

Studies on Temporal and Spatial Variations of Phytoplankton in Lake Chaohu

Dao-Gui Deng*, Ping Xie**, Qiong Zhou, Hua Yang and Long-Gen Guo

(Donghu Experimental Station of Lake Ecosystems, State Key Laboratory for Freshwater Ecology and Biotechnology of China, Institute of Hydrobiology, the Chinese Academy of Sciences, Wuhan 430072, China)

Abstract

Temporal and spatial variations of the phytoplankton assemblage in Lake Chaohu, a large shallow eutrophic lake in China, were studied from September 2002 to August 2003. A total of 191 phytoplankton species was identified, among which Chlorophytes (101) ranked the first, followed by Cyanophytes (46) and Bacillariophytes (28). On average over the entire lake, the maximum total algal biomass appeared in June (19.70 mg/L) with a minimum (5.05 mg/L) in November. In terms of annual mean biomass, cyanobacteria contributed 45.43% to total algal biomass, followed by Chlorophytes (27.14%), and Bacillariophytes (20.6%). When nitrate (NO₃-N) and ammonium (NH₄-N) concentrations dropped in spring, fixing-nitrogen cyanobacterium (*Anabaena*) developed quickly and ranked the first in terms of biomass in summer. It is likely that dominance of zooplanktivorous fish and small crustacean zooplankton favored the development of the inedible filamentous or colony forming cyanobacteria. The persistent dominance of cyanobacteria throughout all seasons may indicate a new tendency of the response of phytoplankton to eutrophication in Lake Chaohu.

Key words: cyanobacterial blooms; eutrophication; Lake Chaohu; phytoplankton; zooplanktivorous fish.

Deng DG, Xie P, Zhou Q, Yang H, Guo LG (2007). Studies on temporal and spatial variations of phytoplankton in Lake Chaohu. *J. Integr. Plant Biol.* 49(4), 409–418.

Available online at www.blackwell-synergy.com/links/toc/jipb, www.jipb.net

Lake Chaohu (117°17'–117°52' E, 31°25'–31°43' N) is one of the five largest freshwater lakes in China, with a total surface area of 780 km². It is a shallow and turbid lake with multiple uses: water supply, commercial fishery, and sightseeing. Since the buildup of the Chaohu gate in 1962 and the Yuxi gate in 1969 (Jin et al. 1995), Lake Chaohu has become an artificially controlled, semi-closed lake with considerable changes to the lake ecosystem. At present, submerged macrophyte are rare.

Eutrophication of Lake Chaohu water has progressed over

the past decades. Cyanobacterial blooms have also developed: cyanobacterial blooms first appeared from the beginning of the 1950s, with no distribution in the pelagic and southern zones of the lake in 1961 (Jin et al. 1995). In the 1980s, cyanobacterial blooms occurred from May to November each year and throughout the lake (Liu and Meng 1988; Tu et al. 1990). Due to heavy algal blooms and worsening water quality, the local government has stopped the operation of the waterworks near Hefei City since 1999 (Zhao et al. 2002). However, there have been no surveys on phytoplankton in the lake after the 1980s.

The aims of the present study were to describe temporal and spatial variations of phytoplankton assemblages in Lake Chaohu and to discuss the possible mechanisms underlying these variations, with an emphasis on cyanobacteria.

Results

Physicochemical variables

The maximum water temperature (approximately 31°C) was recorded in July and August, whereas the minimum water

Received 3 Apr. 2006. Accepted 12 Sept. 2006

Supported by the National Natural Science Foundation of China (30225011) and by a Key Project of the Chinese Academy of Sciences (KSCX2-SW-129).

*Present address: Department of Biology, Huaibei Coal Industry Teachers College, Huaibei 235000, China.

**Author for correspondence.

Tel/Fax: +86 (0)27 6878 0622;

E-mail: <xieping@ihb.ac.cn>.

©2007 Institute of Botany, the Chinese Academy of Sciences

doi: 10.1111/j.1672-9072.2006.00390.x

temperature (3.5 °C) was recorded in January (Figure 1). The highest pH (10.4) was recorded during an outbreak of cyanobacterial blooms in the western zones of the lake. There was a positive relationship between pH and cyanobacterial biomass ($r = 0.49$; $n = 212$; $P < 0.01$).

The fluctuation of mean water depth was small before June in 2003, but increased to a maximum of 5.76 m in July after heavy rainfall (Figure 1). Transparency was usually low (< 1.0 m) and independent of cyanobacterial biomass ($r = -0.13$; $n = 212$; $P > 0.05$). Conductivity was relatively stable, with a peak of 472 $\mu\text{S}/\text{cm}$ in July (Figure 1).

The lake had high nutrient concentrations, except for the concentration of soluble reactive phosphorous, and the seasonal patterns of variation of these nutrients differed (Figure 1). Nutrient concentrations in the western zones were usually higher than in the eastern zones of the lake. The fluctuations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ were greater than those of total nitrogen (TN) and total phosphorus (TP). There were significant negative relationships between cyanobacterial biomass and concentrations of $\text{NO}_3\text{-N}$ ($r = -0.36$) and $\text{NH}_4\text{-N}$ ($r = -0.36$; $n = 212$; $P < 0.01$), but a significant positive relationship was found between TP and cyanobacterial biomass ($r = 0.29$).

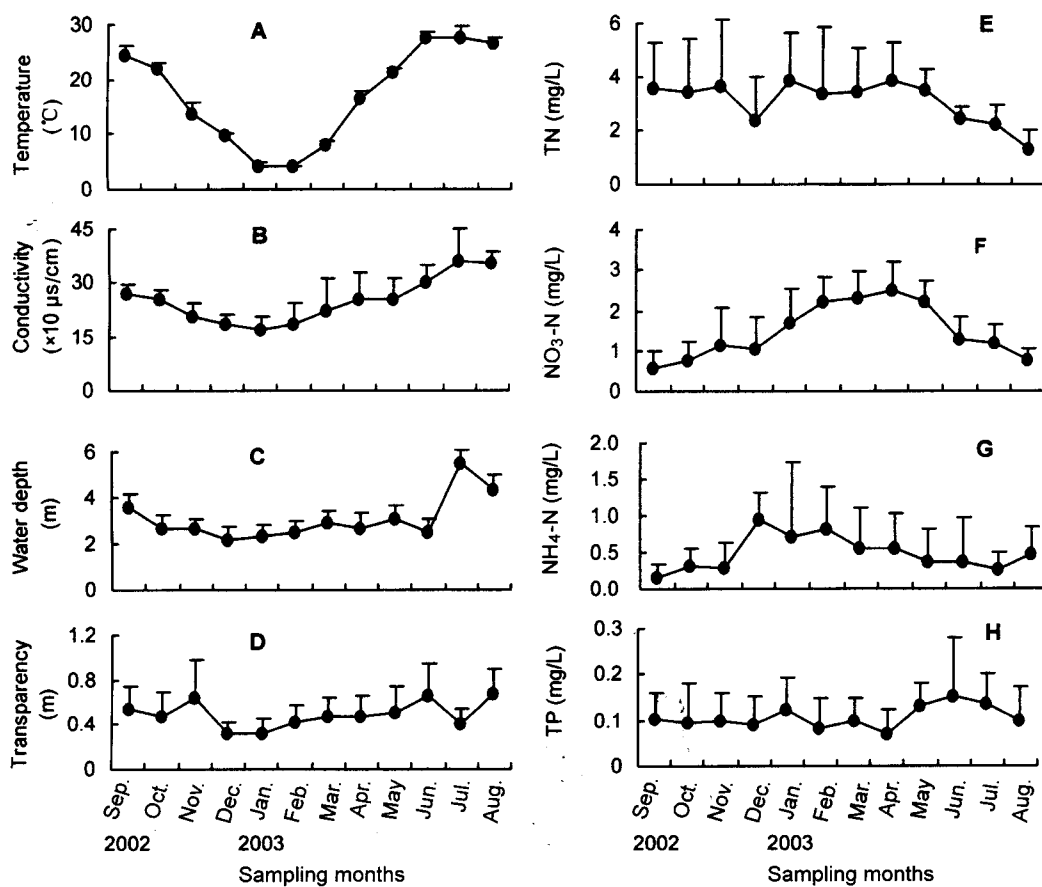


Figure 1. Annual variations of several physico-chemical parameters in Lake Chaohu. Error bars indicate the standard deviations.

- (A) Annual variation of temperature in Lake Chaohu.
- (B) Annual variation of conductivity in Lake Chaohu.
- (C) Annual variation of water depth in Lake Chaohu.
- (D) Annual variation of transparency in Lake Chaohu.
- (E) Annual variation of total nitrogen (TN) in Lake Chaohu.
- (F) Annual variation of nitrate nitrogen ($\text{NO}_3\text{-N}$) in Lake Chaohu.
- (G) Annual variation of ammonium nitrogen ($\text{NH}_4\text{-N}$) in Lake Chaohu.
- (H) Annual variation of total phosphorus (TP) in Lake Chaohu.

Table 1. List of phytoplankton in Lake Chaohu

Chlorophytes	<i>Cocconeis placentula</i> (Ehr.) Hust.
<i>Chlamydomonas</i> sp. ^a	<i>Attheya zachariasii</i> Brun.
<i>C. veinhardtii</i> Dang.	
<i>C. microspheara</i> Pasch	Cyanophytes
et Jah. ^b	<i>Microcystis aeruginosa</i> Kütz ^c
<i>C. ovalis</i> Pasch. ^a	<i>M. wesenbergii</i> Kom. ^b
<i>C. globosa</i> Snow	<i>M. flos-aquae</i> (Wittr.) Kirch ^b
<i>Gonium sociale</i> (Duj.) Warm.	<i>M. incerta</i> Lemm. ^a
<i>Pandorina morum</i> (Muell.) Bory ^a	<i>M. densa</i> G. S. West
<i>Eudorina elegans</i> Ehr. ^b	<i>M. fusco-lutea</i> (Hansg.) Forti
<i>Volvox aureus</i> Ehr.	<i>M. marginata</i> Kütz
<i>Schroederia robusta</i> Korsch.	<i>M. pseudofilamentosa</i> Crow
<i>S. setigera</i>	<i>M. pallida</i> (Farlow) Lemm.
(Schroed.) Lemm.	
<i>S. spiralis</i> (Printz) Korsch.	<i>Dactylococcopsis raphidioidea</i>
	Hansg.
<i>S. nitzschoides</i> (West) Korsch.	<i>D. acicularis</i> Lemm.
<i>Chlorella vulgaris</i> Bey. ^a	<i>Coelosphaerium dubium</i> Grun. ^a
<i>C. ellipsoidea</i> Gren.	<i>C. kuetzingianum</i> Näg.
<i>Chodatella quadriseta</i> Lemm.	<i>Merismopedia elegans</i> A. Br.
<i>C. ciliata</i> (Lag.) Lemm.	<i>M. tenuissima</i> Lemm.
<i>Selenastrum minutum</i> (Näg.)	<i>M. glanca</i> (Ehr.) Näg.
Coll.	
<i>S. gracile</i> Reinsch.	<i>Chroococcus limneticus</i> Lemm.
<i>S. bibrainum</i> Reinsch.	<i>Chroococcus</i> sp.
<i>Selenastrum</i> sp.	<i>Ch. minor</i> (Kütz) Näg.
<i>Kirchneriella lunaris</i> (Kirch.)	<i>Ch. Minutus</i> (Kütz) Näg.
Moeb.	
<i>K. obesa</i> (West) Schm.	<i>Raphidiopsis curvata</i> Fritsch
<i>K. contorta</i> (Schm.) Bohl.	<i>R. sinensis</i> Jao
<i>Ankistrodesmus falcatus</i>	<i>Spirulina major</i> Kütz.
(Cord.) Ralfs	
<i>A. falcatus</i> var. <i>mirabilis</i>	<i>S. princeps</i> W. et. G. S. West
G. S. West	
<i>A. angustus</i> Bern.	<i>S. maxima</i> Setch. Et. Gardn.
<i>A. acicularis</i> (A. Br.) Korsch.	<i>Oscillatoria tenuis</i> Ag.
<i>A. convolutus</i> Cord.	<i>O. amphibia</i> Ag.
<i>A. spiralis</i> (Turn.) Lemm. ^a	<i>O. agardhii</i> Gom.
<i>Closteriopsis longissima</i>	<i>O. splendida</i> Grev.
Lemm.	
<i>Echinosphaerella limnetica</i>	<i>Phormidium tenue</i> (Menegh.) Gom.
G. M. Smith ^a	
<i>Trochiscia reticularis</i>	<i>P. faveolarum</i> (Mont.) Gom.
(Reinsch.) Hansg.	
<i>Oocystis lacustris</i> Chod. ^a	<i>Lyngbya mucicola</i> Lemm.
<i>O. solitaria</i> Wittr.	<i>L. martensiana</i> Men.
<i>O. borgei</i> Snow	<i>Aphanothece</i> sp.
<i>O. parva</i> W. et G. S. West	<i>A. clathrata</i> var. <i>brevis</i> Bachmann
<i>Nephrocystium agardhianum</i>	<i>Aphanocapsa pulchra</i> (Kütz) Kab ^a
Näg.	

Table 1. (continued)

<i>Quadrigula chodatii</i> (Tan- Ful.) G. M. Smith	<i>Apha. elachista</i> W. et G. S. West ^a
<i>Actinastrum hantzschii</i> Lag.	<i>Nostoc paludosum</i> Kütz.
<i>Dictyosphaerium pulchellum</i>	<i>Aphanizomenon flos-aquae</i>
Wood ^a	(L.) Ralfs ^a
<i>D. ehrenbergianum</i> Näg.	<i>Anabaena spiroides</i> Kleb. ^c
<i>Pediastrum biradiatum</i> Mey. ^b	<i>A. circinalis</i> Rab. ^a
<i>P. simplex</i> (Mey.) Lemm.	<i>A. flos-aquae</i> (Lyngb.) Breb. ^b
<i>P. simplex</i> var. <i>duodenarium</i>	<i>Gloeocapsa magma</i> (Breb) Holl
(Bail.) Rabenh. ^b	
<i>P. duplex</i> Mey.	<i>Gloeocapsa</i> sp. ^a
<i>P. duplex</i> var. <i>rugulosum</i>	<i>Rhabdoderma lineare</i> Schm.
Racib ^a	
<i>P. duplex</i> var. <i>gracillimum</i> W.	<i>Cylindrospermum stagnale</i> (Kütz)
et G. S. West ^b	Born. et Flah
<i>P. boryanum</i> (Turp.) Men. ^b	
<i>P. tetras</i> (Ehr.) Ralfs ^a	Bacillariophytes
<i>P. tetras</i> var. <i>tetraodon</i>	<i>Melosira granulata</i> (Ehr.) Ralfs ^c
(Cord.) Rab.	<i>M. granulata</i> var. <i>angustissima</i>
<i>Scenedesmus bijuga</i> (Turp.)	Müll. ^b
Lag. ^a	<i>M. granulata</i> var. <i>angustissima</i>
<i>S. obliquus</i> (Turp.) Kütz.	<i>f. spiralis</i> Hust. ^b
<i>S. arcuatus</i> Lemm.	<i>M. italica</i> (Ehr.) Kütz.
<i>S. platydiscus</i> (G. M. Smith)	<i>M. varians</i> Ag.
Chod.	<i>Cyclotella meneghiniana</i> Kütz. ^b
<i>S. cavinatus</i> (Lemm.) Chod.	<i>C. stelligera</i> Cl. et Grun.
<i>S. quadricauda</i> (Turp.) Bréb. ^a	<i>Coscinodiscus lacustris</i> Grun.
<i>S. dimorphus</i> (Turp.) Kütz.	<i>Tabellaria fenestrata</i> (Lyngby.) Kütz.
<i>S. cfsimipulcher</i> Nach Hindák	<i>T. flocculosa</i> (Roth.) Kütz.
<i>S. denticulatus</i> Lag.	<i>Asterionella formosa</i> Hass ^a
<i>S. brasiliensis</i> Bohl.	<i>Fragilaria intermedia</i> Grun.
<i>S. acuminatus</i> (Lag.) Chod.	<i>F. capucina</i> Desm.
<i>Westella botryoides</i> (W. West)	<i>Synedra acus</i> Kütz.
Wild. ^a	
<i>Westellopsis linearis</i> (G. M.	<i>S. amphicephala</i> Kütz.
Smith) Jao	
<i>Tetrastrum hastiferum</i> (Arn.)	<i>S. ulna</i> (Nitzsch.) Ehr. ^a
Korsch.	
<i>T. heterocanthum</i> (Nord.)	<i>Gyrosigma kiitzingii</i> (Grun.) Cl.
Chod.	
<i>Errerella bornhemensis</i> Conr.	<i>Navicula placentula</i> (Ehr.) Grun. ^a
<i>Micractinium pusillum</i> Fres.	<i>N. dicephala</i> Cl. ^a
<i>Acanthosphaera zachariasii</i>	<i>Navicula</i> sp.
Lemm.	
<i>Golenkina radiata</i> Chod.	<i>Surirella capronii</i> Bréb. ^b
<i>G. paucispina</i> W.	<i>S. ovata</i> Kütz.
et G. S. West	
<i>Crucigenia opiculata</i> (Lemm.)	<i>S. ovata</i> var. <i>pinnata</i> (W. Smith)
Schm.	Hust.
<i>C. quadrata</i> Morr.	<i>Pinnularia viridis</i> (Nitzsch.) Ehr.

Table 1. (continued)

<i>C. tetrapedia</i> (Kirch.) W. et G. S. West	<i>Achnanthes exigua</i> Grun.
<i>C. lauterbornei</i> Schm. ^a	<i>A. lanceolata</i> var. <i>rostrata</i> Hust.
<i>Coelastrum microporum</i> Näg.	<i>Cymbella affinis</i> Kütz.
<i>C. sphaericum</i> Näg.	<i>C. cymbiformis</i> C.A. Agardh
<i>C. reticulatum</i> (Dang.) Senn.	
<i>Cladophora oligoclona</i> Kütz.	Cryptophytes
<i>Microspora stagnorum</i> (Kütz.) Lag. ^b	<i>Chroomonas acuta</i> Uterm. ^a
<i>Ulothrix tenerrima</i> (Kütz.) Kütz.	<i>Cryptomonas erosa</i> Ehr. ^b
<i>Closterium venus</i> Kütz. ^a	<i>C. ovata</i> Ehr. ^a
<i>C. parvulum</i> Naeg. ^b	Euglenophytes
<i>C. gracile</i> Bréb. ^b	<i>Euglena tripteris</i> (Duj.) Klebs
<i>Staurostrum gracile</i> Ralfs	<i>E. geniculata</i> Duj.
<i>S. polymorphum</i> Bréb.	<i>E. ehrenbergii</i> Klebs
<i>Cosmarium botrytis</i> Menegh.	<i>E. tripteris</i> (Duj.) Klebs
<i>Gonatozygon monotaenium</i>	<i>E. oxyuris</i> Schmar.
De Bary	<i>E. acus</i> Ehr.
<i>Euastrum denticulatum</i> (Kirchn.) Gay.	<i>Euglena</i> sp.
<i>Penium cruciferum</i> (De Bary) Wittr.	<i>Phacus longicauda</i> (Ehr.) Duj.
<i>Tetraspora lacustris</i> Lemm.	<i>Trachelomonas</i> sp.
<i>Franceia ovalis</i> (Franc.) Lemm.	Pyrrophytes
<i>Tetraëdron minimum</i> (A. Br.) Hansg.	<i>Ceratium hirundinella</i> (Müller) Schrank ^a
<i>T. trilobulatum</i> (Reinsch) Hansg.	<i>Gymnodinium aeruginosum</i> Stein
<i>T. trigonum</i> (Näg.) Hansg.	Xanthophytes
<i>T. trigonum</i> var. <i>gracile</i> (Reinsch) De Toni	<i>Tribonema affine</i> G. S. West
<i>T. bifurcatum</i> Lag.	Chrysophytes
<i>T. regulare</i> Kütz.	<i>Dinobryon cylindricum</i> Imh.
<i>T. caudatum</i> (Cord.) Hansg.	

^aAnnual mean biomass between 0.01 and 0.1 mg/L. For species with no asterisk, the annual mean biomass is less than 0.01 mg/L.

^bAnnual mean biomass between 0.1 and 1.0 mg/L.

^cAnnual mean biomass between 1.0 and 2.0 mg/L.

Phytoplankton

A total of 191 phytoplankton species was recorded during the study period (Table 1). Chlorophytes ranked the first (101), followed by Cyanophytes (46) and Bacillariophytes (28).

The spatial and temporal distributions of cyanobacterial biomass are shown in Figure 2.

In summer, a high abundance of cyanobacteria occurred at all sampling stations in the western zones, contributing more than 70% to total phytoplankton biomass. Cyanobacteria were more abundant in the southern zone in spring, but in the pelagic

zones in autumn. The proportion of cyanobacteria reached 20%–50% at most sampling stations in the eastern zones, even in winter (Figure 2).

Two genera, namely *Microcystis* and *Anabaena*, comprised 70%–99.8% of the total cyanobacterial biomass. Dominant cyanobacterial species were *Anabaena spiroides*, *A. flos-aquae*, *Microcystis aeruginosa*, *M. flosaquae*, and *M. wesenbergii*, among which *A. spiroides* ranked the first and *M. aeruginosa* second in terms of biomass. Cyanobacteria increased rapidly in spring, began to form surface blooms in May, peaked at most sampling stations in June, and declined in late summer (Figure 3). However, the development of a bloom of *Anabaena* spp. coincided with summer nitrogen (mainly nitrate- and ammonia-nitrogen) depletion. *A. spiroides* reached as high as 70.5 mg/L and *M. aeruginosa* reached 24.8 mg/L in June. *Microcystis* spp. blooms occurred from May to November. *Aphanizomenon flos-aquae*, *Aphanocapsa* sp., and *Oscillatoria* sp. were occasionally found in high abundance at some sampling stations.

When heavy cyanobacterial blooms occurred in summer, the abundance of most Chlorophytes was low, except for species of *Pediastrum*, *Chlamydomonas*, and *Scenedesmus* (Figure 4). Spatially, species of *Pediastrum*, *Scenedesmus*, and *Ankistrodesmus* were more abundant in the eastern zones, whereas a higher biomass of *Chlamydomonas*, *Oocystis*, and *Crucigenia* occurred in the western zones. Bacillariophytes dominated among phytoplankton assemblages in winter (Figure 4) and the dominant diatom genera were *Melosira*, *Cyclotella*, *Synedra*, and *Surirella*. The average biomass was 6.12 mg/L for *Melosira* spp. (in March) and 3.49 mg/L for *Cyclotella* spp. (in February). Spatially, a higher abundance of *Melosira* spp. was found in the eastern zones, whereas in the western zones there was a higher abundance of species of *Cyclotella*, *Synedra* and *Surirella*.

Cryptophytes comprised less than 10% of the total phytoplankton biomass at most stations during the study period. They were more abundant in the south-east zones in summer, but in the western zones in other seasons. Generally, the abundance of Cryptophytes remained relatively high during the outbreak of cyanobacterial blooms (Figure 4). The most important Pyrrophytes was *Ceratium hirundinella*, which occurred in summer and autumn (Figure 4). Euglenophytes (mostly *Euglena* spp.) were frequently found, but made only a minor contribution to total algal biomass. Xanthophytes and Chrysophytes were rare and their contribution to total algal biomass was negligible.

Generally, there was an obvious seasonal succession in the phytoplankton assemblages. Cyanobacteria dominated in summer and autumn, whereas Bacillariophytes was the dominant group in late winter and spring, and Chlorophytes were relatively abundant in spring and autumn.

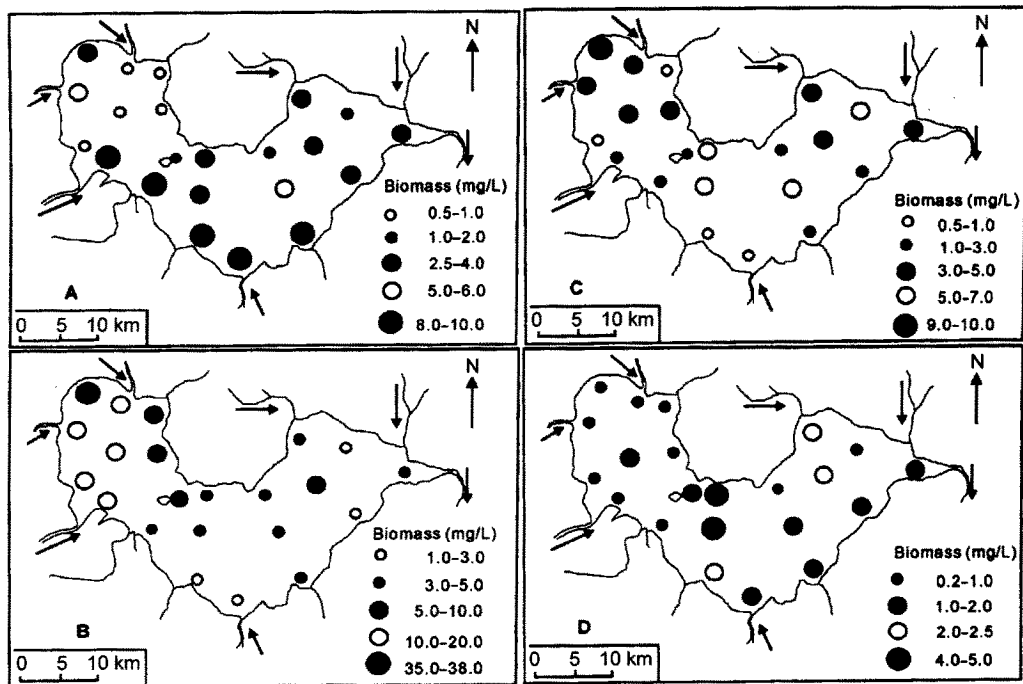


Figure 2. Spatial and temporal distributions of cyanobacterial biomass at the different sampling stations of Lake Chaohu.

- (A) Spatial distributions of cyanobacterial biomass in spring.
 (B) Spatial distributions of cyanobacterial biomass in summer.
 (C) Spatial distributions of cyanobacterial biomass in autumn.
 (D) Spatial distributions of cyanobacterial biomass in winter.

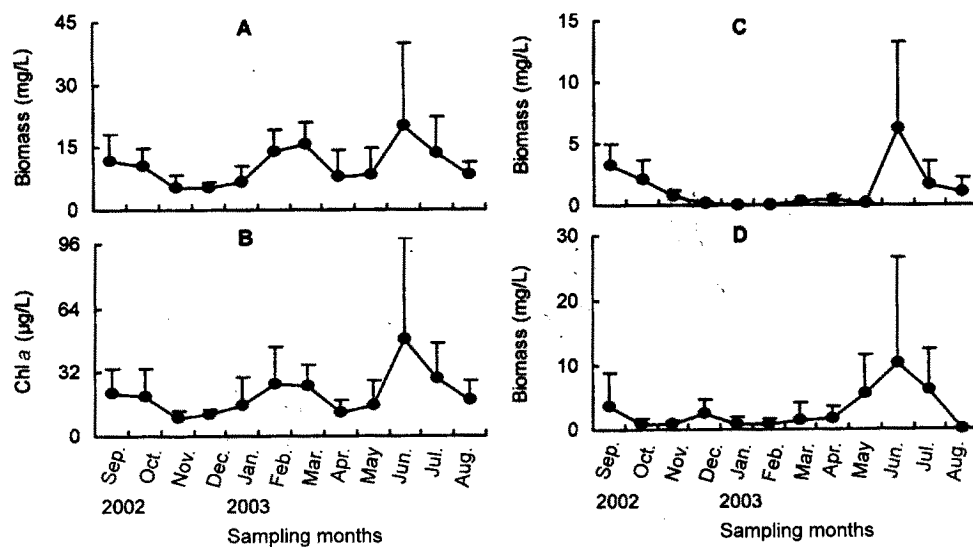


Figure 3. Monthly variations of total phytoplankton biomass in Lake Chaohu, along with *Microcystis* biomass, *Anabaena* biomass and chlorophyll-a. Error bars indicate the standard deviations.

- (A) Monthly variations of total phytoplankton biomass in Lake Chaohu.
 (B) Monthly variations of chlorophyll-a in Lake Chaohu.
 (C) Monthly variations of *Microcystis* biomass in Lake Chaohu.
 (D) Monthly variations of *Anabaena* biomass in Lake Chaohu.

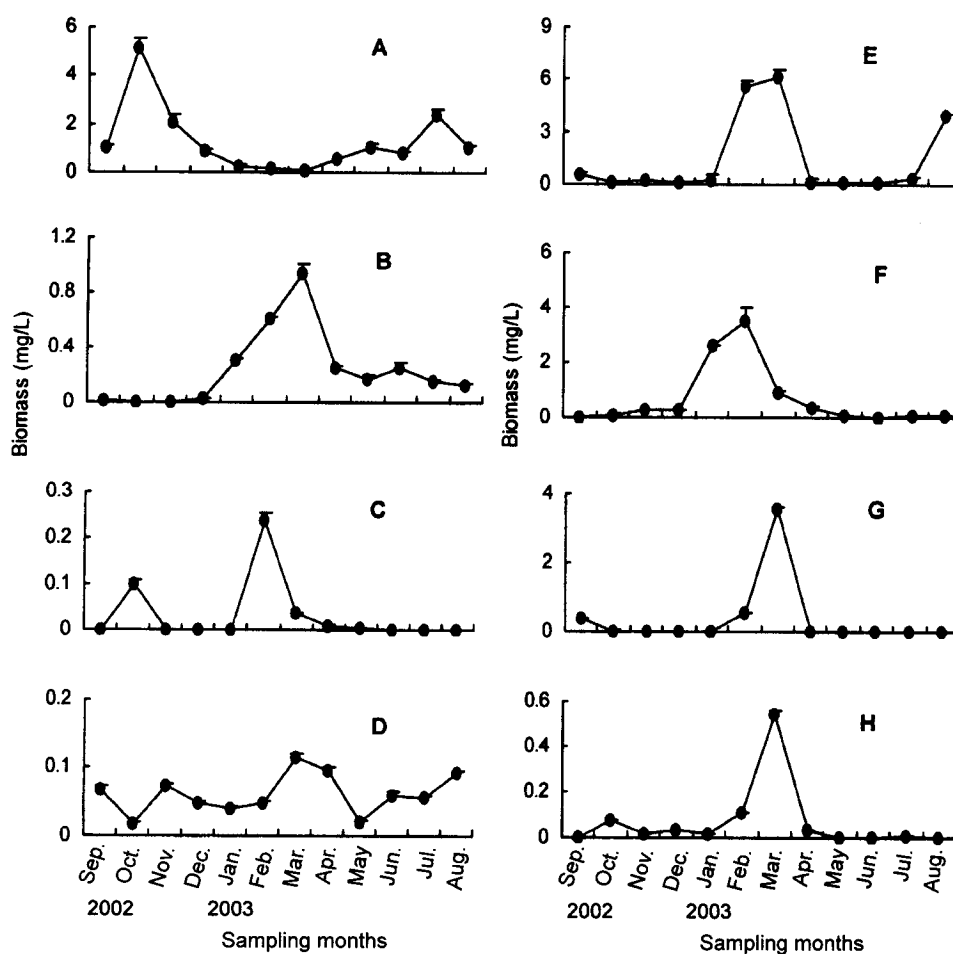


Figure 4. Monthly variations of dominant species of *Chlorophytes*, *Cryptophytes*, *Bacillariophytes* and *Pyrrophytes* in biomass in Lake Chaohu. Error bars indicate the standard deviations.

- (A) Monthly variations of *Pediastrum* spp. Biomass.
 (B) Monthly variations of *Chlamydomonas* spp. Biomass.
 (C) Monthly variations of *Chroomonas acuta* Biomass.
 (D) Monthly variations of *Cryptomonas* spp. Biomass.
 (E) Monthly variations of *Melosira* spp. Biomass.
 (F) Monthly variations of *Cyclotella* spp. Biomass.
 (G) Monthly variations of *Surirella* spp. Biomass.
 (H) Monthly variations of *Ceratium hirundinella* Biomass.

Total phytoplankton biomass and chlorophyll *a*

Monthly means of total algal biomass varied between 5.05 and 19.70 mg/L (Figure 3). The maximum (19.70 mg/L) appeared in June during the outbreaks of cyanobacterial blooms, with a second peak (15.72 mg/L) in March when Bacillariophytes dominated. The minimum (5.05 mg/L) occurred in November. Chlorophyll (Chl) *a* varied from 3.41 to 184.28 $\mu\text{g/L}$ among the stations during the study period. On average over the entire

lake, the maximum concentration of Chl *a* (48.80 $\mu\text{g/L}$) appeared in June, whereas the lowest (8.87 $\mu\text{g/L}$) was found in November. There were significant correlations between Chl *a* and cyanobacterial biomass ($r = 0.87$), as well as with Bacillariophytes biomass ($r = 0.28$; $n = 212$; $P < 0.01$).

Principal component and classification analysis

Principal component and classification analysis (PCCA)

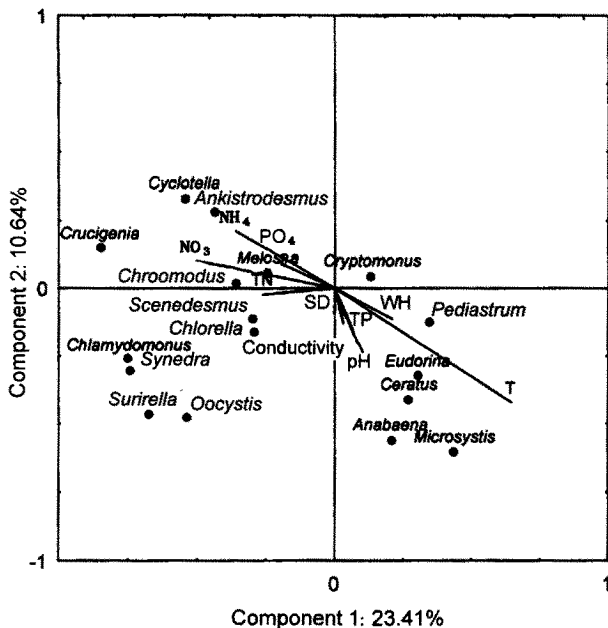


Figure 5. PCCA plot of the main phytoplankton species against environmental variables. Clado-B (cladoceran), Copep-B (copepod), SD (transparency), T (temperature).

identified patterns of variation in the phytoplankton assemblage of Lake Chaohu relative to environmental variables (Figure 5). There were substantial differences in the loadings of the various species on the first two principal components and obvious species groups were taxonomically diverse. The relative positions of the phytoplankton species on the two components reflected a temporal progression of species associations throughout the study. Quadrant I included species such as *Cyclotella*, *Ankistrodesmus*, *Melosira*, *Crucigenia*, and *Chroomonas* that were more abundant in winter; such phytoplankton species were associated with environmental conditions of nitrate ($\text{NO}_3\text{-N}$), ammonium ($\text{NH}_4\text{-N}$), and orthophosphate ($\text{PO}_4\text{-P}$). With an increase in water temperature, Quadrant II, other green algae (e.g. *Chlorella*, *Scenedesmus*, *Oocystis* and *Chlamydomonas*) and Bacillariophytes (*Synedra* and *Surirella*) grew quickly. The role of small green algae (e.g. *Scenedesmus* and *Chlorella*) was obviously weakened from mid-spring to early summer owing to large-bodied *Daphnia* filtering. Subsequently, Quadrant II phytoplankton summer crops (*Microcystis*, *Anabaena*, *Ceratium* and *Eudorina*) dominated and these phytoplankton species were related to several important environmental conditions, including water temperature (T), conductivity, transparency (SD), pH, TP, and cladocera. In autumn, with the decreases in ammonium and nitrate concentrations and T, some small algae (Quadrant IV; e.g. *Cryptomonas* and *Pediastrum*) developed rapidly.

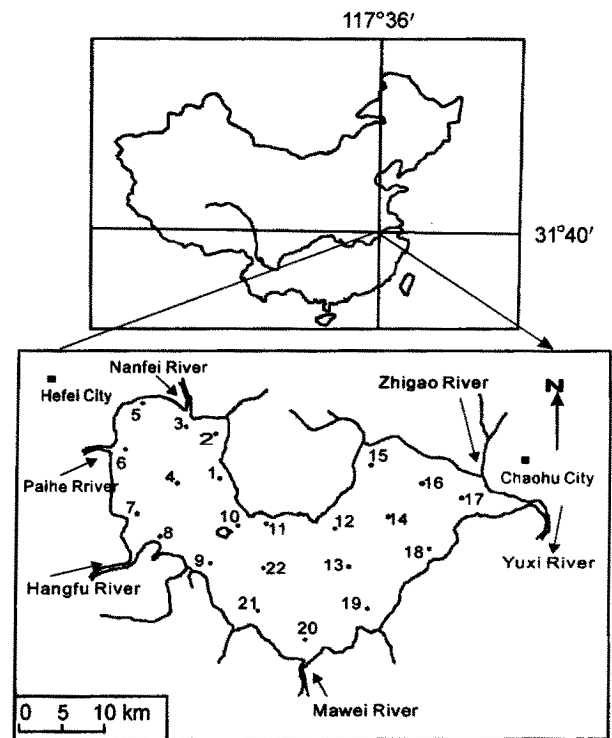


Figure 6. Map of Lake Chaohu and distribution of sampling points.

Discussion

In the present study, both the summer maximum of the algal biomass and PCCA analysis revealed that seasonal variations of the phytoplankton assemblage of Lake Chaohu are basically in agreement with the statement of PEG (Sommer et al. 1986). However, transparency was always low during the study period (Figure 2) and the "clear-water" phase was unclear in Lake Chaohu. The reason for this may be as follows: (i) total algal biomass was higher throughout the study (Figure 3) owing to nutrient availability and the density limit of large-bodied *Daphnia* by zooplanktivorous fish; and (ii) transparency was strongly influenced by suspended silt under wind disturbance because Lake Chaohu is shallow.

In Lake Chaohu, cyanobacterial surface blooms were present during most months (in summer and autumn) of the year, whereas diatoms dominated under conditions of low water temperature. It is well known that warm water and high trophic levels favor cyanobacterial growth (Dokulil and Teubner 2000; Lei et al. 2005) and the formation of cyanobacteria surface blooms (mainly *Microcystis* spp. and *Anabaena* spp.) (Okino 1973; McQueen and Lean 1987; Nalewajko and Murphy 2001; Chen et al. 2003). In Lake Chaohu, the development of cyanobacteria coincided with a sudden drop in both dissolved

inorganic nitrogen (DIN) and TN. It has been reported that many cyanophytes species are superior nitrogen and inferior phosphorous competitors, showing their competitive potential at temperatures above 20 °C, whereas many diatoms are superior phosphorus competitors and inferior competitors for light and nitrogen and show their competitive ability at temperatures below 15 °C (Tilman et al. 1986).

Depletion of DIN favors the development of nitrogen-fixing species of filamentous cyanobacteria (Sommer et al. 1986). In Lake Doi rani, summer depletion of nitrate was accompanied by a very large increase in cyanobacterial biomass, with a shift of dominant cyanobacterial species from *Microcystis* spp. (non-nitrogen-fixing algae) to *Anabaena* spp. (nitrogen-fixing algae; Temponeras et al. 2000). However, in Lake Chaohu, *Anabaena* spp. and *Microcystis* spp. co-occurred and developed during spring and early summer. The sharp decline in these species after July in Lake Chaohu may have been induced by the heavy rainfall between the end of June and mid-July, because it has been reported that rainfall or storms are associated with growth inhibition of filamentous cyanobacteria in shallow lakes (Padisák et al. 1990; Tryfon et al. 1994).

In Lake Chaohu, there was a positive correlation between pH and cyanobacterial biomass. A similar phenomenon was found in Lake Doi rani (Temponeras et al. 2000) and Lake Taihu (Chen et al. 2003). It has been suggested that cyanobacteria are favored in high pH environments, possibly because of their ability to use bicarbonate ion as a carbon source when nitrogen or phosphors depletion occurs in summer (Shapiro 1984; Dokulil and Teubner 2000).

Despite the low transparency (mean 0.49 m) in Lake Chaohu, cyanobacteria (mainly *Microcystis* spp. and *Anabaena* spp.) developed successfully. It has been reported that phytoplankton species with gas vacuoles (such as *Microcystis* spp. and *Ana-*

baena spp.) can either move down to avoid the high irradiance near the water surface or float up when underwater light environments are poor (Ibelings et al. 1991; Brookes and Garf 2001). Thus, high turbidity in Lake Chaohu may be favorable to the development of bloom-forming *Microcystis* spp. and *Anabaena* spp.

In 1952, the annual fish yield from Lake Chaohu was 3 500 tons with 41.1% phytophagous fish (such as *Hypophthalmichthys molitrix* and *Aristichthys nobilis*) and 56.2% zooplanktivorus fish (such as *Coilia ectenes*). Since the 1970s, the proportion of *C. ectenes* remained high (80% in 1973, 61.4% in 1984, and 75% in 2002)(Wang 1987; Lake Chaohu Fishery Administration Committee, unpublished data). The annual fish yield increased from 4 000 tons in 1957 to 4 140 tons in 1984 and approximately 8 000 tons in 2002. At present, the small zooplanktivorus *C. ectenes* and *Neosalanx taihuensis* are predominant, whereas large-bodied crustacean zooplanktons are rare during the warm seasons (Deng et al. unpublished data). It is likely that dominance of zooplanktivorus fish and small crustacean zooplankton favors the development of the inedible filamentous *Anabaena* spp. and colony forming *Microcystis* spp. in Lake Chaohu.

There are no published data on the phytoplankton community in Lake Chaohu before the 1980s (Table 2). In the 1980s, cyanobacteria were predominant (in terms of density or biomass) in summer (August) and autumn (November). However, during the study period, cyanobacteria dominated almost throughout the year, with the higher density in November and a lower density in August. Persistent dominance of cyanobacteria throughout the seasons may indicate a new tendency of the response of the phytoplankton community to eutrophication in Lake Chaohu.

Table 2. Historial changes in the density (×10⁶ cells/L) of major groups of phytoplankton in Lake Chaohu

Years	Months	Cyano.	Bacil.	Chlor.	Eugle.	Crypt.	Total density	Reference
1984	Feb.	0.26	0.73	0.06	0.03	0.002	1.08	Liu and Meng (1988)
	May	0.66	0.012	0.015	0.003	0	0.69	
	Aug.	48.26	0.001	0.11	0.000 2	0.003	48.36	
	Nov.	393.79	0.02	0.39	0.01	0.16	394.38	
1987–1988	Feb.	0.84	1.01	0.52	0.004	0.67	3.04	Tu et al. (1990)
	May	3.35	0.10	0.44	0.05	2.25	6.18	
	Aug.	75.39	0.13	0.20	0.001	0.84	76.56	
	Nov.	54.22	0.28	0.36	0	1.38	56.01	
2002–2003	Feb.	37.00	7.08	12.71	0.002	1.00	57.94	Present study
	May	47.81	0.17	1.65	0.002	0.49	50.12	
	Aug.	26.24	1.94	3.49	0.02	0.45	32.15	
	Nov.	107.70	0.46	1.41	0.008	0.31	109.89	

Cyano., Cyanophytes; Bacil., Bacillariophytes; Chlor., Chlorophytes; Eugle., Euglenophytes; Crypt., Cryptophytes.

Materials and Methods

Quantitative samples were taken monthly from 22 sampling stations in Lake Chaohu (Figure 6). Stations 1–8 are situated in the western zones of the lake, close to Hefei City, and stations 9–22 are in the eastern zones of the lake, near Chaohu City. The lake was ice-free during the sampling period.

Water temperature, transparency, and pH were measured in the field with a thermometer, secchi disk, and portable pH meter, respectively. Determinations of various forms of nitrogen and phosphorus followed the methods described by Xie et al. (2003).

Samples for phytoplankton counts and Chl *a* measurements were collected simultaneously at each station. Each sample was a mixture of subsamples taken from the surface to the bottom with a 2.5 L modified Patalas' bottle sampler at 1 m intervals. Phytoplankton samples were fixed with Lugol's iodine solution and sedimented for 48 h prior to counting under a microscope. Phytoplankton cell volume was determined from average cell dimensions for each species. To count colonial cyanobacteria, the colonies were first disrupted by sonication. The wet weight of the phytoplankton was obtained from cell volume assuming a density of 1 mg/mm³ (Shei et al. 1993).

For Chl *a* measurements, pigments were extracted with 90% acetone at 4 °C in the dark for 24 h. After centrifugation, the absorbance of the supernatant was measured spectrophotometrically against 90% acetone at 750 and 665 nm. Phaeopigment degradation products were analyzed by acidifying the acetone extract with one drop of 2 mol/L HCl for 1 min and remeasuring absorbance at 750 and 665 nm. Concentrations of Chl *a* and phaeopigment products were calculated using the equations of Lorenzen (1967).

Multivariate analyses were based on the biomass of each phytoplankton species obtained from 22 sampling stations (*n* = 212). Logarithmic data were standardized for PCCA using STATISTICA 6.0.

Acknowledgement

The authors are grateful to Lake Chaohu Fishery Administration Committee for the fish data.

References

- Brookes JD, Ganf GG (2001). Variations in the buoyancy response of *Microcystis aeruginosa* to nitrogen, phosphorus and light. *J. Plankton Res.* **23**, 1399–1411.
- Chen YW, Qin BQ, Teubner K, Dikuli MT (2003). Long-term dynamics of phytoplankton assemblages: *Microcystis*-domination in Lake Taihu, a large shallow lake in China. *J. Plankton Res.* **25**, 445–453.
- Dokuli MT, Teubner K (2000). Cyanobacterial dominance in lakes. *Hydrobiologia* **438**, 1–12.
- Ibelings BW, Mur LR, Walsby AE (1991). Diurnal changes in buoyancy and vertical distribution in populations of *Microcystis* in 2 shallow lakes. *J. Plankton Res.* **13**, 419–436.
- Jin XC (1995). *Lakes in China: Research of Their Environment*. Ocean Press, Beijing (in Chinese).
- Lei AP, Hu ZL, Wang J, Shi ZX, Nora Tam FY (2005). Structure of the phytoplankton community and its relationship to water quality in Donghu Lake, Wuhan, China. *J. Integr. Plant Biol.* **47**, 27–37.
- Liu ZQ, Meng RX (1988). A preliminary study of the plankton algae in the Chaohu Lake. *J. Anhui Univ.* **4**, 62–70 (in Chinese with an English abstract).
- Lorenzen CJ (1967). Determination of chlorophyll and phaeopigments: Spectrophotometric equations. *Limnol. Oceanogr.* **12**, 343–346.
- McQueen DJ, Lean RS (1987). Influence of water temperature and nitrogen to phosphorus ratio on the dominance of blue-green algae in Lake St. George, Ontario. *Can. J. Fish. Aquat. Sci.* **44**, 598–604.
- Nalewajko C, Murphy TP (2001). Effects of temperature, and availability of nitrogen and phosphorus on the abundance of *Anabaena* and *Microcystis* in Lake Biwa, Japan: An experimental approach. *Limnology* **2**, 45–48.
- Okino T (1973). Studies on the blooming of *Microcystis aeruginosa*. *Jpn. J. Bot.* **20**, 381–402.
- Padisak J, Toth L, Rajczy M (1990). Stir-up effect of wind on a more or less stratified shallow lake hytoplankton community, Lake Balaton, Hungary. *Hydrobiologia* **191**, 249–254.
- Shapiro J (1984). Blue-green dominance in lakes: The role and management significance of pH and CO₂. *Int. Rev. Ges. Hydrobiol.* **69**, 765–780.
- Shei P, Lin WL, Liu JK (1993). Plankton and seston structure in a shallow, eutrophic subtropic Chinese lake. *Arch. Hydrobiol.* **129**, 199–220.
- Sommer U, Gliwicz ZM, Lampert W, Duncan A (1986). The PEG-model of seasonal succession of planktonic events in fresh waters. *Arch. Hydrobiol.* **106**, 433–471.
- Temponeras M, Kristiansen J, Moustaka-Gouni M (2000). Seasonal variation in phytoplankton composition and physical-chemical features of the shallow Lake Doi rani, Macedonia, Greece. *Hydrobiologia* **424**, 109–122.
- Tilman D, Kiesling R, Sterner R, Kilham S, Johnson FA (1986). Green, blue-green and diatom algae: Taxonomic differences in

- competitive ability for phosphorus, silicon and nitrogen. *Arch. Hydrobiol.* **106**, 473–485.
- Tryfon E, Gouni MM, Mikolaidis G, Tsekos I** (1994). Phytoplankton and physical-chemical features of the shallow Lake Mikri Prespa, Macedonia, Greece. *Arch. Hydrobiol.* **131**, 477–494.
- Tu QY, Gu DX, Yi CQ, Xu ZR, Han JZ** (1990). *The Researches on the Lake Chao Eutrophication*. University of Science and Technology of China, Hefei (in Chinese).
- Wang QS** (1987). Study on ichthyological fauna of Chaohu Lake. *J. Anhui Univ. (Nat. Sci.)* **2**, 70–78 (in Chinese with an English abstract).
- Xie LQ, Xie P, Tang HJ** (2003). Enhancement of dissolved phosphorus release from sediment to lake water by *Microcystis* blooms: An enclosure experiment in a hyper-eutrophic, subtropical Chinese lake. *Environ. Pollut.* **122**, 391–399.
- Zhao Y, Wang ZQ, Yang ZP, Xie CP, Fan Q, Wang Y** (2002). Investigation on water pollution by algae at locations of water collection in Chaohu Lake. *J. Environ. Health* **19**, 316–318 (in Chinese with an English abstract).

(Handling editor: Jin-Zhong Cui)

Lake Chaohu

作者: Dao-Gui Deng, Ping Xie, Qiong Zhou, Hua Yang, Long-Gen Guo
作者单位: Dao-Gui Deng(Department of Biology, Huaibei Coal Industry Teachers College, Huaibei 235000, China), Ping Xie, Qiong Zhou, Hua Yang, Long-Gen Guo(Donghu Experimental Station of Lake Ecosystems, State Key Laboratory for Freshwater Ecology and Biotechnology of China, Institute of Hydrobiology, the Chinese Academy of Sciences, Wuhan 430072, China)
刊名: 植物学报 (英文版) 
英文刊名: JOURNAL OF INTEGRATIVE PLANT BIOLOGY
年, 卷(期): 2007, 49(4)
被引用次数: 2次

参考文献(22条)

1. McQueen DJ; Lean RS Influence of water temperature and nitrogen to phosphorus ratio on the dominance of blue-green algae in Lake St. George, Ontario. Can 1987
2. Tilman D; Kiesling R; Sterner R; Kilham S, Johnson FA Green, blue-green and diatom algae: Taxonomic differences in competitive ability for phosphorus, silicon and nitrogen 1986
3. Temponeras M; Kristiansen J; Moustaka-Gouni M Seasonal variation in phytoplankton composition and physical-chemical features of the shallow Lake Do(i)rani, Macedonia, Greece[外文期刊] 2000(1/3)
4. Sommer U; Gliwicz ZM; Lampert W; Duncan A The PEG-model of seasonal succession of planktonic events in fresh waters 1986
5. Lorenzen CJ Determination of chlorophyll and phaeopigments: Spectrophotometric equations[外文期刊] 1967
6. Liu ZQ; Meng RX A preliminary study of the plankton algae in the Chaohu Lake 1988
7. Lei AP; Hu ZL; Wang J; Shi ZX, Nora Tam FY Structure of the phytoplankton community and its relationship to water quality in Donghu Lake, Wuhan, China 2005
8. Jin XC Lakes in China: Research of Their Environment 1995
9. Ibelings BW; Mur LR; Walsby AE Diurnal changes in buoyancy and vertical distribution in populations of Microcystis in, 2 shallow lakes[外文期刊] 1991
10. Dokulil MT; Teubner K Cyanobacterial dominance in lakes[外文期刊] 2000
11. Chen YW; Qin BQ; Teubner K; Dikuilil MT Long-term dynamics of phytoplankton assemblages: Microcystis-domination in Lake Taihu, a large shallow lake in China[外文期刊] 2003
12. Zhao Y; Wang ZQ; Yang ZP; Xie CP, Fan Q, Wang Y Investigation on water pollution by algae at locations of water collection in Chaohu Lake 2002
13. Xie LQ; Xie P; Tang HJ Enhancement of dissolved phosphorus release from sediment to lake water by Microcystis blooms: An enclosure experiment in a hyper-eutrophic, subtropical Chinese lake[外文期刊] 2003(3)
14. Wang QS Study on ichthyological fauna of Chaohu Lake 1987
15. Tu QY; Gu DX; Yi CQ; Xu ZR, Han JZ The Researches on the Lake Chao Eutrophication 1990
16. Tryfon E; Gouni MM; Mikolaidis G; Tsekos I Phytoplankton and physical-chemical features of the shallow Lake Mikri Prespa, Macedonia, Greece 1994
17. Shei P; Lin WL; Liu JK Plankton and seston structure in a shallow, eutrophic subtropical Chinese lake 1993
18. Shapiro J Blue-green dominance in lakes: The role and management significance of pH and CO₂ 1984
19. Padisak J; Toth L; Rajczy M Stir-up effect of wind on a more or less stratified shallow lake hytoplankton community, Lake Balaton, Hungary[外文期刊] 1990
20. Okino T Studies on the blooming of Microcystis aeruginosa 1973
21. Nalewajko C; Murphy TP Effects of temperature, and availability of nitrogen and phosphorus on the abundance of Anabaena and Microcystis in Lake Biwa[外文期刊] 2001
22. Brookes JD; Ganf GG Variations in the buoyancy response of Microcystis aeruginosa to nitrogen, phosphorus and light[外文期刊] 2001

引证文献(3条)

1. [缪灿](#), [李堃](#), [余冠军](#) [巢湖夏、秋季浮游植物叶绿素a及蓝藻水华影响因素分析](#)[期刊论文]-[生物学杂志](#) 2011(2)
2. [邓道贵](#), [孟小丽](#), [雷娟](#), [张赛](#), [杨威](#), [金显文](#) [淮北采煤塌陷区小型湖泊浮游植物群落结构和季节动态](#)[期刊论文]-[生态科学](#) 2010(6)
3. [邓道贵](#), [孟小丽](#), [雷娟](#), [张赛](#), [杨威](#), [金显文](#) [淮北采煤塌陷区小型湖泊浮游植物群落结构和季节动态](#)[期刊论文]-[生态科学](#) 2010(6)

本文链接: http://d.g.wanfangdata.com.cn/Periodical_zwxb200704001.aspx