85–493	191
Chl-a (μg L^{-1})	12.2–329.4	132.5	42.2–375.1	108.3	66.3–3,012	405.1	15.9–75.6	52.9

Symbols and units see "Materials and Methods"

Table 2 Phytoplankton composition in annual water samples

Phylum	Genus number	Species number
Chlorophyta	35	74
Cyanophyta	15	30
Bacillariophyta	10	20
Euglenophyta	5	14
Chrysophyta	3	3
Cryptophyta	2	5
Pyrrophyta	2	2
Xanthophyta	2	2

Table 3 Phytoplankton species with higher appearing frequency and the dominant (*)

Species	Appearing frequency
Chlorophyta	
*U. variabilis**	0.72
S. quadricauda	0.34
C. microporum	0.32
*E. elegans**	0.20
Euglenophyta	
*E. caudata**	0.32
*E. intermedia**	0.32
Cyanophyta	
L. limnetica	0.84
D. irregularis	0.72
M. aeruginosa	0.72
*P. corium**	0.68
*O. tenuis**	0.66
Bacillariophyta	
*C. meneghiniana**	0.60

Cyanophyta in late spring, autumn and early winter, Bacillariophyta in early summer. Subdominant phyla were Euglenophyta in January, Chlorophyta in spring and autumn, Cyanophyta in summer.

Due to the marked difference in phytoplankton cell size, biomass was a combined measurement of cell density and cell size. It was taken as a determinant of the dominant and subdominant phytoplankton species in water samples. On the other hand, frequency (Table 3), as a ratio of the sample number of an appearing species to the total sample number, was also considered to be a factor in determining species dominance. The dominant species were *Ulothrix variabilis* Kütz. and *Eudorina elegans* Ehr. (Chlorophyceae); *Oscillatoria tenuis* Ag. and *Phormidium corium* (Ag.) Gom. (Cyanophyceae); *Cyclotella meneghiniana* Kütz. (Bacillariophyceae); *Euglena caudata* Hübn. and *Euglena intermedia* (Klebs) Schmitz (Euglenaceae). Dynamics of the dominant species were shown in Fig. 2. The RDT value was represented by the ratio of a dominant species biomass to the total in each sample.

Phytoplankton development was related with some important habitat factors. The occurrence of large euglenoids (mainly *E. caudata* and *E. intermedia*) in mid-to-late winter was probably induced by the increase of irradiation dose, higher availability of nutrients and lower grazing pressure of zooplankton. Then the euglenoids dominated in spring. *P. corium* replaced these euglenoids as dominant species in late spring. *C. meneghiniana* reached its highest biomass in June. In mid-to-late summer *E. elegans* attained maximum biomass. *O. tenuis* dominated in autumn and extended its dominance to early winter. The Chlorophyta species *U. variabilis* overwhelmingly dominated in mid-to-late winter (Fig. 2). The most representative dominant species *O. tenuis* was the major species forming the water blooms in autumn and it appeared with higher frequency in water samples. Before and after domination, these species underwent increase and decrease in biomass gradually. The dynamics of the dominant species coincided with that of the phyla in trends, as illustrated by Figs. 1 and 2.

The relationships between aquatic habitat factors and phytoplankton parameters were shown in Table 4. Water temperatures and pH values were positively and significantly related to biodiversity indices and Euglenophyta biomass. Nutrient enrichment will stimulate the growth of phytoplankton in relation to its biomass in various water

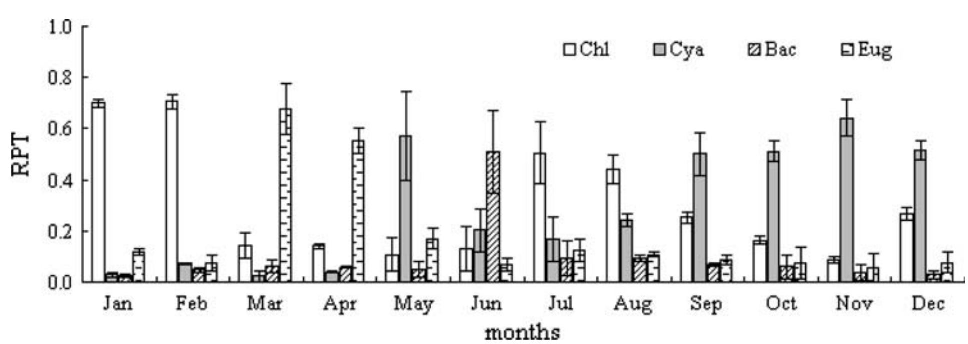

Fig. 1 Seasonal dynamics of the dominant phyla. Chl, Cya, Bac and Eug were abbreviations of Chlorophyta, Cyanophyta, Bacillariophyta and Euglenophyta

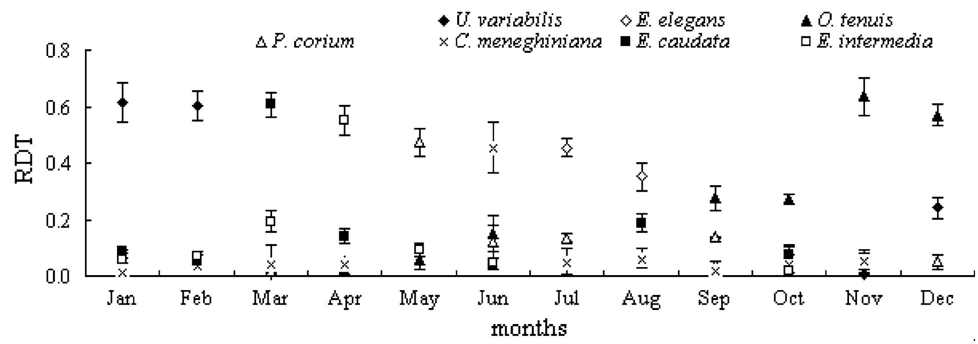

Fig. 2 Seasonal dynamics of the dominant species

Table 4 Correlation coefficients between aquatic habitat factors and phytoplankton parameters

	TEM	pH	AMN	NAN	NIN	DTN	TN	TP
Chl-a	−0.135	0.147	−0.005	−0.083	0.301	0.137	**0.979**[a]	**0.948**[a]
TB	−0.204	0.193	−0.097	−0.003	0.035	0.192	**0.912**[a]	**0.866**[a]
SDI	**0.563**[a]	−0.136	**0.314**[b]	−0.222	**0.468**[b]	0.040	−0.256	**−0.319**[b]
S	**0.643**[a]	0.254	0.135	**−0.329**[b]	**0.562**[a]	−0.098	−0.272	−0.292
CyaB	−0.148	0.062	−0.004	−0.073	0.047	0.253	**0.964**[a]	**0.920**[a]
ChlB	−0.005	−0.200	0.204	0.125	0.312	0.082	−0.103	−0.165
BacB	−0.385	0.058	−0.278	**−0.403**[a]	0.050	**−0.384**[b]	−0.115	−0.150
CryB	−0.020	0.123	0.170	−0.224	**0.811**[a]	0.159	0.231	0.201
ChrB	0.107	−0.247	0.071	−0.007	−0.153	**0.315**[b]	0.175	0.105
PyrB	0.074	−0.163	−0.033	−0.163	−0.102	−0.092	0.013	−0.023
EugB	−0.263	**0.389**[a]	−0.226	0.291	−0.028	−0.076	−0.073	−0.060
XanB	−0.109	0.204	−0.107	**0.383**[b]	0.098	0.023	−0.037	−0.032

[a] Significant at 0.01 level

[b] Significant at 0.05 level

Abbreviations see "Materials and Methods". TB, SDI and S stand for total biomass (mg L^{-1}), Shannon–Weaver diversity index and species richness, and the others for biomass (mg L^{-1}) of phylum: CyaB, Cyanophyta; ChlB, Chlorophyta; BacB, Bacillariophyta; CryB, Cryptophyta; ChrB, Chrysophyta; PyrB, Pyrrophyta; EugB, Euglenophyta and XanB, Xanthophyta

bodies. Phytoplankton in different plant phyla have different demand for nutrition of nitrogen and phosphorus. Aqueous inorganic nitrogen compounds comprise nitrate, nitrite and ammonia nitrogen, which are equilibrated with each other and affect phytoplankton community structure. Nitrate concentrations were negatively correlated with Bacillariophyta biomass, but positively correlated with Xanthophyta biomass. It's interesting to see that nitrite concentrations were directly related to biodiversity indices and Cryptophyta biomass, and that Cyanophyta biomass was related most significantly to the concentrations of total nitrogen and total phosphorus. Other correlations between habitat factors and phytoplankton communities can be noticed in Table 4.

Correlation coefficients between major habitat factors and species biomass were listed in Table 5. The temperature-sensitive species were *Lyngbya limnetica* Lemm., *U. variabilis, C. pyrenoidosa* and *C. meneghiniana*. The pH-sensitive species were *Microcystis aeruginosa* Kütz., *L. limnetica, Dactylococcopsis irregularis* G. M. Smith, *Chlorella vulgaris* Beij., *Chlamydomonas globosa* Snow and *Scenedesmus quadricauda* (Turp.) Bréb. Other relationships can be referred to Table 5.

There were numerous studies about typical phytoplankton species associations with environmental conditions (Komárková and Hejzlar 1996; Temponeras et al. 2000; Dokulil and Teubner 2000). Thirty-one functional groups including major abundant species in temperate lakes were separated by Reynolds et al. (2002). Three dominant species of the 31 assemblages were recognized from the samples in this study. Assemblage G comprised *Eudorina* and *Volvox*, which prefer nutrient-rich water. The peak of *E. elegans* biomass was observed in July with the RDT value of 0.45 (Fig. 2). Chlorophyta dominance was in accordance with *E. elegans* in July (Fig. 1). Assemblage W1 was formed by euglenoids growing in small organic ponds. *E. caudata* and *E. intermedia* dominated in spring, which showed the same dominant period with Euglenophyta. Assemblage R consisted of the cyanoprokaryote *Planktothrix* (formerly

Table 5 Correlation coefficients between major habitat factors and species biomass

	TEM	pH	AMN	NAN	NIN	DTN	TN	SRP	DTP	TP
Cyanophyta										
O. tenuis						0.492[a]				
M. aeruginosa		0.356[b]	0.469[a]							
L. limnetica	0.353[b]	−0.377[b]							−0.287[b]	−0.354[b]
P. corium				−0.309[b]						0.418[a]
D. irregularis		0.625[a]			0.565[a]				0.707[a]	0.634[a]
Chlorophyta										
C. microporum			0.495[b]	0.483[b]		0.572[a]	0.480[b]			
C. vulgaris		−0.376[b]	0.415[b]							
C. globosa		0.376[b]			0.728[a]				0.530[a]	
U. variabilis	−0.606[a]			0.436[a]	−0.445[b]				−0.366[b]	−0.365[b]
S. quadricauda		0.530[a]	−0.524[b]						0.459[b]	0.610[a]
C. pyrenoidosa	0.712[a]		0.443[b]					0.815[a]		
Bacillariophyta										
C. meneghiniana	0.413[b]			0.534[a]		0.389[b]				

[a] Significant at 0.01 level; [b] Significant at 0.05 level

Abbreviations see "Materials and Methods"

Oscillatoria), which has a remarkable capacity for buoyancy regulation and a powerful facility for chromatic adaptation. In small lakes, *Planktothrix* (*P. limosa* and *P. mougeotü*) and *Planktolyngbya* (*P. subtilis*) belonged to this group. *O. tenuis*, which was in assemblage R, dominated in autumn. According to the outlined course of phytoplankton classification, most of the species characterized nutrient-enriched lakes. It's clearly indicated that the West zone of Xinkai Lake was in the process of eutrophication.

Phytoplankton species such as *Oscillatoria* sp., *M. aeruginosa*, *Coelastrum* sp., *S. quadricauda*, *C. meneghiniana*, euglenoids not only observed in the West zone of Xinkai Lake but also in the lake Santa Olalla (López-Archilla et al. 2004). It has been reported that *Microcystis* and *Oscillatoria* cyanobacteria were the most abundant forms, the green alga *Scenedesmus* and the diatom *Cyclotella* dominated in the shallow eutrophic lake Laguna de Bay (Cuvin-Aralar et al. 2004).

The surface blooms in autumn consisted mainly of *Oscillatoria* sp. Although the appearing frequency of *M. aeruginosa* was higher than *O. tenuis* (Table 3), the biovolume of *O. tenuis* was larger. It would enhance resistance to grazing. A more important factor for *O. tenuis* was that it owned gas vesicles which were identified. The buoyancy of the cells, which has been proved by our diel observation in situ, assisted in growing in different depths of the water column by adjusting the volume of gas vesicles. Thus it had an advantage in nutrients competition.

Aquatic habitat factors, such as solar illumination, temperature, pH value, nutrients and their ratios could affect growth, succession and dominance of phytoplankton, while phytoplankton activities could also influence the habitat factors in reverse. It has been measured that photosynthesis induced pH increase in cyanobacterial biofilms (Albertano et al. 2000). Recently, high correlation between pH and total phytoplankton biomass was found in a drinking water reservoir (Albay and Akcaalan 2003). In the shallow lake Santa Olalla (southwestern Spain), where cyanobacteria accounted for more than 99% of phytoplankton cells and bloomed at high pH, an average pH of 9.52 and a total alkalinity of 2.26 mEq L^{-1} have been measured (López-Archilla et al. 2004). The stable high pH values of this hypereutrophic shallow lake were explained by extremely high photosynthetic efficiency and primary productivity. It also has been presented in the West zone of Xinkai Lake, where pH values higher than 9.2 occurred frequently with high phytoplankton productivity. On the other hand, some phytoplankton species adapted themselves to the environment and related their biomass or biovolume to the habitat factors. For instance, the biomass of *D. irregularis* and *S. quadricauda* showed statistically significant correlations with pH value (Table 5), which suggested an adaptive growth in weak alkaline water. The biomass of *U. variabilis* was negatively related to water temperature significantly and it dominated in winter (Fig. 2; Table 5). However, the biomass of *C. pyrenoidosa* in the same phylum Chlorophyta was positively correlated with temperature significantly and it grew well in summer. The opposite correlations between the species and the habitat made the correlations between the phylum and the water environmental factors complicated.

Seasonal dynamics of phytoplankton in the West zone of Xinkai Lake underwent the following processes, large euglenoids had their maximum biomass in spring after slowly growing in late winter, the cyanobacterium *P. corium* replaced the euglenoids and dominated in late spring, the growth of diatom *C. meneghiniana* followed with the decrease of *P. corium* biomass in June, the chlorophyte *E. elegans* dominated in mid-to-late summer, then the autumn bloom of *O. tenuis* occurred and the continuing dominance was showed in early winter, the chlorophyte *U. variabilis* overwhelmingly dominated in mid-to-late winter. The West zone of Xinkai Lake was characterized as a eutrophic water body by means of functional classification of phytoplankton species and water quality comparison with other shallow lakes. The landscape lake in this study is a typical small shallow lake within Tianjin city, the investigation results should be a reference to this kind of urban small water bodies.

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