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The temporal and spatial distribution, composition and abundance of Protozoa in Chaohu Lake, China: Relationship with eutrophication

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Abstract

Systematic investigations into the temporal and spatial distribution, composition and abundance of protozoa in two regions with different trophic levels in Chaohu Lake, a large, shallow and highly eutrophic freshwater lake in China, were conducted during 2002–2003. A total of 114 species of protozoa, including phytomastigophorans, zoomastigophorans, amoebae and ciliates, were identified from 120 polyurethane foam unit (PFU) samples exposed at four stations and from various types of natural substrates. Of the 114 taxa, 36 core species were found on PFU substrates and 23 of these were found on natural ones. Protozoan abundance and chemical–physical parameters at nine sampling stations, four in the western lake and five in the eastern part, indicate trophic gradient changes along the lake. Seasonal variations in the species composition of major groups at littoral PFU sampling stations illustrate the effect of a severe algal bloom on the protozoan community structure. Temporal and spatial distributions of individual abundance as functions of water temperature and trophic status were revealed. This study demonstrates again that the PFU artificial substrate method samples protozoan communities more effectively than routine natural substrate methods.

Keywords: Protozoan community; Eutrophication; Polyurethane foam unit (PFU); Chaohu Lake

Introduction

Numerous studies have indicated that protozoa constitute a significant portion of the microzooplankton community (e.g. Beaver and Crisman 1989a, b; Finlay and Esteban 1998; Sherr 1984). Because of their small size and high metabolic rate, protozoa play a substantial role in nutrient regeneration in the water column (Bays and Crisman 1983; Pace and Orcutt 1981). Although often neglected in lake studies, protozoa have been considered a major link in the limnetic food web and perform key functions in energy flow and element cycling in freshwater ecosystems. Autotrophic flagellates are responsible for the bulk of primary production in most aquatic habitats; protozoan grazers transfer the production of algae and of the bacteria that grow on algal exudates to higher trophic levels in the food chain. Changes in the community structure of protozoa may significantly affect other components of the aquatic food web, and thus may influence the distribution and abundance of both lower and higher organisms (Beaver and Crisman 1989a; Cairns and McCormick 1993; Carrick and Fahnenstiel 1992; Finlay and Esteban

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1998; Foissner 1992; Pace and Orcutt 1981; Sherr 1984; Xu et al. 1999, 2001).

The structure and composition of macrozooplankton (cladoceran and copepod) assemblages are significantly altered with increasing eutrophication, but the response of microzooplankton (rotifers and protozoa) to a trophic gradient is not as well documented. Across a variety of lake types, protozoa are consistently an abundant component of the planktonic community, and their abundance apparently increases with increasing eutrophy. A few researches have shown that the species composition and individual abundance of protozoa were strongly related to lake trophic status as measured by such analyses as phosphorus, nitrogen and chlorophyll *a* concentrations, and that the structure and composition of planktonic protozoan assemblages in lakes (Phytomastigophora, Zoomastigophora, amoebae and ciliates) can objectively reflect the change in water quality (Bays and Crisman 1983; Beaver and Crisman 1989a, 1990; Foissner 1996; Gomes and Godinho 2003; Henebry and Cairns 1984; Pratt and Balczon 1992; Xu et al. 1999).

There are many freshwater and salt lakes in China from the Qinghai-Tibet Plateau at an elevation of 3000–4000 m above sea level to near sea level in the lower basins of Chang Jiang (the Yangtze River). Recently, rapid developments in industrial and agricultural production and quick growth of populations in China have brought about many environmental problems, water pollution probably the most critical among them. Many lakes in China are now being subjected to high levels of eutrophication due to sewage discharge from urban and rural areas. In the past, a few studies in smaller freshwater and salt lakes have considered changes in the relative importance of macrozooplankton, but investigations into protozoan ecology are almost totally lacking in any of the larger lakes in China.

Situated centrally in the southern China plain, with a subtropical climate, Chaohu Lake is a large freshwater lake which plays an important part not only in intensive commercial fishing, but also for water supply, irrigation, navigation, tourism and recreation as well as being of great conservation value in its wildlife and wetland system. However, Chaohu Lake, which before the 1960s was a clear and beautiful lake supporting rich biodiversities of fish and other aquatic species, is now the main recipient of pollutants from Hefei City (capital of Anhui Province). The principal pollutant inflow to the lake is from the Nanfei River which discharges a total 1.8×10^8 tons per year of untreated domestic and industrial wastewater from Hefei City into the west region of the lake (Fig. 1). Annually the quantities of the main nutrients discharged into the lake from city wastewater are 18,368 tons of total nitrogen (TN) and 1050 tons of total phosphorus (TP). The nutritional input from the farmlands on which chemical fertilizers are intensively used around the lake also increase the lake's eutrophication. Limnological and related studies made over more than ten years indicate that Chaohu Lake is both organically polluted (high COD) and highly enriched in nitrogen and phosphorus, and average concentrations of TN, TP and COD_{Mn} in the whole lake were 2.30, 0.204 and 12.7 mg/L, respectively (Chen and Wang 1999; Han 1998; Tu et al. 1990; Yin and Bernhardt 1992). However, to the best of our knowledge, no previous research has been carried out on the protozoan communities.

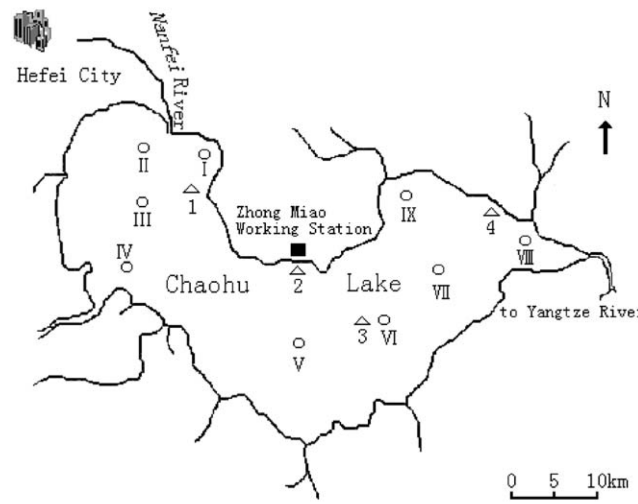

Fig. 1. Map of Chaohu Lake showing protozoan sampling sites Δ—PFU protozoan collection sites, stations 1 and 2, nearer to the Nanfei River inflow, are regarded as in the western part and stations 3 and 4 in the eastern part of the lake. ○—quantitative sampling sites, stations I–IV in the western part and stations V–IX in the eastern part.

The objectives of this investigation are: (1) to publish the first records of protozoan taxonomic composition, variations of taxonomic richness and relative abundance in relation to season or water temperature and eutrophication; (2) to analyze biological and chemical parameters of two lake regions, western and eastern parts, to indicate trophic gradient changes among nine sampling sites; (3) to describe seasonal variations in the percentage composition of species of major protozoan groups at the littoral polyurethane foam unit (PFU) sampling stations to illustrate the effect of a severe algal bloom on protozoan community structure; and (4) to compare protozoan colonizers of an artificial substrate, polyurethane foam, with protozoan assemblages on nearby natural substrates.

Materials and methods

Chaohu Lake (117°16′46″–117°51′54″E, 30°43′28″–31°25′28″N) is located on one of the tributaries of the Yangtze River and is one of the five largest freshwater lakes in China, with a catchment area of about 9200 km^2

and a surface area of 753–774 km^2. It contains approximately $32.3 \times 10^8\,m^3$ of water in the rainy season, with a residence time of about 150 days, but only $17.2 \times 10^8\,m^3$ of water, with a residence time of about 210 days in the dry season (Tu et al. 1990). Its depth varies according to the hydrologic conditions, being usually below 4 m (maximum depth 6 m, mean 3 m), which is shallow for a lake of such size. The lake does not appear to stratify in any season, being stirred by frequent winds and by the movement of many boats.

Artificial substrates, PFU, were used in the main study to collect protozoa from Chaohu Lake. PFU are readily colonized by many protozoan species, and provide a very effective method for sampling planktonic, periphytic and benthic assemblages of protozoa in a new habitat (Cairns and Pratt 1986; Lugo et al. 1998; Shen et al. 1990; Xu et al. 1999, 2002; Yongue and Cairns 1973). These qualitative protozoan samples were collected in spring (April), summer (July), autumn (October) and winter (December) during 2002–2003 by anchoring PFU blocks $5 \times 6.5 \times 7.5$ cm at a depth of 30 cm below the water surface at four sites in littoral and open water regions of the lake, stations 1 and 2 in the western part and stations 3 and 4 in the eastern part (Fig. 1). PFU samples were collected after 1, 3, 6, 9, 15 and 20 days submersion. For a detailed description of the use of the PFU method see Xu and Wood (1994, 1999).

Protozoa were extracted from PFUs by manually squeezing water from the units into a clean glass beaker (200 mL). Protozoan taxon richness was determined from living material by pipetting two or three drops of well-mixed deposit material from the bottom of the beaker onto a slide and examining the whole field at $\times$ 100–400 magnification. Identification of live protozoa was made using standard books and protozoological keys (Foissner et al. 1999; Kudo 1966; Lee et al. 1985; Page 1976; Patterson and Hedley 1992; Shen et al. 1990); the examination of all samples was usually completed within a few hours of collection. Identification of naked amoebae is difficult and was rarely attempted beyond generic level.

To compare natural protozoan communities with those in the PFUs, samples from various types of natural substrates in the vicinity of the littoral PFU sites were collected by sucking materials from a variety of surfaces (mud, wood, leaves, rocks, boat and submerged vegetation) using a clean rubber bulb and placing the sample material into clean, 250 mL, screw-top jars with adequate air space. These samples were immediately taken back to a laboratory at the lake-side Zhong Miao Laboratory for examination.

Samples for the physical and chemical analyses and chlorophyll *a* measurements were collected monthly from December 2002 to November 2003 at nine hydrological stations, four (I–IV) in the western lake and five (V–IX) in the eastern part (Fig. 1). Samples were collected for the determination of the abundance of protozoa from the same nine hydrological stations in the same months as the PFU samples. To estimate protozoan abundance, 1 L mixed water samples from upper, middle and bottom layers of the water column were taken with an integrating organic glass sampler on each sampling occasion. There was no attempt to analyze vertical profiles as the lake is shallow and unstratified. Each sample was fixed with acidified Lugol's iodine for later counting of flagellates and ciliates in the laboratory, but identification of species was not attempted in these samples. No attempt was made to count fixed sarcodines. All samples were concentrated to 30 mL by being allowed to stand for 48 h in a settlement funnel. Four subsamples (0.1 ml) of the final concentrate were placed in a perspex counting chamber and enumerated under a light microscope at a magnification of $\times 400$. The four replicate sub-samples from each water sample yielded SE of $<8\%$ of the mean values of counts.

Other parts of the samples were used for chemical and physical analyses and chlorophyll *a* measurements using standard techniques (APHA 1982). All biological and chemical–physical values are based on annual means.

Seasonal data of protozoan abundance, TP and TN in the two lake regions were compared by two-way analysis of variance using the SPSS 11.5 computer package.

Results and discussion

Chemical and physical parameters

Water quality data derived from the present investigation show that the dissolved oxygen contents of the two lake regions were commonly below saturation and the average concentrations of N, P and COD have greatly exceeded the National Grade III Standards of Surface Water (National Standard issued by EPA of China). The content of chlorophyll *a* is typical of an eutrophic–hypereutrophic condition (Table 1). Table 1 also shows that almost all physical–chemical and biological parameters displayed differences between the west and east lake regions, notably lower values of DO and water transparency and distinctly higher contents of TN, TP, COD and chlorophyll *a* in the west lake region. The annual mean TN concentrations were significantly different in the two regions of the lake (two way analysis of variance test, $F_{1,7} = 97.209$, $p < 0.001$), but the difference between seasons was not significant ($p = 0.092$). Similarly the annual mean TP concentrations in the two parts of the lake were significantly different (two way analysis of variance test, $F_{1,7} = 141.984$, $p < 0.001$), but the difference between seasons was not significant ($p = 0.247$). These

Table 1. A comparison of physical–chemical and biological parameters (mean of 12 monthly values with standard deviation) of the two lake regions in the Chaohu Lake during 2002–2003

Parameters	West lake region	East lake region
Temperature (°C)	16.31 ± 7.55	17.11 ± 8.37
pH	7.92 ± 0.69	8.12 ± 0.56
Conductivity (ms m^{-1})	23.37 ± 9.34	24.19 ± 8.25
Transparency (cm)	37.0 ± 10.45	61.58 ± 18.40
DO (mg L^{-1})	6.97 ± 1.88	7.63 ± 1.52
COD_{Mn} (mg L^{-1})	21.30 ± 3.27	10.36 ± 5.55
BOD_5(mg L^{-1})	4.15 ± 1.13	1.81 ± 0.59
0il (mg L^{-1})	0.13 ± 0.05	0.04 ± 0.014
TP (mg L^{-1})	0.30 ± 0.12	0.11 ± 0.05
TN (mg L^{-1})	3.09 ± 1.25	1.41 ± 0.28
NH_4^+–N (mg L^{-1})	0.60 ± 0.38	0.28 ± 0.12
Chlorophyll *a* (mg m^{-3})	30.48 ± 25.67	16.51 ± 5.14

differences are doubtless attributable to the location of pollutant inflows.

Taxonomic composition, core species and taxa distribution

Ciliates, sarcodines, and autotrophic and heterotrophic flagellates were all abundant in the Chaohu Lake. A list of all protozoan species identified from PFUs at the four sampling sites is given in Table 2. A total of 114 protozoan species were obtained from the 120 PFUs examined and many were also found on various types of natural substrates. The 114 protozoan taxa comprised 31 flagellates (including algal flagellates), 28 sarcodines and 55 ciliates. Of these three groups of protozoans, the ciliates exhibited the greater diversity and abundance in the whole lake, but it is very difficult to collect and identify all of the smaller amoebae and flagellates, so this list is certainly not exhaustive, and new records of species will be found with further investigation. Thirty-six 'core' species were among the most abundant species in almost all PFU samples, and 23 of these were also found on natural substrates (Table 2).

There are no previous data on protozoan species in the lake, so it is impossible to assess how communities are changing. Also it would be beyond the scope of this paper to attempt a detailed comparison with other published protozoan lake faunas, but some points of interest can be made briefly. The diversity of the eutrophic–hypereutrophic Chaohu Lake is lower than that of the mesoeutrophic Douglas Lake in Michigan (13 km^2 in area and 25 m in depth), which contained 248 protozoan species in 1977 and 149 species in 1982 (Pratt and Cairns, 1985). It is premature to attempt an explanation for this, but many factors, such as water quality, predation and other environmental elements, may influence species composition and community development of protozoa in aquatic ecosystems.

There is a considerable difference in the number of protozoan species between the west lake (PFU sampling sites 1–2) and the east lake (PFU sites 3–4). A greater species diversity occurred in sampling stations 3 and 4 with 102 and 101 protozoan species. Numbers of protozoan species clearly declined to 76 and 80 at stations 1 and 2 and many species common in a normal lake environment, such as *Gonium pectorale*, *Sphaeroeca volvox*, *Arcella*, *Difflugia*, *Carchesium polypinum* and *Oxytricha chlorelligera*, were absent from sampling sites 1 and 2. A decrease in the species diversity is a commonly accepted indication of pollution. The poorer species richness in the west region probably results from the inflow of very large amounts of pollutants by discharge from the Nanfei River. Severe stress, whether caused by heavy metals, extreme organic pollution, pH or temperature fluctuation, or a sharp change in any environmental factors, usually reduces the number of species and increases the concentrations of tolerant forms (Cairns et al. 1972; Ruthven and Cairns 1973; Xu et al. 1999, 2001).

Seasonal variations in the percentage composition of species of major groups at the littoral PFU sampling stations

The seasonal percentage composition of flagellate, sarcodine and ciliate species at the littoral PFU sampling stations is given in Fig. 2. Generally, the percentage composition of species of major protozoan groups at the open PFU sampling sites followed the same pattern of ciliates > flagellates > sarcodines in all seasons. However the order in these littoral PFU samples changed in the summer season when flagellates outnumbered ciliates. In the summer, with a high water temperature (25–30 °C), an algal bloom often forms a thick layer of cyanobacteria (of up to 6×10^7 cells L^{-1}) along littoral regions of Chaohu Lake, where it is drifted by the prevailing northwest wind.. The bloom layer, which is mainly dominated by the species *Microcystis aeruginosa* and *Anabaena spiroides*, may range from several centimeters to more than 1 m thickness, and releases an unpleasant smell; the farmers in local villages used to collect the thick blooming algae for use after fermentation as organic fertilizer on rice fields (Yin and Bernhardt 1992). Protozoan communities found on PFU immersed under the blooming layer comprised a richer diversity of flagellates and a lower number of ciliate species. Almost all taxa of large-bodied ciliates such as *Euplotes*, *Stentor*, *Paramecium* and *Stylonychia* frequently found in other seasonal samples disappear at

Table 2. Taxonomic composition and total numbers of species of protozoa collected from PFUs at the four sampling stations (1 and 2 in west part, 3 and 4 in east part) in Chaohu Lake

Name of species	Stations			
	1	2	3	4
Flagellates				
Euglena sp. ^{n} *	+	+	+	+
E. viridis (Ehrenberg)	+	+	+	+
E. acus (Ehrenberg)	+	+	+	+
Phacus pyrum (Ehrenberg) *	+	+	+	+
Chlorogonium elongatum (Dang)	–	+	+	–
Synura urella (Ehrenberg)	+	+	+	+
Anisonema acinus (Dujardin) ^{n} *	+	+	+	+
Eudorina elegans (Ehrenberg)	+	+	+	+
Pandorina morum (Müller) Bory	+	+	+	+
Trachelomonas hispida (Perty) Stein	–	–	–	+
Petalomonas mediocanellata (Stein)	+	+	+	+
Ceratium hirundinella (Müller) Schrank	–	+	–	+
Cryptomonas ovata (Ehrenberg) ^{n} *	+	+	+	+
C. erosa (Ehrenberg)	+	+	+	+
Spumella (Monas) *sociabilis* (H. Meyer)	+	+	+	+
Urceolus pascheri (Skvortzov)	+	+	+	+
Chlamydomonas microsphaera (Pasch.et Jah.) ^{n} *	+	+	+	+
C. reinhardi (Dang)	+	+	+	+
Peranema trichophorum (Ehrenberg) Stein	+	+	+	+
Gymnodinium aeruginosum (Stein)	+	+	+	+
Gonium pectorale (Müller)	–	–	+	+
Carteria globosa (Korsch)	+	+	+	+
Mastigella commutans (H.Meyer) Goldschmidt	+	+	+	+
Oikomonas socialis (Moroff) ^{n} *	+	+	+	+
Rhynchomonas nasuta (Klebs)	+	+	+	+
Tetramitus pyriformis (Klebs)	+	+	+	+
Sphaeroeca volvox (lauterborn)	–	–	–	+
Monosiga ovata (Kent)	+	+	+	+
Trepomonas agilis (Dujardin)	+	+	+	+
Bodo saltans (Ehrenberg) ^{n} *	+	+	+	+
B. globosus (Stein)	+	+	+	+
Sarcodines				
Difflugia sp.1	–	–	+	+
Difflugia sp.2	–	–	+	–
Actinophrys sol (Ehrenberg) ^{n} *	+	+	+	+
Amoeba proteus (Leidy)	+	+	+	–
Amoeba sp. ^{n} *	+	+	+	+
Thecamoeba sp.	+	+	–	+
Arcella sp.1	–	–	+	+
Arcella sp.2	–	–	+	+
Raphidiophrys viridis (Archer) ^{n} *	+	+	+	+
Centropyxis sp.1	–	+	–	+
Centropyxis sp.2	–	–	+	+
Cochliopodium sp.	+	+	+	+
Nebela dentistoma (Penard)	–	–	–	+
Vahlkampfia sp.	+	+	+	+
Naegleria sp.	–	–	+	–
Actinosphaerium sp. ^{n} *	+	+	+	+
Saccamoeba sp.	+	+	+	+
Cyphoderia sp.	+	+	+	+
Euglypha sp.	+	+	+	+
Chaos carolinense (Wilson)	+	+	+	+
Mayorella sp.1 *	+	+	+	+

Table 2. (*continued*)

Name of species	Stations			
	1	2	3	4
Mayorella sp.2	+	+	+	+
Mayorella sp.3	+	+	+	+
Hartmannella sp.1 [n] *	+	–	+	–
Hartmannella sp.2	+	+	+	+
Heterophrys radiata (West)	–	–	+	–
Acanthocystis sp.	–	–	+	–
Acanthocystis sp.	–	–	–	+
Ciliates				
Litonotus obtusus (Maupas) [n] *	+	+	+	+
L. carinatus (Stokes) *	+	+	+	+
L. cygnus (Müller)	–	–	+	+
Aspidisca cicada (Müller) Claparede & Lachman [n] *	+	+	+	+
A. lynceus (Ehrenberg) *	+	+	+	+
Cinetochilum margaritaceum (Perty) [n] *	+	+	+	+
Cyclidium citrullus (Cohn) [n] *	+	+	+	+
C. oblongum (Kahl)	+	+	+	+
Lembadion bullinum (Perty)	–	–	+	–
L. lucens (Maskell)	–	–	–	+
Vorticella campanula (Ehrenberg) [n] *	+	+	+	+
V. cupifera (Kahl) *	+	+	+	+
V. picta (Ehrenberg)	–	–	+	+
V. microstoma (Ehrenberg) [n] *	+	+	+	+
Halteria grandinella (Müller) *	+	+	+	+
Coleps hirtus (Müller) [n] *	+	+	+	+
C. hirtus minor (Kahl)	–	+	+	+
Chilodonella uncinata (Ehrenberg) [n] *	+	+	+	+
C. labiata (Stokes)	–	–	+	+
C. bavariensis (Kahl)	–	–	+	–
Tachysoma pellionella (Müller-Stein)	+	+	+	+
Paramecium caudatum (Ehrenberg) *	–	–	+	+
Holosticha kessleri (Wrzesniowski)	–	–	+	+
Uroleptus caudatus (Claparede & Lachman) *	–	+	+	+
Glaucoma scintillans (Ehrenberg)	+	+	+	+
Euplotes affinis (Dujardin) [n] *	+	+	+	+
E. eurystomus (Wrzesniowski)	–	–	+	+
Spirostomum minus (Roux)	+	–	–	+
Stylonychia notophora (Stokes) [n]*	–	+	+	+
S. mytilus (Müller)	–	–	+	+
Urostyla viridis (Stein) *	+	+	+	+
Urocentrum turbo (Müller) *	+	+	+	+
Strobilidium gyrans (Stokes) *	+	+	+	+
Acineta tuberosa (Ehrenberg)	–	–	+	–
Sphaerophrya soliformis (Lauterborn) *	+	+	+	+
Trochilia minuta (Roux)	+	+	+	+
Stentor polymorphus (Müller) *	–	+	+	–
S. coeruleus (Ehrenberg)	+	–	–	+
Colpidium colpoda (Ehrenberg) Stein	–	–	+	+
Astylozoon faurei (Kahl)	+	+	–	+
Frontonia acuminata (Ehrenberg)	+	+	+	+
Holophrya sulcata (Penard)	+	–	+	+
Carchesium polypinum (Linnaeus)	–	–	+	+
Oxytricha chlorelligera (Kahl)	–	–	+	+
Strombidium viride (Stein)	+	+	+	+
Prorodon ovum (Ehrenberg)	+	+	+	+
Epistylis rotans (Svec) [n] *	+	+	+	+

Table 2. (*continued*)

Name of species	Stations			
	1	2	3	4
E. lacustris (Imhoff)	+	+	+	+
Opercularia phryganeae (Kahl)	+	+	+	+
Obertrumia aurea (Ehrenberg) Foissner	–	–	+	+
Paruroleptus caudatus (Stokes)	–	+	+	–
Lacrymaria olor (Müller)	–	–	–	+
Metopus es (Müller)	–	–	+	–
Trithigmostoma srameki (Foissner)	+	+	+	+
Mesodinium pulex (Claparede and Lachmann) ″ *	+	+	+	+
Total number of species: 114	76	80	102	101

Presence is denoted by (+), absence by (–). Those 36 core species found on PFUs are marked *, and those 23 on natural substrates are marked ″.

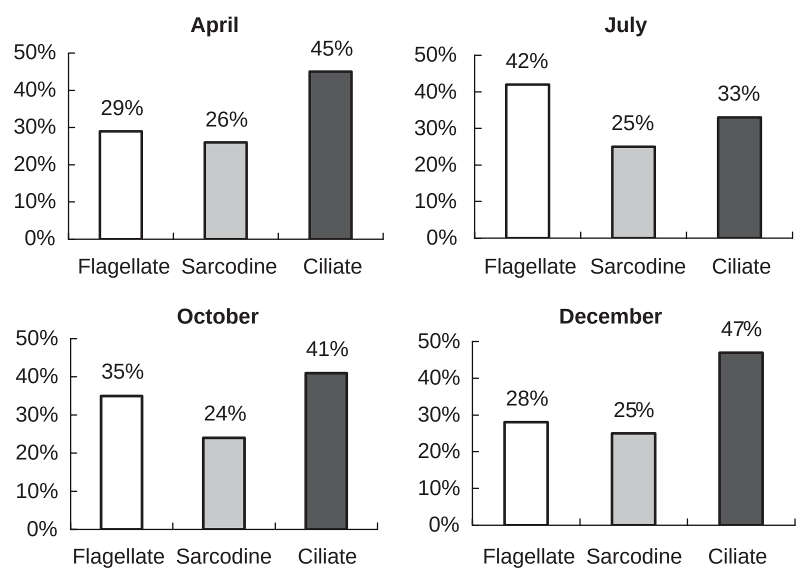

Fig. 2. Seasonal variations in the percentage of flagellate, sarcodine and ciliate species in protozoan samples from littoral PFU stations.

this time, and are progressively replaced by small-sized ciliates such as *Cyclidium*, *Trochilia*, *Cinetochilum,* *Halteria* and *Aspidisca*. This typical summer bloom of cyanobacteria clearly influences the community structure of protozoa. Many researches have shown that cyanobacterial blooms in eutrophic waters produce a variety of toxic bioactive secondary metabolites, especially microcystin which is believed to have strongly deleterious effects on crustaceans, molluscs and fish (Carmichael 1994; Keila et al. 2002; Magalhaesa et al. 2003).

Abundance and temporal and spatial variations of total populations

The abundance of protozoan cells in Chaohu Lake determined during this study showed clear temporal and spatial changes which appeared to be strongly related to variations in the trophic gradients and other environmental factors. Quantitative analyses of the total protozoan populations from integrated depth samples at nine sampling sites gave an annual average of 20.2×10^3 ind. L^{-1}. The highest mean cell density of these nine sites occurred in the autumn with 34×10^3 ind. L^{-1} at water temperatures ranging from 14.5 to 20.5 °C. Spring densities were a little lower with 20×10^3 ind. L^{-1} at a temperature of 16.5–18.8 °C, falling to 18×10^3 ind. L^{-1} in the summer at 25.5–30.5 °C, and to 10.5×10^3 ind. L^{-1} in the winter at 2.5–3.8 °C (Fig. 3). The lower cell density in the summer was probably due to higher water temperatures and dilution by flooding which frequently happened in the rainy season at that time. In winter the low water temperatures are likely to substantially affect planktonic protozoan populations, since the growth and reproduc-

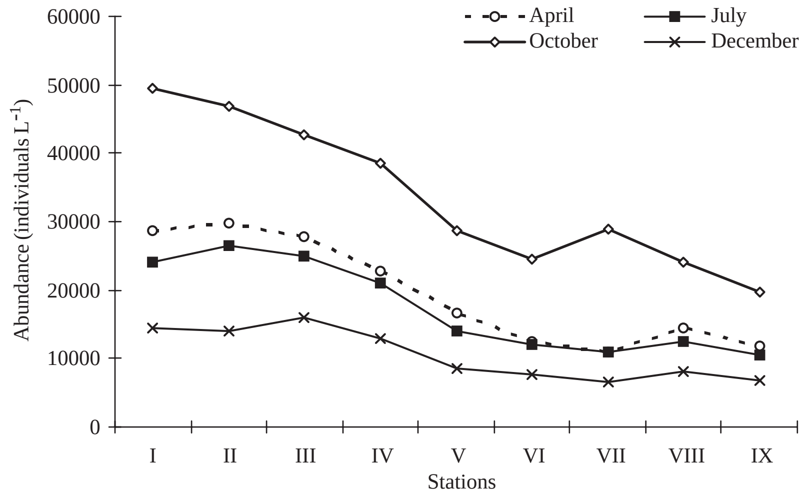

Fig. 3. Seasonal variations of protozoan abundance at the nine quantitative stations in Chaohu Lake. Stations I–IV are in the west part and stations V–IX in the east part of the lake (see Fig. 1).

tion of freshwater protozoans are strongly correlated with temperature (Finlay et al. 1979). Beaver and Crisman (1990) suggested that temperature may have a particularly intense effect on shallow productive lakes.

The decrease in species richness in the west part, as compared with the east region, was accompanied by an increase in the total individual abundance of protozoans in the west region, as is evident in Fig. 3. The mean annual cell density of the west region with a higher trophic level was 28,500 ind. L^{-1} and this was near twice the average abundance of individuals in the eastern lake region with 14,400 ind. L^{-1}. The protozoan abundance was significantly different in the two regions of the lake (two way analysis of variance test, $F_{1,7} = 214.761$, $p < 0.001$), and protozoan abundances were also significantly different between seasons (two way analysis of variance test, $F_{3,7} = 134.645$, $p < 0.001$). The interaction between lake region and season also had significant effects on protozoan abundances (two way analysis of variance test, $F_{3,7} = 8.619$, $p < 0.001$). The same tendency was found in phytoplankton data from the past 10 years, where the total production of phytoplankton in the west region has risen to nearly twice that in the east part of the lake, the most rapid increases having occurred in recent times, with a change to dominant species tolerant of eutrophic conditions throughout the whole lake (Tu et al. 1990).

Chaohu is a very eutrophic lake which yields phytoplankton population densities in excess of 39.4 mg chlorophyll *a* m^{-3} annually, and maximal concentrations of about 240 mg m^{-3} in some lake areas in summer (Tu et al. 1990). As this is near to the top of the productivity range for lakes, one might expect that protozoan populations would be correspondingly large. However, abundances of the main protozoan populations in Chaohu Lake were in fact lower than those of other eutrophic lakes (Beaver and Crisman 1990; Gomes and Godinho, 2003). The reason is the intense cultivation of the fish *Hypophthalmichthys molitrix* and *Aristichthys nobilis*, biomanipulated to control the algal bloom in the lake. These species of fish are distributed throughout the whole lake and showed strong predation on phytoplankton and zooplankton at all seasons. Their guts were frequently found to be filled with flagellates and ciliates. Xie (2003) has proposed that the predation pressure of these two species of fish on microplanktonic populations should be more intense than by macrozooplankton assemblages, although cladocerans and copepods may greatly reduce algal and ciliate concentrations within a eutrophic body of water. It is probable that the numerical abundance of nano- and picoflagellates was greatly underestimated due to the difficulty of counting them in the fixed condition.

Overall, the abundance of protozooplankton in Chaohu Lake is similar to values reported by other workers from eutrophic lakes, although the density of populations in this lake is somewhat lower than that in some other high trophic level water bodies. However, comparisons must be made with care, since in many instances the whole water column was not sampled, so that mean values may be an under or over estimate, and some studies concentrate on specific size classes, or species, rather than the whole community (Laybourn-Parry et al. 1990). These differences in annual plankton cycles are primarily quantitative and probably related to the different morphometry of the basin. Among factors that strongly influence the population density of planktonic protozoans are the water quality, quantity of available food, temperature, and predation (Beaver and Crisman 1990).

Comparison of colonization rates on PFU substrate and natural substrate species

In recent years, the PFU method has been widely used to sample protozoan communities and to assess water quality in various types of water body. Researches show that PFUs accumulate populations of planktonic, periphytic and benthic protozoans and that the PFU method could offer advantages in comparison with routine natural substrate methods (Cairns and Pratt 1986; Lugo et al. 1998; Niederlehner and Cairns 1990; Xu et al. 1999; Yongue and Cairns 1973). The species diversity of protozoa sampled from PFUs in each of the four sampling seasons (mean 72.5 species) was higher than that from natural substrates (mean 56 species), probably because organisms that prey on protozoa, such as snails, many insect larvae and large crustaceans (cladocera, copepods), which live and feed on natural substrates, are excluded from the interior of the PFUs.

Conclusion

Chaohu Lake suffers from intense eutrophication caused by both organic pollution and high enrichment with N and P in the wastewater discharge from Hefei City. Our data show that the changes of protozoan community structure objectively reflect the gradient of eutrophic status within the lake. Comparative biological data showed trends in the diversity and density of constituent species in the two lake regions. The species richness was clearly lower and the cell density was distinctly higher in the west region with higher trophic level in comparison with the east region. A decrease in species diversity accompanied by an increase in total individual abundance of the tolerant protozoans is typically attributed to a poorer water quality, and this is doubtless the cause here. Seasonal variations in the percentage composition of species of major groups at the littoral PFU sampling stations illustrate the effect of the severe algal bloom on protozoan community structure.

Our research provided further evidence that the characteristics of the structure and composition of protozoan community in lakes can objectively reflect the change in water quality and that the PFU artificial substrate method offers an effective technique for assessing protozoan diversity.

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