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The effects of temperature and nutrient ratios on *Microcystis* blooms in Lake Taihu, China: An 11-year investigation

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ABSTRACT

The temporal distribution of bloom-forming cyanobacteria- *Microcystis* and its correlation with related physical and chemical variables including the total nitrogen-to-total phosphorus ratio (TN:TP), the ammonium-to-nitrate ratio (NH_4-N:NO_X-N), water temperature, and pH in the north part of Lake Taihu (Meiliang Bay) were investigated, using a continuous, 11-year record of environmental data (1992–2002) and phytoplankton species. A multivariate statistical analysis, canonical correspondence analysis (CCA), revealed a negative correlation between the *Microcystis* and TN:TP, and a positive correlation between the *Microcystis* and NH_4-N:NO_X-N, water temperature and pH. Warm water temperature was the principal force driving *Microcystis* blooms, which were preceded declining concentrations of nitrogen compounds. *Microcystis* tended to dominate (*Microcystis* contributed above 50% to total algal mass) in the north part of Lake Taihu during summer when the TN:TP mass ratio was less than 30, NH_4-N:NO_X-N was below 1, and a critical water temperature ranged from 25 °C to 30 °C, respectively. Meanwhile, suspended solids (SS) concentrations exceeded 10 mg l^{-1} and pH exceeded 8.0 during blooms. Overall, this study advances our understanding of nutrient enrichment and high ambient temperature influences on *Microcystis* biomass.

1. Introduction

Eutrophication is one of the most serious ecological problems facing freshwater and coastal ecosystems worldwide (Nixon, 1995; Smith et al., 2006). It causes predictable increases in the biomass of noxious and toxic algae in lakes and reservoirs, in streams and rivers, and in wetland and marine ecosystems (Smith, 2003). Cyanobacterial dominance, and sometimes bloom formation, is among the most visible symptoms of accelerated eutrophication of lakes and reservoirs (Moss et al., 1996).

Lake Taihu was oligotrophic as recently as the 1950s, but increased nutrients inputs related to population and economic growth have led to eutrophication (Cai et al., 1996; Chen et al., 2003b). Most pollutants come from rivers discharging into Meiliang Bay (Fig. 1) and other parts of the lake (Huang, 2000), causing severe eutrophication in Meiliang Bay. As a consequence, phytoplankton diversity has decreased since 1981, but cyanobacteria populations (*Microcystis* and *Anabaena*) have increased (Pu and Yan, 1998) and can comprise 85% of summer phytoplankton biomass (Chen et al., 2003a). Annual cyanobacterial blooms have clogged intakes at municipal waterworks, interrupted domestic and industrial water supply, disrupted tourism and fisheries, and caused losses in fish cultures (Pu and Yan, 1998).

In order to better understand the mechanisms of bloom-forming cyanobacteria, considerable research on abiotic factors have been conducted, including nutrient loading rates and ratios with hydrodynamic and light conditions. Many experimental studies established that high concentration of phosphorus, along with a low N:P supply ratio (Schindler, 1977), thermal stratification, reduced transparency and an increase in water temperature and pH (Dokulil and Teubner, 2000; Jacoby et al., 2000; Oliver and Ganf, 2000) are favorable for the production of cyanobacterial blooms. However, previous studies have only investigated the effects of singular environmental factors on the growth and/or abundance and/or photosynthesis of cyanobacteria populations. In addition, most studies addressing cyanobacteria responses to changes in irradiance, temperature, and nutrients have been undertaken in the laboratory; few studies have addressed these important topics under field conditions, using a relatively long-term monitoring record.

In recent years multivariate statistical analysis, especially canonical correspondence analysis (CCA) has been widely employed to examine patterns and relationships in large-scale ecological data sets. Additionally CCA has proved useful for qualitative analysis of the interactions between the ecological

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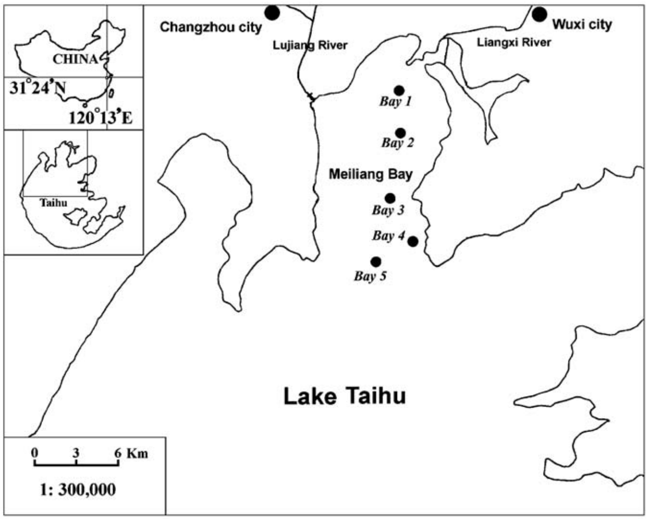

Fig. 1. Location of Lake Taihu, China and the sampling stations in Meiliang Bay (the north part of Lake Taihu). Cited from Chen et al. (2003a).

factors that influence plankton communities in highly complex systems. Hansel-welch et al. (2003) showed the annual variation in abundance of filamentous algae by using CCA. Ke et al. (2008) used it to explore the phytoplankton succession during the spring–summer periods in 2004 and 2005 in Meiliang Bay of Lake Taihu. CCA was also performed to elucidate the relationship between *Microcystis* operational taxonomic unit composition and the environmental factors in Lake Taihu (Tan et al., 2009). However, key physical and nutrient thresholds favoring cyanobacterial performance cannot be quantitatively described in CCA.

This paper concentrates on the long-term changes of *Microcystis* biomass using monthly monitoring data covering the period 1992–2002 in Meiliang Bay of Lake Taihu. CCA was also applied to explore the correlation between multi-environmental variables and *Microcystis*. The main purposes of this study are (1) to evaluate the synergistic effects of nutrient mass ratios (TN:TP, NH_4-N:NO_X-N) on bloom-forming cyanobacteria, especially *Microcystis* biomass; (2) to determine which range of nutrient ratios are suitable for the growth of *Microcystis* in Lake Taihu according to field sampling data.

2. Method

2.1. Site description

Lake Taihu is the third largest freshwater lake in China, with an area of 2338 km^2 and an average depth of about 2.0 m. It is located between 30°05′ and 32°08′N and between 119°08′ and 121°55′E, downstream of the Changjiang river (Fig. 1). For further details on morphological, hydrological and biological properties of Lake Taihu, see Chen et al. (2003a). Meiliang Bay is situated in the northern part of Lake Taihu, which is one of the most eutrophic bays. The surface area of the bay is 132 km^2 with a mean depth of 2.0 m. The Liangxi and the Lujiang river, connected to the Meiliang Bay, discharge effluents from the cities of Wuxi and Changzhou. In response to heavy industrial and agricultural pollution, the bloom-forming cyanobacteria in Meiliang Bay has been frequently observed during the past decades.

2.2. Analytical methods

Observations of water quality and phytoplankton community structure were conducted monthly at sites bay 1–bay 5 from 1992 to 2002. Eleven years with continuous monthly sampling at five stations gives a total of 660 observations. At each site, integrated water samples were taken using a 2 m long and 10 cm diameter plastic tube. Physicochemical variables such as suspended solids (SS), water temperature, pH, COD and nutrient concentrations (NO_2-N, NO_3-N, NH_4-N, TN, TP) were analyzed following Chinese standard methods (see Chen et al., 2003a,b for details). NO_3-N and NO_2-N concentrations were summed to give total oxidized inorganic nitrogen (NO_X-N). Phytoplankton samples were fixed with Lugol's iodine solution and sedimented for 48 h prior to counting on a microscope (Chen et al., 2003b). *Microcystis* cell numbers were counted from colonies and single cells. Phytoplankton species were identified according to Hu et al. (1980). Algal biovolumes were calculated from cell numbers and cell size measurements. These biovolumes were converted to biomass based on the assumption that 1 mm^3 of volume equals 1 mg of fresh-weight biomass. Proportions of phytoplankton were calculated using algal biomass. The common *Microcystis* species in Lake Taihu are *Microcystis aeruginosa*, *M. flos-aquae* and *M. wesenbergii*. The composition of cyanobacteria was calculated as an annual average of the five sampling stations in Meiliang Bay. Four seasons were used at fixed time periods: spring, March–May; summer, June–August; autumn, September–November; winter, December–February.

2.3. Statistical analysis

The CANOCO v.4.5 computer program was used to perform all of the multivariate and ordination analyses (ter Braak and Smilauer, 1998). The first gradient length of detrended correspondence analysis (DCA) was used to select the appropriate model (ordination procedure) for the constrained ordinations. Standard deviations of about 2.0 units or greater (which are representative of a relatively long gradient) indicate that numerical analyses assuming unimodal species distributions, such as canonical correspondence analysis (CCA), would be the most appropriate for this dataset. In the present study, mean monthly physicochemical variables and the most prominent algal taxa in the Meiliang Bay were subjected to DCA and CCA. Before performing the analysis, the data were $\ln(x+1)$ transformed. In order to determine the variables best related to the phytoplankton dynamics, a Monte Carlo permutation test was applied.

3. Results

The phytoplankton assemblage was mainly composed of four abundant algal groups namely Cyanobacteria, diatoms, green algae and Cryptophyceae (Chen et al., 2003a). Cyanobacteria contribution accounted for 38.3% of total phytoplankton biomass in Meiliang Bay between 1992 and 2002. *Microcystis* dominated among the cyanobacteria, which accounted for 85.7% of the total cyanobacteria biomass in Meiliang Bay (Fig. 2).

The long-term dynamics of TN:TP mass ratios and *Microcystis* biomass from 1992 to 2002 are presented in Fig. 3. TN:TP mass ratios in Lake Taihu were highly dynamic, but seasonal patterns were evident. High TN:TP mass ratio (the highest value was 126.0 in 1995) was observed in winter and early spring, and low TN:TP mass ratio (the lowest value was 5.2 in 1993) in late summer and early autumn. In contrast, the *Microcystis* biomass in Meiliang Bay exhibited an opposite seasonal trend with maximum values usually appearing after TN:TP mass ratio was lowest. The summer maxima of *Microcystis* biomass peaked at 112.0 mg l^{-1} in August 1998, which accounted for 94.5% of the total phytoplankton biomass. The lowest *Microcystis* biomass was observed in 2002 in Meiliang Bay.

Mean monthly NH_4-N:NO_X-N ratios in Meiliang Bay exhibited a similar seasonal trend to TN:TP mass ratios, but an opposite