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Unexpected malformations in
Xenopus tropicalis



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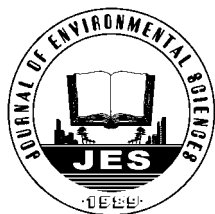
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Influence of sunlight on the proliferation of cyanobacterial blooms and its potential applications in Lake Taihu, China

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ABSTRACT

To learn the relationship between sunlight intensity and cyanobacterial proliferations for the further control of the heavy blooms, enclosure experiment were conducted in Meiliang Bay, Lake Taihu by regulating the natural light intensities with different shading ratio (0% (full sunlight), 10%, 25%, 50% and 75% of original natural sunlight intensities) from September to November in 2010. The results indicated that phytoplankton biomass (mean) decreased significantly when the shading ratios reached 50% or more. Higher shading ratios (e.g. 75%) were very efficient in controlling the average and total cyanobacterial bloom biomass, while 50% shading ratio was proven very effective either in controlling the peak value of phytoplankton biomass or postponing the occurrence of cyanobacterial blooms in Lake Taihu. In addition, phytoplankton composition and photosynthesis efficiency were also affected by altering the shading ratios, and in turn, they might also act on phytoplankton growth. Based on the results from the present study, intermediate shading strategies such as regulation of water level or turbidity through the hydrology regulations would probably be an effective and efficient method in controlling cyanobacterial blooms in large and shallow lakes.

Introduction

Occurrence of harmful blooms in freshwaters such as lakes, reservoirs, ponds and so on has been recognized as a serious environmental problem. Although many factors could influence cyanobacterial status in different phases (Kong and Gao, 2005), the process of its formation, maintenance and decline is a result of the combined effects of different environmental factors including physical, chemical, biological factors and cyanobacterium itself (Paerl et al., 2001; Kong and Gao, 2005; Song et al., 2007b).

Solar radiation is the energy source of aquatic ecosystem especially for phytoplankton and other photosynthetic organisms. Although phytoplankton including cyanobacteria

have some physiological and ecological strategies to adapt solar irradiation change (Darley, 1982; Stal and Moezelaar, 1997; Paerl et al., 2001; Kong and Gao, 2005; Song et al., 2007b; Lee, 2008), light change could still affect macromolecule synthesis, physiological activity, phenotype and buoyancy regulation etcetera of cyanobacteria (Darley, 1982; Bormans et al., 1999; Xiao et al., 2012), and the regulation of community structure of phytoplankton (Havens et al., 1998; Litchman, 1998), distribution of phytoplankton species as well (Mur and Schreurs, 1995). In addition, it could also affect the onset and duration of the cyanobacterial blooms (Zhang et al., 2012). As a result, light is often considered to be one of the limiting factors of phytoplankton growth (Darley, 1982).

There were several studies on the relationships between the light or light combined with other factors and phytoplankton growth (Jassby and Platt, 1976; Mur et al., 1977; Huisman and Weissing, 1994; Litchman, 1998;

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Flder and Burns, 2005; Carneiro et al., 2009; Chen et al., 2009a; Mehnert et al., 2010; Kunath et al., 2012), however, the general results and conclusions from most of these studies were conducted only in laboratory and need to be further confirmed under field conditions. In the literatures, light shading was occasionally used for the control of phytoplankton in drinking water sources (Kojima, 2000; Chen et al., 2009b; Wan and Zhu, 2009). Kojima (2000) invented a “partial shading method” in a small reservoir for farm irrigation. Results from this study indicated that cyanobacterial growth could be inhibited when the shaded water surface areas were over 30%, and very significant reductions in phytoplankton biomass were observed in those groups with the shaded water areas over 60%. Another outdoor simulation experiment indicated that the inhibition effect of phytoplankton growth was achieved with the shading ratio over 67% (Wan and Zhu, 2009). The study by Chen et al. (2009b) also suggested that harmful blooms could be controlled by shading (shading ratio $\geq 90\%$).

To develop new control technologies associated with light shading in large and shallow lakes, it is very critical to investigate the relationships between the change of cyanobacterial biomass and light shading ratios under field conditions, particularly with *in situ* enclosure experiments. However, investigation concerning the above issues are still lacking at present. Results from this study will contribute to the establishment of the effective and efficient strategies for the control of cyanobacterial blooms in Lake Taihu.

1 Materials and methods

1.1 Site description

Lake Taihu ($119^{\circ}54'E-120^{\circ}36'N$, $30^{\circ}56'E-31^{\circ}33'E$), the third largest freshwater lake in China, is located in the highly developed and densely populated Yangtze Delta, the water depth of Lake Taihu ranges from 1 to 2.5 m (average 1.89 m) with a total water surface area of about 2338 km², and a mean water volume of approximately 4.43×10^{12} L (Song et al., 2007a). The lake serves as an important resource for drinking water, irrigation, aquaculture and industrial waters, in addition to being a popular recreational and tourist attraction (Song et al., 2007a). Due to rapid economical development and the intensive use of water resources, the lake water is becoming more seriously polluted (Song et al., 2007a). The occurrence of heavy cyanobacterial blooms in warm seasons has increased in frequency and intensity in recent years, especially in Meiliang Bay lies in the northern part of the lake (Song et al., 2007a). In the present study, the enclosures located at the Meiliang Bay of Lake Taihu ($31^{\circ}24'N$ and $120^{\circ}13'E$).

1.2 Experimental design

Five enclosures (each 5 m \times 5 m \times 2 m) were built with rubber cloth (above the surface of water column) and geotextile (underwater), open to the air above and sediment at bottom in Meiliang Bay (Fig. 1a). Five shading rates of 0% (full sunlight, control group, CG), 10% (EG1), 25% (EG2), 50% (EG3) and 75% (EG4) were employed by covering the enclosures with white sieve cloth (the pore size of the cloth ranged between less than 0.01 mm and 2.00 mm) (Fig. 1b). The experiment was conducted from 16 September to 7 November 2010. Before the experiment, harmful bloom biomass was removed with a phytoplankton net (pore size, 0.064 mm). Water and algae samples were collected constantly (14:00–15:00) from both the surface (s, 0.5 m from the surface of water column) and the bottom (b, 1.7 m from the surface of water column) during the experiment. From each enclosure, water samples were taken from 6 sites at the same depth and then mixed them thoroughly for further analysis.

1.3 Sample analysis

Air temperature was measured with a thermometer. Wind direction and average wind speed were measured according to the standard protocols using an anemometer

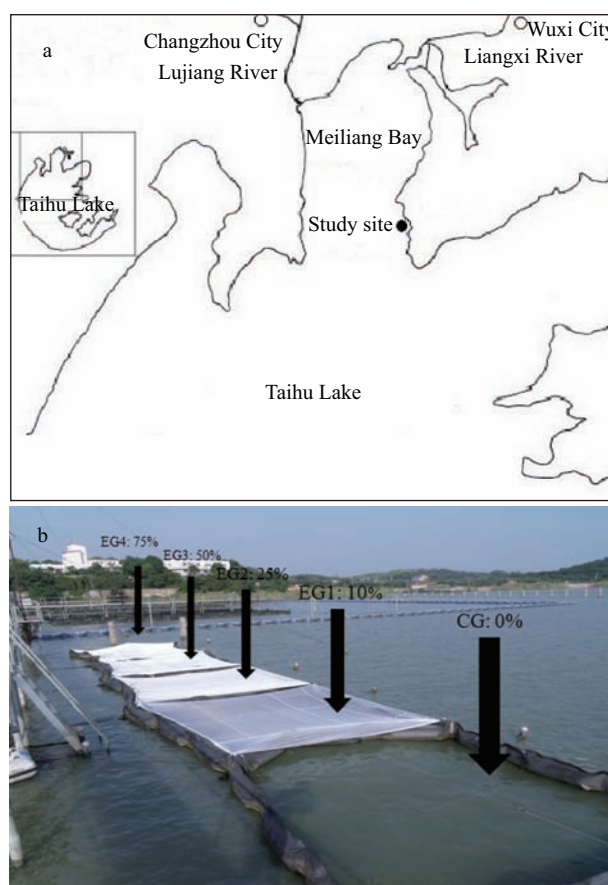


Fig. 1 Location of study site (a, revised from Chen et al., 2003) and the enclosure experiment design (b).

and dogvane (PH-SD2, Wuhan Xinpuhui Technology Co., Ltd., China). Transparency (SD) was measured using a Secchi Disk. Water temperature (WT), electrical conductivity (EC), pH, oxidation-reduction potential (ORP), turbidity (Tur) and dissolved oxygen (DO) were monitored using an YSI Multiparameter Water Quality Sonde (6600 V2 \oplus , Yellow Springs Instruments, USA).

Total nitrogen (TN), total phosphorus (TP), total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were analyzed according to Jin and Tu (1990). Chlorophyll *a* (Chl-*a*) was analyzed according to standard methods (Mitchell and Kiefer, 1984). Fixed phytoplankton was identified and enumerated by light microscope, according to the previously reported methods (Zhang and Huang, 1991; Hu and Wei, 2006). Phytoplankton biomass was converted from the Chl-*a* concentration and the biomass of *Microcystis* spp. was calculated from cell abundance according to the method described by Reynolds (2006).

Chlorophyll fluorescence was measured using a diving multiwavelength pulse-amplitude-modulated fluorometry (Diving-PAM, Heinz Walz GmbH, Germany), and optical fiber of Diving-PAM is aligned vertically to the smooth side of quartz cuvette under the dark conditions when measured (Perkins et al., 2006). The initial slope (*a*), maximum relative electron transport rate (rETR_{max}) and half-saturation light intensity (*I_k*) were calculated from the fitted rapid light curve according to Jassby and Platt (1976).

1.4 Statistical analysis

Statistical analysis was conducted with SPSS (version 16.0) followed by Nonparametric Tests-2 Independent Samples (Mann-Whitney U, between surface and bottom) or Nonparametric Tests-K Independent Samples (Kruskal-Wallis H, among five groups) to identify the sources

of detected significance. In all cases, comparisons that showed a *P* value 0.05 were considered significant. The Spearman correlation analysis was also conducted with SPSS (version 16.0).

2 Results

2.1 Meteorology and physical-chemical parameters

During the experiment, air temperature ranged between 17.5 and 33.8°C. The variations of daily total Σ PAR (photosynthetically active radiation, 400–700 nm, the data was provided by CNERN, Taihu Laboratory for Lake Ecosystem Research (CNERN TaiLLER)), water temperature (mean \pm SE) and wind speed were shown in **Fig. 2**. Two rapid cooling processes were recorded from 21 to 27 September (temperature decreased from 29.32 to 22.94°C) and from 24 to 29 October (temperature decreased from 20.64 to 13.76°C), respectively (**Fig. 2b**). The physical-chemical parameters were shown in **Table 1**, and results indicated that there was no significant difference in these parameters between the surface water and the bottom water of investigated enclosures except SD. However, significant differences (*P* < 0.05) in pH values, DO and TDP were observed between the five enclosures (**Table 1**).

In order to explain the differences in TDP among different enclosures, the correlations between Chl-*a* and nutrients were further analyzed and data were shown in **Table 2**. Results indicated that TN, TP and TDN were significantly correlated with phytoplankton biomass in all the investigated enclosures (**Table 2**). Additionally, TDP were found to be negatively correlated with phytoplankton biomass in EG3 and EG4, but no significant correlations were found in both EG1 and EG2 (**Table 2**).

Table 1 Physical-chemical parameters of surface and bottom water in the five enclosures during the experiment

Physical-chemical parameter	CG: 0%		EG1: 10%		EG2: 25%		EG3: 50%		EG4: 75%	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
SD (cm)	24.9	9.0–45.0	25.9	9.0–47.0	24.9	10.0–40.0	25.2	9.0–40.0	25.1	10.0–40.0
WT (°C)	21.56	13.79–29.76	21.49	13.78–29.66	21.40	13.76–29.29	21.33	13.71–28.99	21.32	13.68–29.10
EC (mS/cm)	0.505	0.490–0.515	0.505	0.494–0.515	0.506	0.498–0.515	0.506	0.498–0.516	0.507	0.498–0.518
pH**	8.45	7.70–9.20	8.32	7.57–9.08	8.20	7.52–8.88	8.10	7.50–8.86	7.95	7.50–8.58
ORP (mV)	488.6	299.0–587.5	492.7	313.4–588.9	496.4	334.5–585.4	484.4	346.9–574.7	482.0	325.8–588.8
Tur (NTU ⁺)	39.8	12.5–112.1	37.0	12.1–120.2	35.6	12.7–105.9	33.6	9.5–124.5	30.2	10.0–114.9
DO (mg/L)*	7.99	2.44–11.46	7.22	1.00–12.97	6.72	1.65–10.80	6.45	1.38–10.15	5.90	1.78–9.49
TN (mg/L)	2.14	1.16–5.11	1.98	1.17–5.46	1.75	1.19–3.80	1.72	1.09–2.64	1.64	1.06–2.76
TP (mg/L)	0.173	0.066–0.462	0.152	0.066–0.359	0.135	0.061–0.315	0.128	0.049–0.242	0.125	0.049–0.239
TDN (mg/L)	0.77	0.53–1.22	0.76	0.50–1.04	0.80	0.49–1.34	0.82	0.48–1.15	0.84	0.56–1.16
TDP (mg/L)**	0.029	0.016–0.050	0.023	0.007–0.046	0.021	0.003–0.048	0.022	0.004–0.050	0.025	0.005–0.051

* Significance at *P* < 0.05, ** significance at *P* < 0.01 (*n* = 5).

SD: transparency, WT: water temperature, EC: electrical conductivity, ORP: oxidation-reduction potential, Tur: turbidity, DO: dissolved oxygen, TN: total nitrogen, TP: total phosphorus, TDN: total dissolved nitrogen, TDP: dissolved total phosphorus.

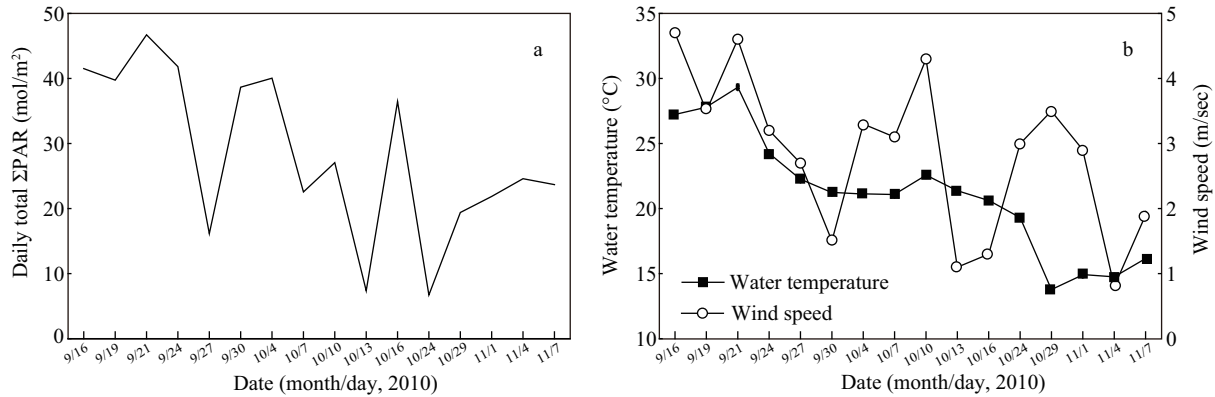


Fig. 2 Daily total Σ PAR (a), water temperature (mean \pm SE) and wind speed (b) during the experiment.

2.2 Phytoplankton biomass

Significant variations in phytoplankton biomass (based on Chl-*a* concentration) were observed in both the surface and the bottom of the water columns in all the enclosures (**Fig. 3a** and **b**). As indicated from **Fig. 3a**, the phytoplankton biomass in surface water ranged 14.58–250.08 $\mu\text{g/L}$ in CG, 13.80–216.38 $\mu\text{g/L}$ in EG1, 13.87–172.52 $\mu\text{g/L}$ in EG2, 11.13–102.25 $\mu\text{g/L}$ in EG3 and 11.30–107.72 $\mu\text{g/L}$ in EG4, respectively. The variations of phytoplankton biomass from bottom water was quite similar to those in

surface water, ranged 14.67–212.40 $\mu\text{g/L}$ in CG, 12.26–121.67 $\mu\text{g/L}$ in EG1, 12.47–95.10 $\mu\text{g/L}$ in EG2, 9.33–81.24 $\mu\text{g/L}$ in EG3 and 10.91–120.72 $\mu\text{g/L}$ in EG4, respectively (**Fig. 3b**). Furthermore, there is an interesting phenomenon when compared EG3 with EG4. In the early control stage, from 30 September to 10 October, phytoplankton biomass in EG3 and EG4 has similarly variation tendencies, and phytoplankton biomass has a continuous increase in EG3 and EG4. However, phytoplankton biomass in EG4 began to decrease from the peak on 10 October very quickly. As

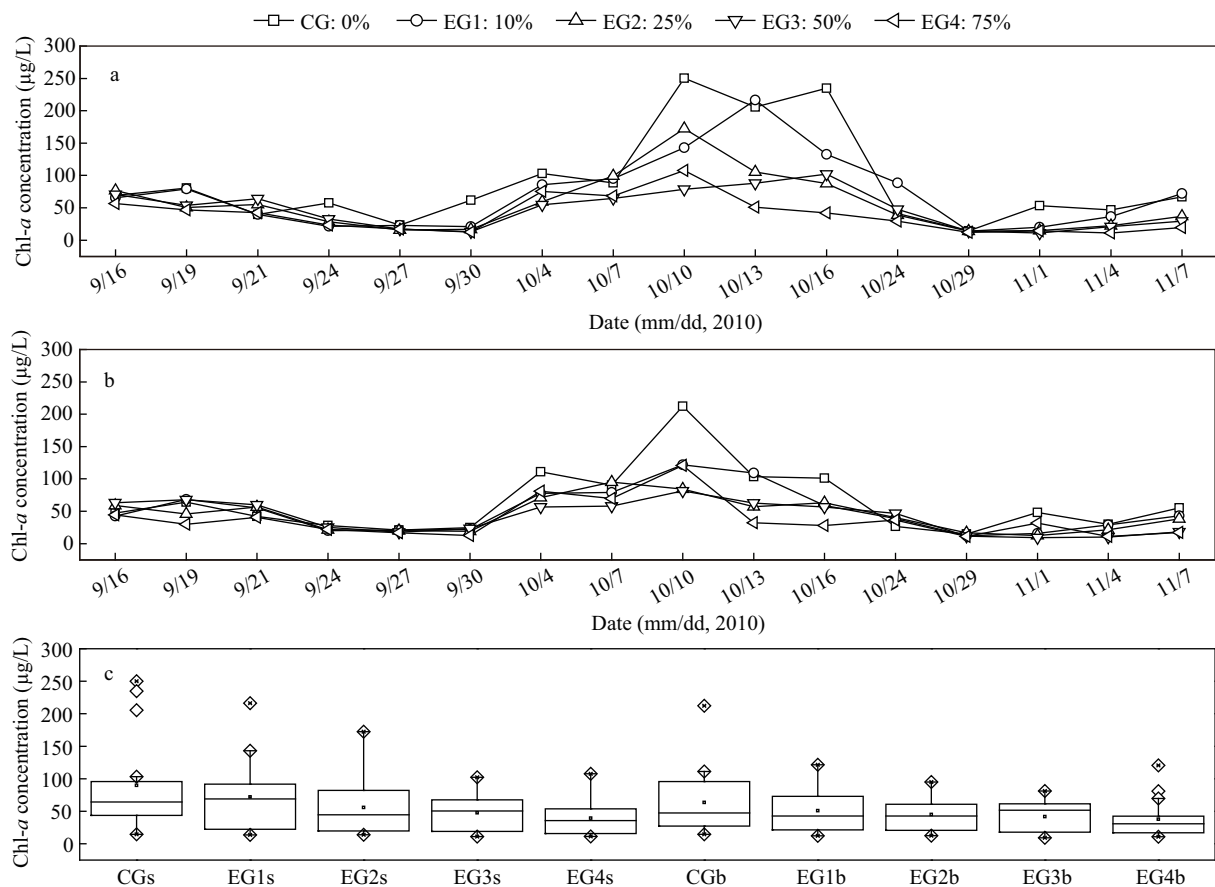


Fig. 3 Variation of surface (a) and bottom (b) phytoplankton biomass (Chl-*a*) and the box chart of Chl-*a* (c) in five enclosures during the experiment.

Table 2 Spearman correlations between chlorophyll *a* and nutrients in different enclosures

Shading ratio	TN	TP	TDN	TDP
CG: 0%	0.833**	0.689**	-0.527**	0.000
EG1: 10%	0.749**	0.716**	-0.519**	-0.119
EG2: 25%	0.866**	0.827**	-0.532**	-0.219
EG3: 50%	0.839**	0.786**	-0.588**	-0.385*
EG4: 75%	0.835**	0.824**	-0.555**	-0.403*

* Significance at $P < 0.05$, ** significance at $P < 0.01$.

a comparison, phytoplankton biomass increased a little bit and reached its peak values in EG3 on 16 October.

The box chart of Chl-*a* concentration in different enclosures (Fig. 3c) was used to display the heterogeneity of Chl-*a* distributions and to detect the outlier value. The mean phytoplankton biomass from both surface and bottom of the water columns decreased with the increase of shading ratios. In addition, the all the 1st quarter of surface and the 3rd quarter of bottom water decreased dramatically with the shading ratios ranged from 0% to 10%. Results also indicated that the Chl-*a* concentrations in EG4 were lower than that in EG3 as a whole, however, there were no outlier value in EG3 from both the surface and the bottom water.

The Chl-*a* concentrations from both surface and bottom of the water columns in CG (mean = 76.77 $\mu\text{g/L}$) and EG1 (mean = 61.52 $\mu\text{g/L}$) were significantly ($P < 0.05$) higher than that from EG3 (mean = 44.70 $\mu\text{g/L}$) and EG4 (mean = 38.61 $\mu\text{g/L}$). Similarly, the Chl-*a* concentrations in both surface and bottom of the water columns from EG1 were significantly ($P < 0.05$) higher than that from EG4. The mean concentration of Chl-*a* in both surface and

bottom of the water columns from EG2 was 50.51 $\mu\text{g/L}$. For the phytoplankton biomass, it decreased from 21 to 27 September and from 24 to 29 October, respectively (Fig. 3a, b). The mean value of water temperature decreased (rapid cooling process) from 29.32 to 22.94°C and from 19.30 to 13.76°C respectively (Fig. 2b) during the above experiment periods. Moreover, the Spearman correlation coefficient (r) between Chl-*a* and WT are 0.856 ($P < 0.01$) and 0.871 ($P < 0.01$) respectively in the course of the above experiments.

2.3 Phytoplankton composition

We identified a total of 39 kinds of phytoplankton species, including 10 Cyanophyta, 17 Chlorophyta, 7 Bacillariophyta, 2 Xanthophyta, and 1 Euglenophyta, Cryptophyta and Pyrrophyta respectively. During the experiment, the dominant species was *Microcystis* spp., which accounted for 90.41% \pm 0.51% of the total phytoplankton biomass (by abundance cells/L). Concerning the phytoplankton biomass, there was no significant difference among the five enclosures. However, *Microcystis* proportions (by biomass mg/L) were quite different from one to another. Generally, the *Microcystis* proportions in surface water were a little bit higher than that in bottom water in all the enclosures, but no significant difference could be determined with statistic analysis.

As shown from Fig. 4, the percentage of *Microcystis* decreased obviously in all enclosures in the first three days except in EG2 enclosure. The lowest value was observed in EG4 on 19 September, and then the percentage of *Microcystis* in all the enclosures except EG2 increased smoothly after two days until 27 September. From October 4 to 16, the *Microcystis* proportion from CG, EG1 and EG2 were relatively stable (Fig. 4), while in EG3 and EG4

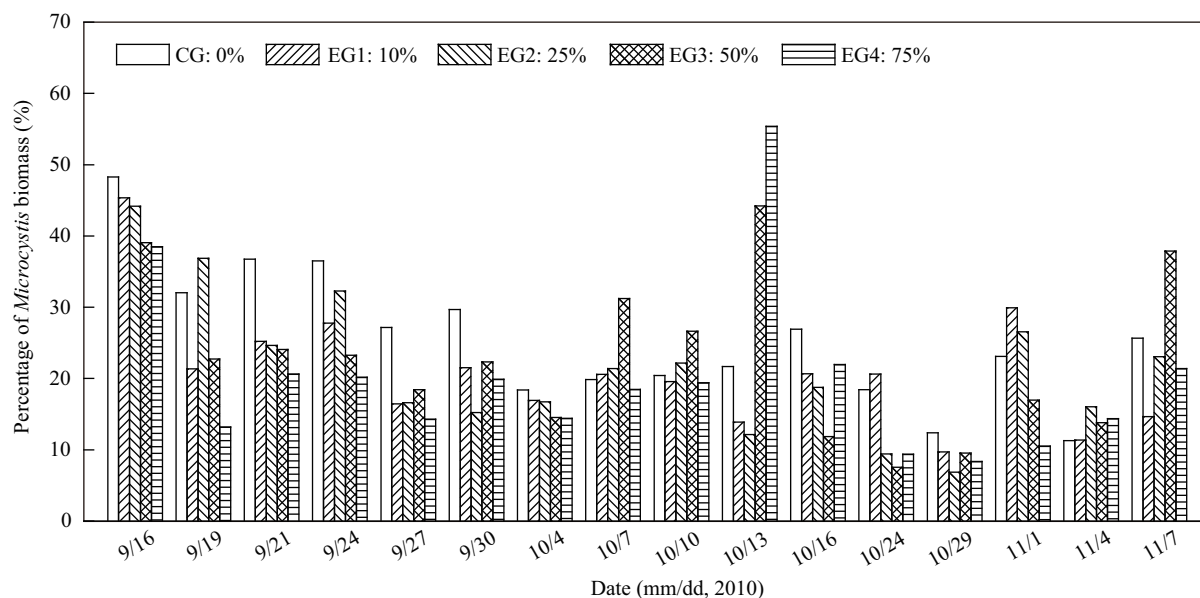


Fig. 4 Variation of percentage of *Microcystis* biomass (the mean value of surface and bottom).

the maximum proportion of *Microcystis* occurred on 13 October. Following that, they all decreased quickly and reached the lowest value on 29 October. In the following days, the proportion of *Microcystis* in CG, EG1, EG2 and EG3 varied every several days until the end of the experiment. While in EG4, the proportion of *Microcystis* increased gradually to the end of the experiment (Fig. 4).

Spearman correlation coefficient (r) between *Microcystis* proportion and WT is 0.526 ($P < 0.01$). From 10 to 13 October, water temperature ranged from 22.58 to 21.37°C, and the wind speed and daily total Σ PAR decreased dramatically (Fig. 2). During the experiment period, statistical analysis indicated that *Microcystis* proportion was correlated with wind speed ($r = -0.873$, $P < 0.01$) and daily total Σ PAR significantly ($r = -0.781$, $P < 0.05$) in EG3 and EG4.

2.4 Photosynthesis efficiency

The maximum quantum yield (F_v/F_m , Fig. 5a), α (Fig. 5b), $rETR_{max}$ (Fig. 5c) and I_k (Fig. 5d) of phytoplankton increased with shading ratios from 27 September to 29 October, respectively. No significant differences in F_v/F_m , I_k and $rETR_{max}$ were observed among five groups (Fig. 5a, c and d). Whereas the α value of phytoplankton in CG was significantly lower than that in EG2, EG3 and EG4

($P < 0.05$, Fig. 5b). In addition, the Spearman correlation coefficient between F_v/F_m and incident light intensity was -0.397 ($P < 0.05$), and the Spearman correlation coefficient between WT and α , $rETR_{max}$ and I_k were 0.480 ($P < 0.01$), 0.517 ($P < 0.01$) and 0.600 ($P < 0.01$) respectively.

3 Discussion

3.1 Phytoplankton growth

Phytoplankton growth was usually affected by light, temperature, nutrients and phytoplankton themselves as well. If the nutrients were sufficient, the limitations of phytoplankton growth could be negligible (Jhnk et al., 2008; Qin et al., 2010; Zhang et al., 2012). In present study, the habitat of phytoplankton could be altered when treated with light shading method, although the nutrient background was very high (Chen et al., 2003; Qin et al., 2010). In the control group, no significant correlations between phytoplankton biomass and TDP could be determined, while significantly negative correlations between phytoplankton biomass and TDN were observed instead (Table 2), indicating that the background phosphorus might be high enough to maintain phytoplankton growth. This result was

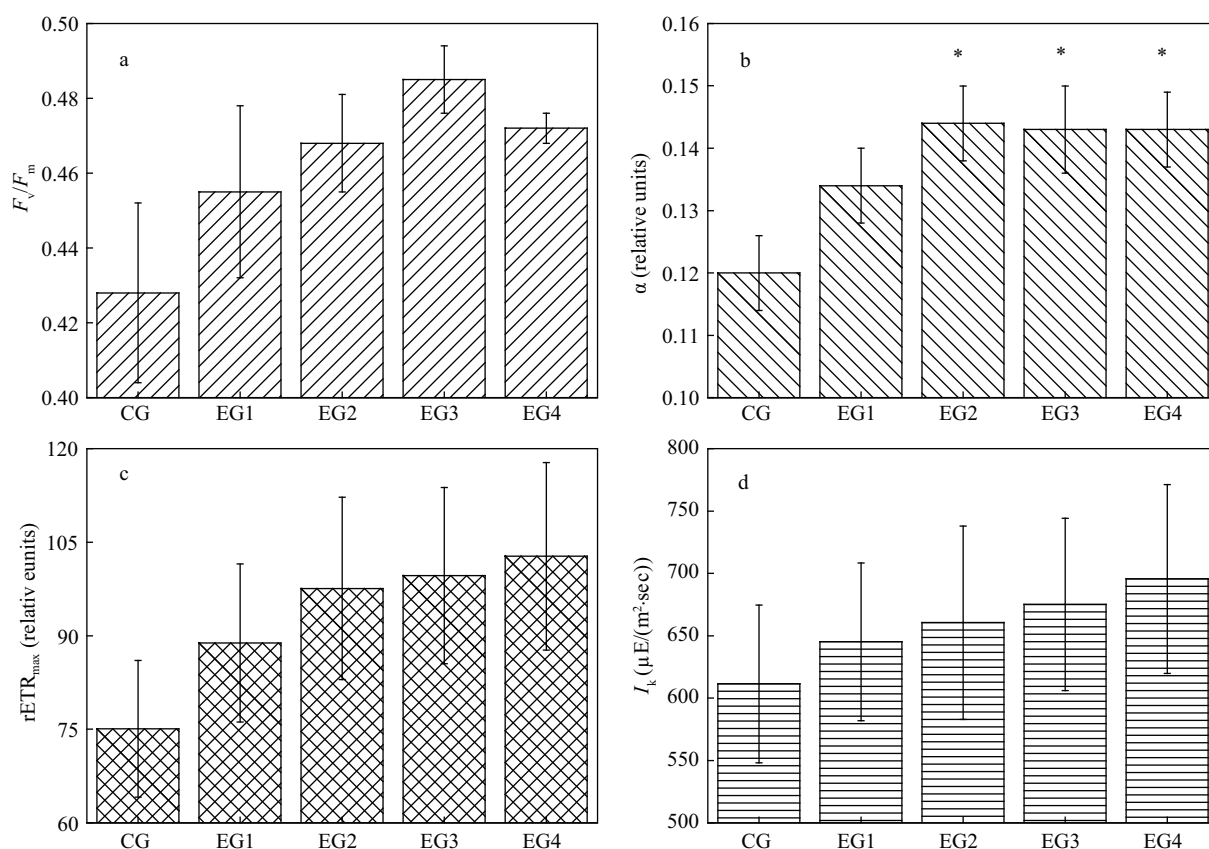


Fig. 5 Maximum quantum yield (F_v/F_m , a), initial slope (α , b), maximum relative electron transport rate ($rETR_{max}$, c) and half-saturation light intensity (I_k , d) of phytoplankton (mean \pm SE) in surface water from 27 September to 29 October, 2010 (significant differences were indicated by * $P < 0.05$).

consistent with the report by Xu et al. (2010), in which, nitrogen was the primary limiting nutrient in summer and autumn bloom period (the same investigation periods as ours) in Lake Taihu. However, nutrients were found to be significantly correlated with phytoplankton biomass in those groups treated with high shading ratios (EG3 and EG4). This phenomenon might be caused by light limitations (Nalewajko et al., 1981; Havens et al., 2001; Powell et al., 2008; Duhamel et al., 2012), which was consistent with the results by Sterner et al. (1997). In this study, phosphorus was considered to be enhanced if the light was reduced (Sterner et al., 1997).

Temperature is another important factor influencing phytoplankton growth (Darley, 1982; Kong and Gao, 2005; Song et al., 2007b; Jöhnk et al., 2008; Ye et al., 2011). The optimal temperature for most phytoplankton ranged between 18 and 25°C (Darley, 1982). In present study, water temperature was considered within this optimal range before 24 October (Fig. 2b). In this period (autumn), the temperature might not be the major limitation (Wang et al., 2007). Furthermore, phytoplankton could still grow according to our results, when water temperature was lower than 18°C. However, the phytoplankton biomass decreased very quickly from 21 to 27 September and from 24 to 29 October, which might be caused by the rapid cooling process.

The population density of phytoplankton could be increased with an increase of the incident light intensity, while the critical light intensity of phytoplankton would be decreased with an increase of incident light intensity (Huisman, 1999). In present study, the transparency and turbidity had no significant difference among five enclosures, as a result, the mean of phytoplankton biomass decreased with the increase of shading ratio. Phytoplankton would regain capability of immediate photosynthesis and re-growth exponentially when re-exposed to light after distributing under prolonged darkness (Vincent, 1982; Furusato et al., 2004). The difference of phytoplankton biomass peak between EG3 and EG4 might be caused by a relatively long acclimate in lower irradiance of phytoplankton in EG4. Our results from EG3 were similar as the study by Rier et al. (2006), in which, the growth efficiency for acclimated phytoplankton was higher than unacclimated phytoplankton. In addition, it was reported that cyanobacteria would accumulate on surface of the water columns when wind speed was lower than 3.0 m/sec (Zhang et al., 2008). Results from our study also confirmed the above statement and the cyanobacterial biomass from surface water was much higher than that from the bottom of water columns.

3.2 Phytoplankton composition

It is reported that *Microcystis* contributed 40% to 98% of total phytoplankton biovolume in Lake Taihu from May to October (Chen et al., 2003). However, *Microcystis* pro-

portions in most of the five enclosures were no more than 40% in our research. This might be caused by the two rapid cooling periods (Chen et al., 2003; Imai et al., 2009). In second rapid cooling period, the percentage of *Microcystis* biomass decreased much more rapidly compared with the first cooling period. Optimal temperature for most algae ranged between 18 and 25°C (Darley, 1982), however, the optimal temperature for *Microcystis* ranged from 24 to 34°C (Ganf, 1974). As a result, *Microcystis* was more sensitive to rapid cooling process (Coles and Jones, 2000; Reynolds, 2006).

Cyanobacteria (e.g. *Microcystis* spp.) likely favored lower irradiance when compared with chlorophytes and diatoms (Huisman et al., 1999; Coles and Jones, 2000; Xu et al., 2012). It also favored low turbulent environment (Huisman et al., 2004; Kong and Gao, 2005; Song et al., 2007b) and could adapt itself to low light intensity environment using its special pigment systems or via regulated buoyancy (Bormans et al., 1999; Kong and Gao, 2005; Song et al., 2007b; Lee, 2008). In present study, there are no significant differences in *Microcystis* proportion either among five groups or between surface and bottom in any enclosure, which may be caused by the unstable light intensities and the wind speed during the experiment. In addition, *Microcystis* (especially colony) had remarkable abilities to adapt themselves to the stress conditions, such as darkness, low temperature etc. (Wu et al., 2008). This could explain the high proportion of *Microcystis* in EG3 and EG4 on October 13.

3.3 Photosynthesis efficiency

The analysis of phytoplankton chlorophyll fluorescence yield is an important tool for the investigation of its photosynthesis both in laboratory (Wu et al., 2008; Zhang et al., 2011; Xu et al., 2012) and in the field (Zhang et al., 2008, 2011; Alderkamp et al., 2010). F_v/F_m is an indicator of phytoplankton photosynthetic capacity, and its value could vary with the phytoplankton species. When the value decreased significantly, it may be caused by a stress condition (Han et al., 2003). The F_v/F_m might be correlated with incident light intensity or affected by UV radiation (Häder et al., 1998; Lee, 2008). In present study, phytoplankton from those treatments without shading would be exposed to high irradiance especially from later morning to earlier afternoon (e.g. our sampling time), which would result in significant photoinhibition (Han et al., 2003; Zhang et al., 2008). However, phytoplankton could recover by themselves when the photoinhibition effect was reduced (Han et al., 2003; Zhang et al., 2008; Xu et al., 2012).

The trend of α , $rETR_{max}$ (likely P_m , the maximum photosynthesis rate) and I_k values for phytoplankton were very similar among different groups and values altered with water temperature. These results were coincident with Coles and Jones (2000), in which, the above three parameters could be also influenced by temperature (Coles

and Jones, 2000; Reynolds, 2006). Furthermore, the α , $rETR_{max}$ and I_k under high light condition were usually considered to be higher than that under low light condition (Ralph and Gademann, 2005; Perkins et al., 2006; Zhang et al., 2011). In our study, the three parameters increased with increase of shading ratio though there were no significant differences. This might be caused by the partial photoinhibition in high light intensity groups and no photoinhibition in low light intensity groups. On the other hand, α value in CG was significantly lower than that in other groups (e.g., EG2, EG3, EG4), indicating the increase of light utilization ability of cyanobacteria with shading ratios (Perkins et al., 2006; Zhang et al., 2011).

3.4 Control effect

Therefore, the effect of light intensity on phytoplankton growth in raw water (Meiliang Bay, Lake Taihu) was a combined consequent of incident light intensity, phytoplankton biomass and composition and photosynthesis efficiency. If wind, temperature and nutrients were taken into consideration, it would be more complex. One purpose of this study was to find out the optimal shading ratios for the control of harmful blooms in Lake Taihu.

Previous studies regarding the shading and the control of blooms had proved that light shading could significantly decrease the phytoplankton biomass (Kojima, 2000; Chen et al., 2009a, 2009b; Wan and Zhu, 2009), and the control effect could be enhanced by aeration (Chen et al., 2009a, 2009b). It was also reported that light shading would improve water quality to a certain degree (Kojima, 2000; Chen et al., 2009a, 2009b), however, it may increase the nutrient concentrations due to the lysis of increasing of dead phytoplankton cells (Wan and Zhu, 2009).

In present study, the phytoplankton biomass (the mean during the experiment) in EG3 and EG4 was reduced to less than 50 $\mu\text{g/L}$, which was significantly lower than that in the control group, indicating 50% or higher shading ratios were very effective in controlling harmful blooms in Lake Taihu. Furthermore, compared to higher shading ratio group (EG4), intermediate shading ratio (EG3) would decrease the maximum value of phytoplankton biomass and delay the peak time of the blooms. Therefore, higher shading ratio would be the better choice to control average and total phytoplankton biomass. On the other hand, to control the maximum value of phytoplankton biomass or to postpone the occurrence of heavy cyanobacterial blooms, 50% of shading ratio could be considered first.

There were several options for the control of harmful blooms (Paerl, 2008), in which, light shading was to keep the phytoplankton under prolonged darkness and to further limit algal available light resource and thereby to reduce algae biomass (Chen et al., 2009a). In addition, it can also decline the depth of eutrophic zone. Light shading could be used to control harmful blooms around water intake location (Chen et al., 2009a) or small water bodies

(Kojima, 2000), while it was not practical to shade over 50% of the water surface for a large lake like Taihu. As a result, it is necessary to find out other ways to change the light intensities which has the potential applications in a large lake. The ratio of mixing depth (Z_{mix}) to photic depth (Z_{eu}) is very important for light gradient and phytoplankton growth and distribution in aquatic ecosystem (Mur and Schreurs, 1995; Huisman, 1999; Reynolds, 2006). However, it would be less important in shallow lakes because of holomixis. Furthermore, it was reported that the hydrodynamic effect, particular the wind-induced disturbance had significant influence on the cyanobacterial occurrence in Lake Taihu (Qin, 2009). Thus, water levels and turbidity would definitely influence light resource of water columns. Consequently, water levels and turbidity could be considered in the control of harmful bloom in a large and shallow lake (e.g. Lake Taihu). The high mineral turbidity could reduce light availability and hence limit algal abundance (Gikuma-Njuru and Hecky, 2005) although phytoplankton density could also influence turbidity and light attenuation in turn (Huisman, 1999; Porat et al., 1999). On the other hand, water quantity might determine water quality in a certain degree (Lind and Dvalos-Lind, 2002). Reducing the water levels might induce light limitation of phytoplankton production because of the re-suspension clay and the high turbidity. At the same time, it could also induce algal bloom because of sufficient light energy and the excessively high nutrient concentrations. Therefore, it is important to consider the spatial differences in actual practice of bloom control. This study will provide valuable information associated with the control of cyanobacterial blooms via the regulation of light sources.

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