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RESEARCH ARTICLE

Effects of episodic sediment resuspension on phytoplankton in Lake Taihu: focusing on photosynthesis, biomass and community composition

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Abstract Sediment resuspension is an important characteristic of large shallow lakes. To further understand the influence of sediment resuspension on the nutrients release, the algal photosynthetic activity, algal biomass and algal community composition, a 2×5 factorial (2 water types and 5 turbulence intensities) bioassay experiment was carried out for 2 weeks. 2 water types: one type water was filtered through GF/F filter to remove all indigenous algae (Filtered group) and the other type was source water without filtering through GF/F filter (Non-filtered group). 5 turbulence intensities in the experiment simulated the different intensity of the field wind-induced turbulence in Lake Taihu, with different turbidities (0, 30, 70, 150, 250 NTUs). Results showed that sediment resuspension had significant effects on the nutrients release that could be absorbed to support algae growing. Different turbulence intensities had no significant effects on the photosynthetic activities. The time variation of photosynthetic parameters in the Filtered and Non-filtered groups indicated that algae could moderate themselves to adapt to different intensities turbulence environment to be more in favor of photosynthesis. In addition, sediment resuspension also brought sediment-associated algae back into the water body increasing the algal biomass. The community composition in the Filtered group and Non-filtered group showed that the new phytoplankton community formed from the resuspended algae was similar to the original community. So, the research highlights the importance of sediment resuspension in long-term management goals and restoration efforts for these types of ecosystems.

Keywords Sediment resuspension · Nutrients · Photosynthetic activities · Algal biomass · Algal community composition

Introduction

Episodic sediment resuspension is a crucial physical process that strongly influences nutrient repletion and its dependent biological activities in large and shallow lakes (Kristensen et al. 1992; Schallenberg and Burns 2004). Resuspension occurs when the bottom shear stress exceeds the critical shear stress, which in turn depends on the water content and sediment grain size (Håkanson and Jansson 1983), A number of factors could trigger resuspension including wind-induced wave disturbances (Hamilton and Mitchell 1997; Wu et al. 2013), current and turbulence fluctuations (You et al. 2007; Luo et al. 2006), as well as bioturbation caused by fish and benthic fauna (Zhang et al. 2010).

Sediment resuspension has long been recognized as an important factor regulating the structure and function of lake ecosystems (Bloesch 1995; Scheffer 1998). Entrainment of surficial sediments into the water column due to wind events generally occurs in the scale of hours to days (Kristensen et al. 1992; Blom et al. 1994). Long-term effects of sediment resuspension involves the reduction

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of light penetration into lakes and enrichment with nutrients of the water column (Carrick et al. 1993; Reddy et al. 1996), which would impact the biological productivity of lake ecosystems. However, understanding about the effects of such events on the biomass and productivity of the phytoplankton community and the fluorescence characteristic are still little understood and under debate.

Several studies have been done to establish the relationship between sediment resuspension and algal biomass (Hamilton and Mitchell 1997; Ogilvie and Mitchell 1998; Wu et al. 2013). Although some results showed negative correlations, others also found that the increase in algal biomass always lags behind resuspension events due to consequential light limitation and nutrient repletion (Schelske et al. 1995; Ding et al. 2012; Zhu et al. 2014). The net effect of a resuspension event on planktonic primary productivity relied not only on nutrient but also on the light availabilities (Schallenberg and Burns 2004). Furthermore, the entrainment of benthic algae into the water column with sediment resuspension could also increase algal biomass in the water body (Schelske et al. 1995), therefore, sediment resuspension could also affect phytoplankton community structures (Jeppesen et al. 1991, 2007; Gulati and Donk 2002).

Although both physical and chemical factors influence algal biomass and phytoplankton community in large shallow lakes (James et al. 2009), little is known about how sediment resuspension affects the capacity of phytoplankton photosynthesis (Mazumder and Havens 1998; Havens et al. 1999). Decreased light availability could limit the photosynthetic activity (Izagirre et al. 2009) and influence the algal community composition (Newcombe and Macdonald 1991). However, reduced biomass of primary producers is not tantamount to the reduction in total primary production, because the photosynthetic efficiency of algae can quickly change through some adaptive mechanisms when the growing environment conditions of the aglae are limited (Parkhill and Gulliver 2002). For example, Burkholder (1992) showed the physiological adaptations of algae to turbidity through increasing the phosphate retention by algae.

Stressful conditions, just like nutrient deprivation, high/low light availability, low temperature and high salinity concentrations, can negatively or positively affect microalgal physiology manifested mainly in the changes in the level of their pigments, primarily chlorophyll *a* (chl *a*) (Li et al. 2008; Rosenberg et al. 2008). Tracking chl *a* fluorescence variations could provide an extremely sensitive mechanism to examine energy metabolism in photosynthetic cells and then to monitor the algae growing condition (Oxborough et al. 2000; Schreiber et al. 2002). Light energy absorbed by the different chlorophylls can either do photochemical work or re-emitted as heat or fluorescence. Thus, the proportion of energy used to do photochemical work is inversely related to the amount of fluorescence emitted by chl *a* (Schreiber et al. 2002).

Methods based on chl *a* fluorescence to measure photochemical responses of phytoplankton were recently developed, making field-based measurements possible especially providing information on the major processes in light capture and electron transport, which together provide an estimate of the rate of photosynthesis (Regel et al. 2004; Zhang et al. 2008; White et al. 2011). Pulse Amplitude Modulated (PAM) Fluorimeter has become one of the most common, non-invasive and rapid techniques to measure chlorophyll fluorescence and photosynthetic capacity (Oxborough et al. 2000; Schreiber et al. 2002; Baker 2007). A multi-wavelength phytoplankton PAM (Phyto-PAM) (Walz, Effeltrich, Germany) can distinguish different broad algal groups based on their pigment composition such as cyanobacteria, chlorophytes, and diatoms/dinoflagellates derived from four different excitation wavelengths (665, 645, 520, and 470 nm) (Zhang et al. 2008). It also determines the physiological state of the algae by measuring their relative electron transport rate and maximum quantum efficiency.

In this study, a 2-week bioassay experiment was conducted to reveal the effects of sediment resuspension on phytoplankton. Specifically, this study aims to (1) assess the effects of turbulence intensity on nutrient availability in the water column; (2) determine consequences of sediment resuspension on algal photosynthesis activity by measuring the chl *a* fluorescence variation and (3) determine whether sediments could serve as algal seed stock during resuspension events.

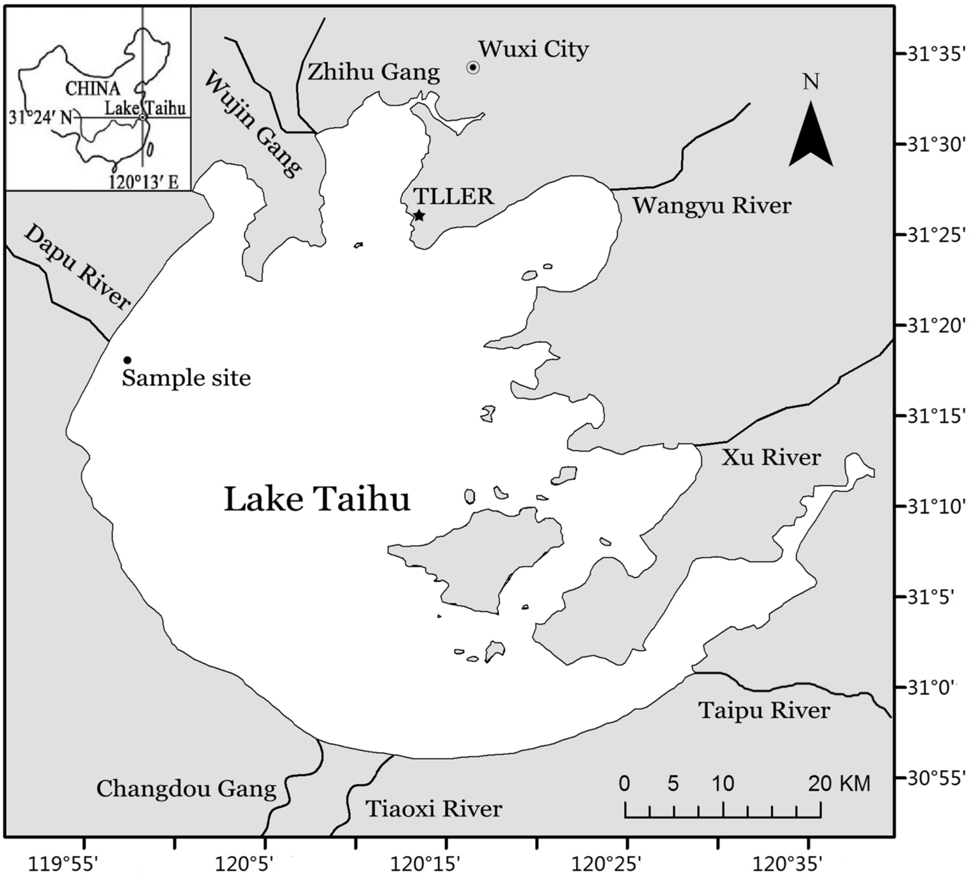
Material and method

Lake and site description

Lake Taihu, the third largest freshwater lake in China, is a large (area 2338 km^2) and very shallow (average depth 1.9 m) lake in the Yangtze River delta (Fig. 1). With a dynamic ratio of >0.8 (Håkanson 1982), Lake Taihu is highly prone to wind-induced resuspension events. Since 1980s, Lake Taihu has heavily suffered from anthropogenic eutrophication resulting from rapid industrialization and intense urbanization. Since then, algal blooms have been observed to break out every summer.

Investigation on the sediment spatial distribution at 723 sites in Lake Taihu revealed that muck sediment covered about 1100 km^2 of lake bed accounting for about 47.5% of lake area (Luo et al. 2004). Affected by Southeast monsoon, high deposits of sediments were observed in the western zone and northern bays of Lake Taihu with most thickness being more than 4 m (Luo et al. 2004). Lake

Fig. 1 Location of Lake Taihu and the sampling site. Sediment collected site (*circle* with a point); TLLER (Taihu Laboratory for Lake Ecosystem Research) (pentagon)



Taihu has a complicated river and channel network, which was charged from the northern and western watersheds and discharged via the eastern basin (Qin et al. 2007). The inflow water contains high loads of phosphorus and nitrogen (Xu and Qin 2005). So, the hydrology and nutrients loading to the lake result in a trophic gradient characterized by hypertrophic conditions in the northern part and mesotrophic conditions in the southeastern part of Lake Taihu (Chen et al. 2003). Satellite imaging also showed that algal blooms developed in most parts of the northwestern and central lake after both typhoon events (Zhu et al. 2014).

Experimental design

Bioassay experiments were conducted in August, 2011. A 2×5 factorial design as described in Dzialowski et al. (2008), consisted of two types of lake water (Non-filtered lake water with coarsely filtering through phytoplankton net and Filtered lake water with filtering through GF/F to remove algae from the coarsely filtered lake water) and five sediment concentrations (turbidity: 0, 30, 70, 150, and 250 NTUs). The experiment frame was showed in the Fig. 2.

The five turbidities in the experiment were based on observed levels in Lake Taihu. The every 10-min interval of turbidity were recorded by Taihu Laboratory for Lake Ecosystem Research. The daily mean turbidity was 91.1 ± 58.9 (±SD) (with 676 records) NTUs ranging from 8 to 430.8 NTUs from 2007 to 2009 (Table 1). Based on the records, we believe that the experimental turbidity of 30, 70, 150, and 250 NTUs realistically simulate the range of turbidity that are likely to occur during resuspension events.

The surface water was collected from Dapu River inlet located at the western region of Lake Taihu (Fig. 1 sampling site). The water samples were transported to the lab and filtered through the phytoplankton net (200 μm) to remove the macro-zooplankton (Vanni and Temte 1990). The coarsely filtered water sample was divided into two parts: one part was directly packed in 15 1-L bioassay bottles, namely Non-filtered group; the other part was further filtered through a GF/F filter (Whatman, pore size = 0.7 μm) to remove all algae, which were subsequently packed in the remaining 15 1-L bioassay bottles, namely Filtered group without algae or background turbidity.

3 sediment cores collected from sampling site by sediment sampling device. The upper 2 cm of the sediment cores were cut out and were mixed together. Mixed sediments were added to 1-L bioassay bottles in the non-filtered group and the filtered group until the turbidity levels were equal to the four target turbidity of 30, 70,

Fig. 2 The experiment design and frame

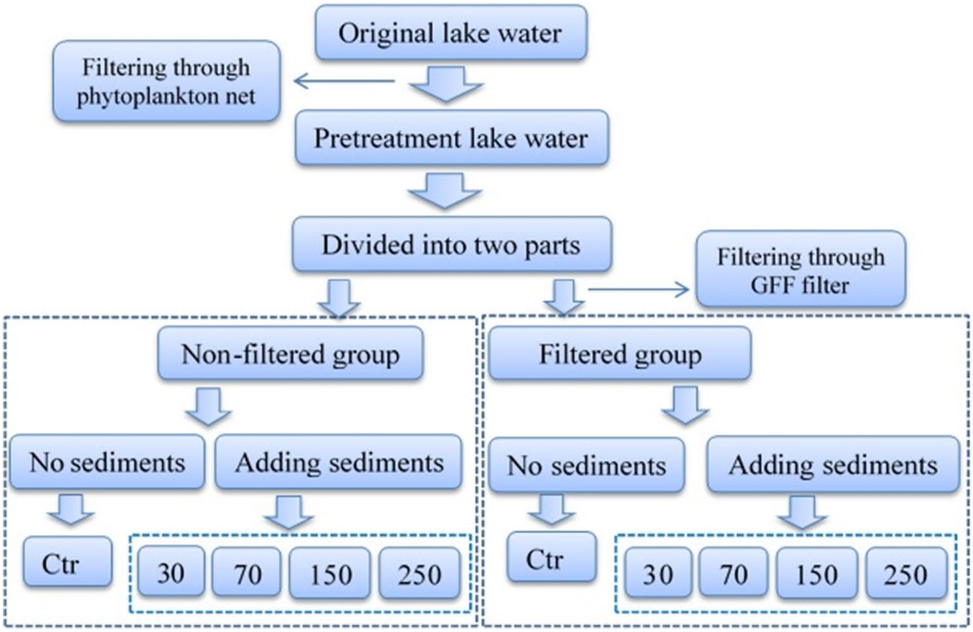


Table 1 Four turbidity concentrations designed based on the daily mean turbidity during 2007–2009 in Lake Taihu

Turbidity	<50	50–100	100–200	>200
Records number	175	264	199	38
Mean NTUs	34.5	73.3	133	256
Designed NTUs	30	70	150	250

150 and 250 NTUs, as measured by Turbidity meter (PTS1000 PTS, China) and their corresponding sediment concentrations were recorded.

All Filtered and Non-filtered treatments were inoculated in 1-L biomass bottles with 3 replicates each. Bioassay bottles were then incubated in a growth chamber (GZX-300BS-III) at 25 °C lit by cool white fluorescent lamps under 12:12 light: dark cycle for a total of 14 days to reduce potential variances caused by bottle effects (Fig. 3). Sediments within the bottles were thoroughly resuspended stirred in the thermostatic oscillator (HZ82-2, 60 ± 5 r/min) for half hour. Water samples (30 ml) were collected on the first and last 2 days to determine change in dissolved nutrients and chl *a* concentrations and 5 ml was sampled every other day were to monitor photosynthetic characteristics using Phyto-PAM. Before the experiment, 500 ml of the coarsely filtered water were collected to determine the algal biomass and community composition in the water. At the end of the experiment, 500 ml water samples in the Filtered and Non-filtered treatments were also collected to determine algal biomass and community composition in the water.

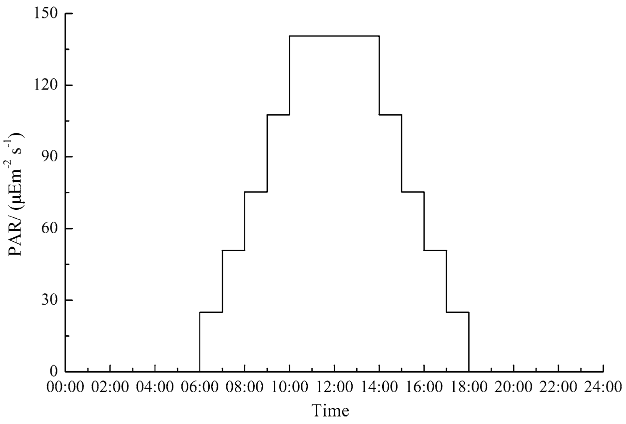


Fig. 3 Photosynthesis photon flux density in the growth chamber during the experiment incubation, equivalent to photosynthetically active radiation (PAR) in Taihu Lake

Nutrients and chlorophyll analyses

The collected water samples every other day were further divided into two sub-samples. One subsample was used to measure total nitrogen (TN) and total phosphorus (TP) by spectrophotometry after digestion with alkaline potassium persulfate (Jin and Tu 1990). The One subsample was immediately filtered through a GF/F filter for all dissolved nutrients, chl *a* retained on the GF/F filter was detected using spectrophotometric detection at wavelengths 665 and 750 nm, following extraction with hot 90% ethanol

(Jespersen and Christoffersen 1987). Meanwhile, dissolved total phosphorus (DTP) and dissolved total nitrogen (DTN) concentrations were determined by spectrophotometry after digestion with alkaline potassium persulfate (Jin and Tu 1990). Nitrate (NO_3–N), ammonium (NH_4–N) and soluble reactive phosphorus (SRP`) concentrations were measured following the standard methods used in China as described in Jin and Tu (1990).

Photosynthetic characteristics of phytoplankon

Chl *a* fluorescence was measured every 2 days using the Phyto-PAM (Walz, Effeltrich, Germany) equipped with a special Emitter-Detector Unit Phyto-ED. Photosynthetic activity were assessed by measured different parameters, namely F_v/F_m (maximum quantum efficiency of photosystem II), $rETR_{max}$ (maximum relative electron transport rate), α (initial slope of the rapid light curve), E_k (Light saturation).

In brief, 3 ml samples were collected from each treatment with a pipette and transferred into a measuring cup and incubated in the dark. After 15 min, the initial fluorescence (F_0) was determined by measuring the irradiance right after opening the cup and the maximum fluorescence (F_m) was measured after exposure to a 600 ms pulse of saturating irradiance. Then, the maximum quantum yield of Photosystem II (PS) was determined following the formula of Juneau & Harrison (2005):

$$F_v/F_m = (F_m - F_0)/F_m \tag{1}$$

where F_v= F_m-F_0, F_v/F_m reflects the greatest potential of the phytoplankton's photochemical reaction. The rapid light curve (RLC) was obtained via the curve fitting model of Platt et al. (1980) through increasing PAR of actinic light every 10 s from 1 μmol/(s m^2) to 800 μmol/(s m^2). Using the Platt model, the obtained $rETR_{max}$ represents the maximum potential relative electron transfer rate without photoinhibition, while α reflects light use efficiency. The saturation values E_k were also obtained from the curve. The value was determined from the interception point of the α value with the maximum photosynthetic rate as follows:

$$E_k = rETR_{max}/\alpha \tag{2}$$

Variations in chl *a* concentrations in subsamples were also monitored by measuring the fluorescence yields, which were then used to determine the growth rates of phytoplankton.

Algal biomass and community composition

The algae biomass was expressed as wet weight biomass. To determine algae density and enumeration, algae samples were preserved with Lugol's iodine solution (2% final concentration) and sedimented in a plastic bottle for 48 h. Cell density was measured with a Sedgwick–Rafter counting chamber under magnification of ×200 to ×400. Algae species were identified according to Freshwater algae in China (Hu et al. 1980).Algal volumes were calculated from cell density and cell size measurements. Cell volumes were estimated by approximation from the most similar simple geometric solid form after measurement of at least 40 algal units (Wang et al. 2010). Conversion to wet weight biomass assumed that 1 mm^3 of volume was equivalent to 1 mg of wet weight biomass.

Statistical analysis

To test for significant differences among and between the various treatments, one-way analysis of variance (ANOVA) was employed in the origin 8.0 software. Post-hoc multiple comparisons of treatment means were performed by Tukey's least significant difference procedure. All statistical calculations were performed in Statistical Product and Service Solutions (origin 8.0) statistical package, and the level of significance used was set at $p < 0.05$ for all tests.

Repeated measure analysis of variance (RM-ANOVA) was used to determine if sediment resuspension had significant effects on nutrient concentrations and algal biomass. The RM-ANOVA provides a number of comparisons both within and between treatments. However, for the purposes of this research we focused on several specific comparisons. First, results from the non-filtered bioassay experiments (with algae) were used to determine how resident algal communities responded to resuspension events, presumably through nutrient additions. Second, results from the filtered bioassay experiments (without algae) were used to determine if the benthic algae was later established following resuspension events. Tukey's Honesty Significant Differences (HSD; $p = 0.05$) was used to determine significantly different treatments.

Two-way ANOVA was used to test for significant effects of the filtration effect and sediment addition (0, 30, 70, 150, and 250 NTUs) on concentrations of total and dissolved nutrients. When necessary, nutrient data were log transformed to help meet the assumptions of normality.

Results

Nutrients

TN concentrations in the initial 2 days were significantly higher in both Filtered and Non-filtered groups ($p < 0.05$) that were exposed to high turbulence (Fig. 4a) but no distinct effects on DTN, NH_4–N and NO_3–N (Fig. 4b–d, $p > 0.05$). Most nitrogen in the water column were found

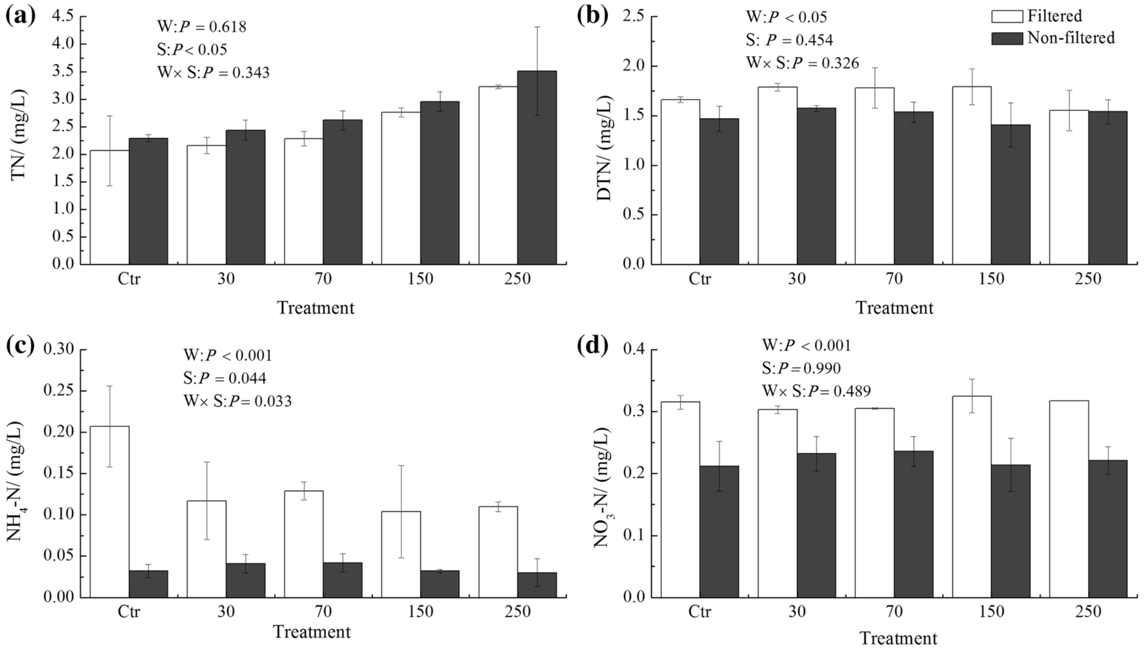


Fig. 4 The mean concentrations of nitrogen, total nitrogen (TN, **a**), dissolved total nitrogen (DTN, **b**), nitrate (NO_3–N, **c**), ammonium (NH_4–N, **d**) in the initial 2 days of the experiment

in dissolved form and dissolved nitrogen in all treatments were significantly higher in Filtered group than in the Non-filtered group ($p < 0.05$; Fig. 4b), especially NH_4–N and NO_3–N (Fig. 4c, d). The same pattern was observed with the TP in the initial 2 days where it increased with turbulence intensity in all treatments ($p < 0.001$; Fig. 5a). However, DTP and SRP were not significantly correlated with turbulence intensity in the two groups ($p > 0.05$; Fig. 5b, c). TP in the Non-filtered treatments were a little higher than in the Filtered group (Fig. 5a), on the contrary, DTP and SRP concentrations in the Filtered group was significantly higher than in the Non-filtered group ($p < 0.001$; Fig. 5b, c).

Interestingly, TN concentrations in the last 2 days in the Filtered group became higher when compared to the start of the experiment. However, the opposite trend was observed for TN in the Non-filtered group (Figs. 4a, 6a). TN concentrations in the Filtered group was significantly higher than in the Non-filtered group ($p < 0.001$; Fig. 6a). After the 14-day incubation, DTN, NH_4–N and NO_3–N in the last 2 days were significantly less than

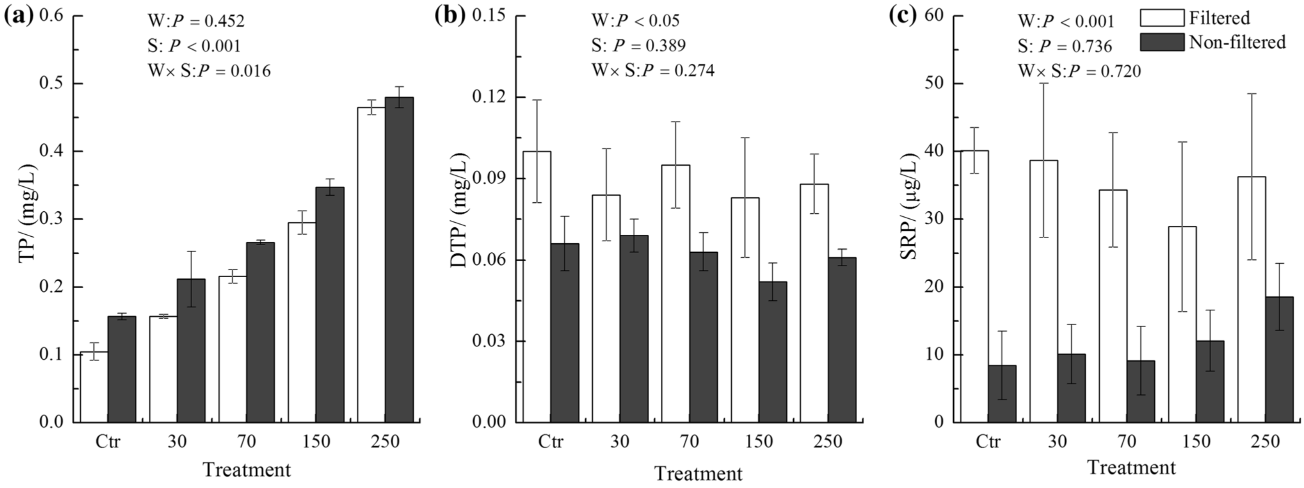


Fig. 5 The mean concentration of phosphorus, total phosphorus (TP, **a**), dissolved total phosphorus (DTP, b), soluble reactive phosphorus (SRP, c) in the initial 2 days of the experiment

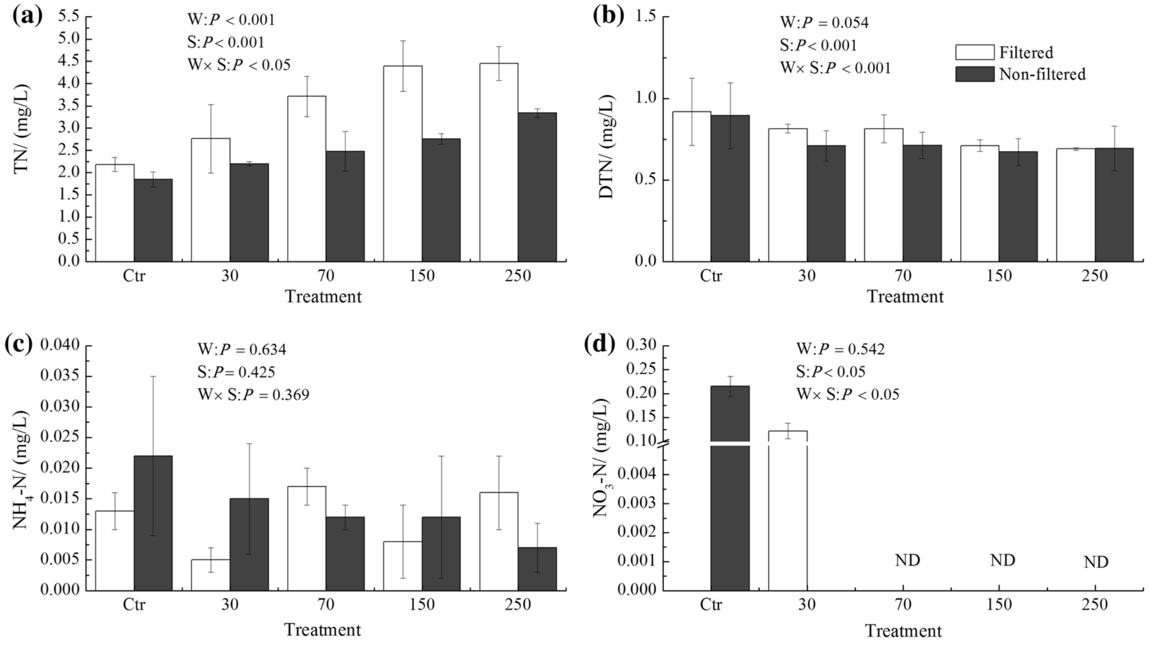


Fig. 6 The mean concentration o of nitrogen, total nitrogen (TN, **a**), dissolved total nitrogen (DTN, **b**), nitrate (NO_3–N, **c**), ammonium (NH_4–N, **d**) in the final 2 days of the experiment; (ND, no data)

the initial levels, with no NO_3-N concentration detected out in the 70, 150 and 250 treatments in two groups (Fig. 6b–d). TP concentrations in the last 2 days were higher than in initial 2 days, particularly in the Non-filtered group ($p < 0.001$; Fig. 7a), while the DTP levels were lower (Fig. 7b) including the SRP concentrations (Fig. 7c). SRP levels however showed no significant relationship with turbulence intensity.

Chlorophyll a

For the initial 2 days for the Filtered group, chl *a* was not detected in in the Ctr (Fig. 8a). Chl *a* concentrations were less than 10.00 μg/L in the 30, 70, 150, 250 treatments in the Filtered group. After the 2-week incubation, chl *a* increased to 6.99 μg/L in the Ctr and had a significant increase in the other four treatments ($p < 0.001$) reaching the maximum of 90.14 μg/L in 30 treatment and the minimum of 48.15 μg/L in 250 treatment (Fig. 8b). In the

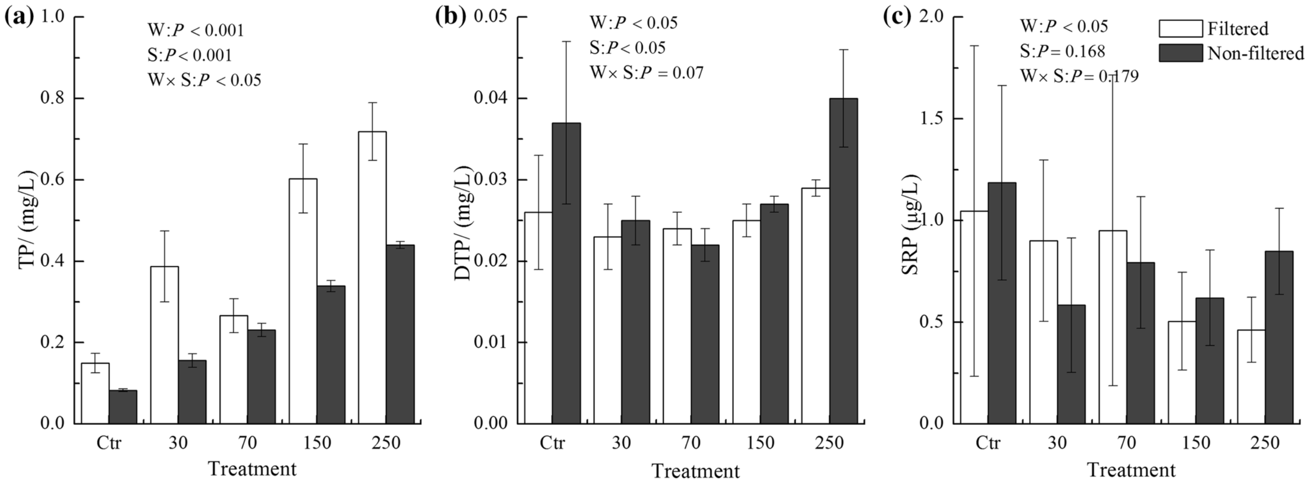


Fig. 7 The mean concentrations of phosphorus, total phosphorus (TP, **a**), dissolved total phosphorus (DTP, **b**), soluble reactive phosphorus (SRP, **c**) in the final 2 days of the experiment

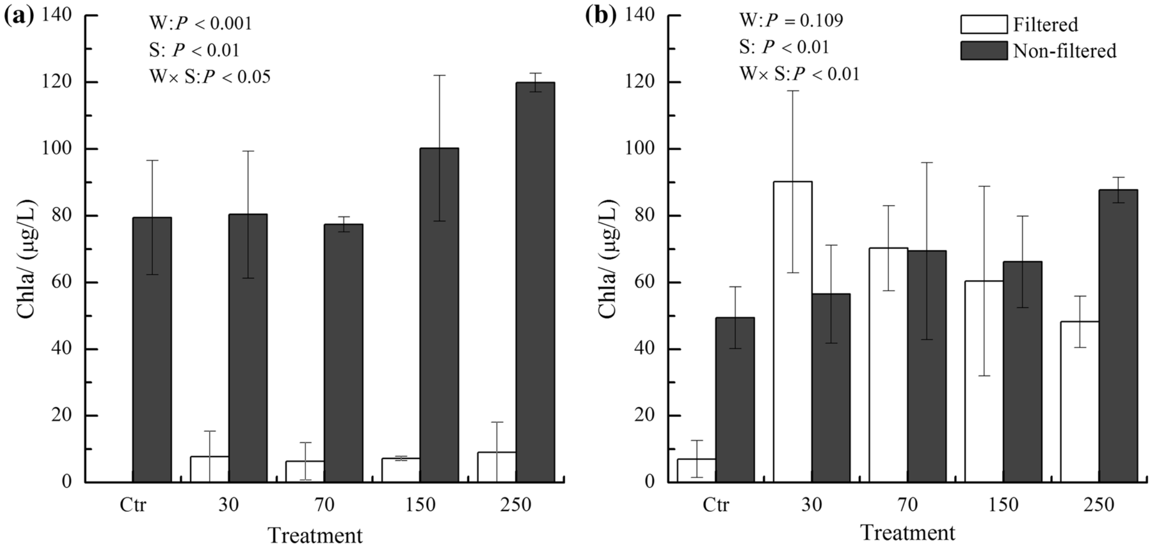


Fig. 8 The initial (**a**) and the final (**b**) Chl a concentrations in all treatments

Non-filtered group, the initial chl *a* in Ctr was 79.42 μg/L, which increased with turbulence intensity and attained a maximum level of 119.87 μg/L in the 250 treatment (Fig. 8a). Interestingly, chl *a* remarkably decreased in the all treatments towards the end of the study ($p < 0.001$) decreasing to 85.8 μg/L in 250 treatment.

At the start of the experiments, chl *a* levels in both groups are different significantly (W: $p < 0.001$), even among the Ctr treatments (S: $p < 0.001$; Fig. 8a). After 2 weeks, no significant difference was observed among the treatments and groups (W: $p = 0.109$) but remained significantly different among the Ctr treatments (S: $p < 0.01$; Fig. 8b).

Algae fluorescence properties

For the Filtered group, F_v/F_m ratios in the Ctr were less than the limit of detection at the initial 2 days (Fig. 9a). The F_v/F_m ratios in the 30, 70, 150 and 250 treatments was the lowest on the first day during the experiment. The

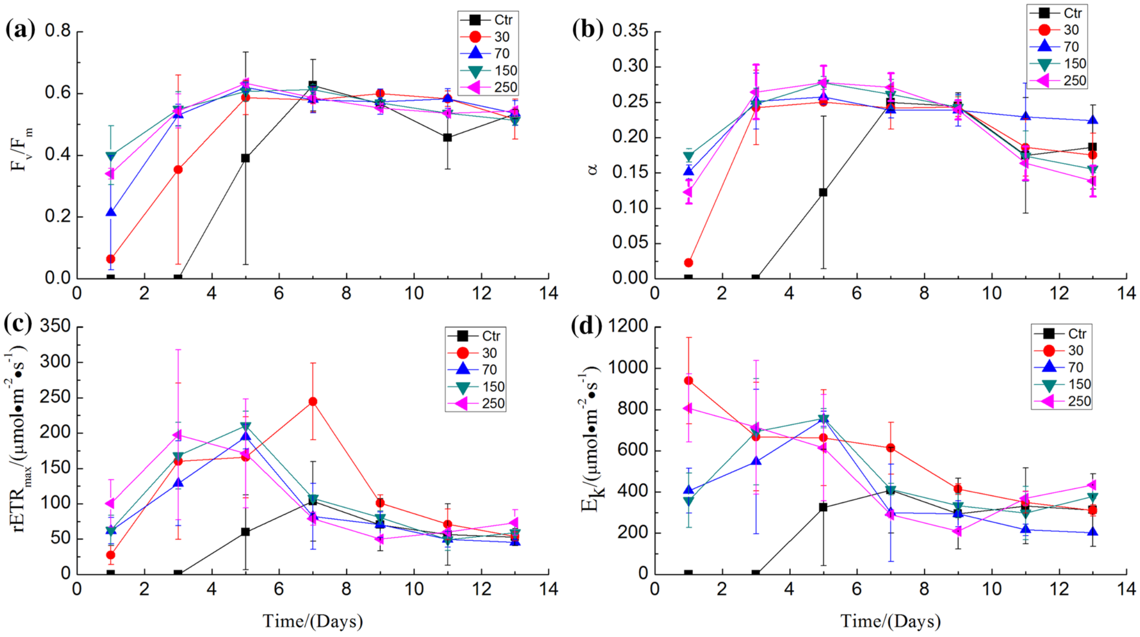


Fig. 9 The time variation of F_v/F_m ratios (**a**), α values (**b**), $rETR_{max}$ (**c**), E_k (**d**) in the Filtered group during the experiment incubation

average F_v/F_m ratio in the Filtered group was the minimum 0.368 ± 0.262 in the Ctr and the maximum 0.541 ± 0.072 in the 150 treatment. The F_v/F_m ratios generally increased with turbulence intensity but did not show significant variation between treatments in the Filtered group ($p > 0.05$). The time variation of parameter α rapidly increased in the initial 4 days and then slowly decreased in the last few days. The mean α value was the minimum (0.140 ± 0.105) in the Ctr and the maximum (0.227 ± 0.035) in the 70 treatment (Fig. 9b). There are no notable differences of α values among treatments and Ctr in the Filtered group ($p > 0.05$). The $rETR_{max}$ (the maximum of the relative electron transport rate) in the Ctr were not detected in the initial 2 days and increased to 104.3 μmol/(s m^2), then decreased in the last 6 days (Fig. 9c). The $rETR_{max}$ in the 30, 70, 150 and 250 treatments increased at the first three tests before decreasing towards the end of the experiment. The average $rETR_{max}$ were the minimum 48.91 ± 37.40 μmol/(s m^2) in the Ctr and the maximum 117.72 ± 76.35 μmol/(s m^2) in the 30 treatment. The time variation of E_k in the Filtered group showed the decline trend in the initial days and then fluctuated between 200 and 450 μmol/(s m^2) (Fig. 9d). The minimum E_k was 238.94 ± 167.08 μmol/(s m^2) in the Ctr and the maximum E_k was565.63 ± 222.82 μmol/(s m^2) in 30 treatment.

For the Non-filtered group, the time variation of F_v/F_m ratios showed that F_v/F_m ratios decreased in the initial 5 days and then fluctuated between 0.45 and 0.60 (Fig. 10a). The average F_v/F_m ratios were the minimum 0.549 ± 0.063 in the Ctr and the maximum 0.587 ± 0.057 in the 70 treatment. The F_v/F_m ratios were significantly correlated with turbulence intensity ($p < 0.05$). Lastly, the F_v/F_m ratios in the Non-filtered group were significantly higher than the Filtered group ($p < 0.05$). The average parameter α was the minimum 0.194 ± 0.027 in the Ctr and the maximum 0.226 ± 0.030 in the 150 treatment (Fig. 10b).There were no notable differences of α values among treatments and Ctr ($p > 0.05$). The time variation of $rETR_{max}$ in the Non-filtered group showed the decline trend (Fig. 10c). As shown, the average $rETR_{max}$ were the minimum 93.09 ± 44.01 μmol/(s m^2) in the Ctr and reached the highest levels of 127.21 ± 50.89 μmol/(s m^2) in the 250 treatment. With the turbulence intensity increasing, the average $rETR_{max}$ also slightly increased. The $rETR_{max}$ in the Non-filtered group were a bit higher that in the Filtered group. The time variation of E_k in the Non-filtered group showed the decline trend in the initial days and then fluctuated between 300 and 550 μmol/(s m^2) (Fig. 10d). The maximun average E_k was 546.17 ± 201.62 μmol/(s m^2) in the 250 treatment (Fig. 10d) and the minimum average E_k was 464.87 ± 169.18 μmol/(s m^2) in the 30 treatment.

Algae community composition

At the beginning, after the original lake water filtering through phytoplankton net, the algae communities in the coarsely filtered water were mainly composed of species belonging to Cyanophyta, Chlorophyta, Bacillariophyta and Euglenophyta, with standing biomass 0.013, 0.020, 0.012 and 0.024 mg/L, respectively (Table 2). And the cell

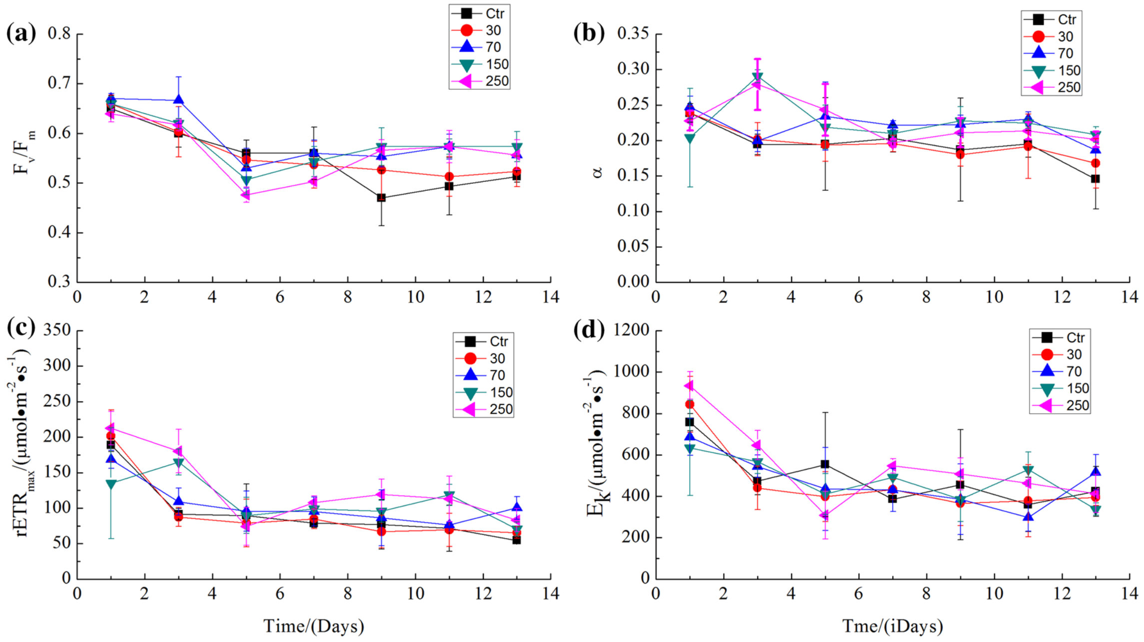


Fig. 10 The time variation of F_v/F_m ratios (a), α values (b), $rETR_{max}$ (c), E_k (d) in the Non-filtered group during the experiment incubation

Table 2 The standing biomass and the cell abundance value of the phytoplankton in the initial coarsely filtered water and in the Filtered and Non-filtered group

		Cyanophyta		Chlorophyta		Bacillariophyta		Euglenophyta		Total standing biomass (mg/L)
		Standing biomass (mg/L)	Cell abundance value	Standing biomass (mg/L)	Cell abundance value	Standing biomass (mg/L)	Cell abundfance value	Standing Biomass (mg/L)	Cell abundance value	
Initial state		0.013	0.891	0.020	0.030	0.012	0.062	0.024	0.018	0.069
Filtered group	Ctr	0.020	0.715	0.631	0.152	0.037	0.122	0.030	0.010	0.718
	30	0.039	0.634	0.042	0.222	0.072	0.123	0	0	0.152
	70	0.087	0.628	0.082	0.215	0.204	0.152	0	0	0.374
	150	0.046	0.615	0.022	0.137	0.219	0.248	0	0	0.288
	250	0.045	0.493	0.098	0.350	0.154	0.145	0.034	0.011	0.331
Non-filtered group	Ctr	0.056	0.705	0.074	0.271	0.051	0.023	0.003	0	0.184
	30	0.159	0.924	0.034	0.051	0.038	0.025	0	0	0.231
	70	0.045	0.591	0.045	0.129	0.324	0.277	0.003	0.001	0.418
	150	0.068	0.613	0.065	0.211	0.304	0.174	0.007	0.001	0.445
	250	0.076	0.697	0.046	0.087	0.438	0.216	0	0	0.560

abundance value were Cyanophyta 0.891, Chlorophyta 0.030, Bacillariophyta 0.062 and Euglenophyta 0.018.

Over the 2-week experiment incubation, for the Filtered group, the standing biomass largely increased from the initial state (Table 2). The minimum of the total standing biomass was 0.152 mg/L in the 30 treatment and the maximum of the total standing biomass was 0.718 mg/L in the Ctr. The standing biomass showed no significant relationship with turbulence intensity in the Filtered group ($p > 0.05$). The algal community in the Ctr and other four treatments were mainly composited by Cyanophyta, Chlorophyta and Bacillariophyta. The cell abundance of Cyanophyta in the Ctr and other four treatments covered more than 50% algal cell density (Table 2).

In the Non-filtered group over incubation, the algae standing biomass linearly increased with turbulence intensity reaching maximum level of 0.560 mg/L in the 250 treatment. The standing biomass in the 30, 70, 150 and 250 treatments in the non-filtered group were higher than that in the Filtered group. The standing biomass had obvious differences between treatments ($p < 0.05$). The algal community mainly included Cyanophyta, Chlorophyta and Bacillariophyta. The cell abundance of algae in the Non-filtered group showed that more than 60% algae cell density was Cyanophyta in the Ctr and other four treatments.

Discussion

Effects of sediment resuspension on water column nutrients

Sediment resuspension brought particles back into the water column, increasing the TN and TP concentrations. The simulated experiment and field observation showed that TN and TP were positively related to turbulence intensity (Figs. 4a, 5a) (Schallenberg and Burns 2004; Ding et al. 2012; Zhu et al. 2014). Compared with particulate nutrients, the net effect of sediment resuspension on available phosphorus and nitrogen is more complex and variable (Søndergaard et al. 1992; Hamilton and Mitchell 1997; Ogilvie and Mitchell 1998; Schallenberg and Burns 2004). Results of incubation experiments showed that the dissolved N and P varied and had no significant relationship with turbulence intensity (Figs. 4, 5, 6, 7). The effect of resuspension on the phosphorus availability not only depends on the nutrient differences in the water–sediment interface (Søndergaard et al. 1992), but also depends on pH (Scheffer 1998), the sorption–desorption on the particles (Hamilton and Mitchell 1997; Schallenberg and Burns 2004) and other factors. This in part could possibly explain why the dissolved nutrients in the Filtered group were remarkably higher at the initial stage of the experiment

(Figs. 4b–d, 5b, c). Therefore, sediment properties (e.g. water content, Fe/P ratios and particle size) should be taken into consideration when looking at the effects of sediment resuspension on the dissolved nutrients (Søndergaard et al. 1992; Scheffer 1998). Lastly, the release of dissolved nutrients were also related to the duration or period of resuspension, which contributes to the physical distribution of both the particles and the dissolved components (Søndergaard et al. 1992). Some research also found that the phytoplankton could rapidly utilize the nutrients and accelerate nutrients cycling (Søndergaard et al. 1992; Zhu et al. 2005). Considering the luxury uptake by the phytoplankton, that maybe another factor inducing that the dissolved nutrients in the filtered group were higher than those in the non-filtered group.

Effects of sediment resuspension on chlorophyll a fluorescence

The ability to intercept and utilize light by algae are the complex mechanisms that determine net productivity and species succession (Brookes et al. 2003). The photosynthetic characteristics of the phytoplankton are affected by nutrients, temperature, light and other environmental factors which moderated them to adapt to the local living environment (Suggett et al. 2009). The nutrients concentration and the proportion of different nutrients had a profound effects on the photosynthetic activity of phytoplankton (Li et al. 2016). In our experiment, the initial nitrogen and phosphorus concentration were higher, especially available nitrogen and phosphorus. The photosynthetic response of the phytoplankton to the episodic sediment resuspension found that the photosynthetic parameters (especially, F_v/F_m) were highest on the first day (Fig. 10). With the incubation continuing, nutrients were consumed by the algae for propagation, therefore, nutrients could limit the algae growth, that is to say, the photosynthetic activity of the algae were inactivated.

F_v/F_m of the phytoplankton was positively correlated with chl *a* that the more vigorous photosynthesis could lead to the increase of the algae biomass (Li et al. 2016). It was in accord with our experiment results. The initial chl *a* in the Filtered group were lower than that in the Non-filtered group. So, the initial F_v/F_m, α, $rETR_{max}$, E_k in the Filtered group were very low, with no detectable data in Ctr (Fig. 9). While, with chl *a* increasing in the Filtered group, the photosynthetic activity generally rise. All photosynthetic parameters in the Non-filtered group were significantly higher than that in the Filtered group on the initial 2 days. Accordingly, chl *a* in the Non-filtered group were higher than that in the Filtered group in the initial 2 days.

Nevertheless, The time variation of the photosynthetic parameters (F_v/F_m, α, $rETR_{max}$, E_k) showed that the impact was temporary, as one week later, chl *a* fluorescence activity fluctuated in the stability range (Figs. 9, 10). Other research also found that Chlorophyll-related activities could quickly respond to environmental stresses and resource availability (e.g. nutrients, light, predation) (Lagus et al. 2007; Zhang et al. 2007). Due to high exposure to frequent turbulence mixing in shallow lakes, algae are adapted to fluctuating light conditions and exhibit a broad range of physiological adaptations or acclimation strategies. These strategies could help the algae maximize photosynthetic rates at light levels ranging from light-limiting to damaging (Cullen and Lewis 1988; Cullen and Macintyre 1998). In this study, all photosynthetic parameters measured in the two groups indicated that phytoplankters could moderate themselves to adapt to all kinds of environmental change and reached high photosynthetic rates.

Effects of sediment resuspension on algal biomass and community composition

These experiments suggest that turbidity levels can affect the phytoplankton of Lake Taihu. Algal biomass increased following sediment resuspension in the bioassay experiments (Fig. 8a, b, S: $p < 0.01$). Sediment resuspension indirectly affected algal biomass by repleting the water column with nutrients. Previous studies (Zhu et al. 2005, 2014; Ding et al. 2012) have demonstrated that the increase in nutrients following resuspension could help alleviate nutrient limitation in Lake Taihu, favoring algal growth.

In addition, sediment resuspension could also have direct effects on algal biomass. The significant entrainment of chlorophyll a by sediment resuspension has been observed in other shallow lakes (Schelske et al. 1995; Hamilton and Mitchell 1997; Ogilvie and Mitchell 1998). Positively, resuspension could transport benthic algae and dormant algal cells (i.e. cysts) in the sediment back into the water column (Millie et al. 2003; Dzialowski et al. 2008). Studies in Lake Taihu found lots of algal hypnospore and even vegetative algal forms in the sediments (Wu et al. 2008; Gu et al. 2011). Once exposed to optimum conditions (e.g. temperature, light) in the pelagic waters, hypnospores could easily revert back to their motile forms and then potentially seed a bloom. The results from the Filtered group bioassay allowed us to determine if the algae in the sediments were able to re-establish after resuspension since the old algal communities were initially removed by filtration. The increase of algal biomass in all turbulent treatments were significant relative to the Ctr (without sediment, 0 mg/L in the initial) in the initial few days (Fig. 8a) and especially after 2 weeks (Fig. 8b). So, it indicates that the algae within the sediment were brought back into the water column following resuspension events and successfully established communities in the absence of the resident/old algal communities (Table 2).

Algal biomass in the Non-filtered group responded differently to sediment resuspension relative to the Filtered group in the initial experiment (W: $p < 0.001$; Fig. 8a), but there was no significant difference in the algal biomass between two groups at the end of the 2-week incubation (W: $p = 0.109$; Fig. 8b). The biomass of phytoplankton in Lake Taihu during summer were highest compared to the other seasons (Qin 2009; Song et al. 2010). The decrease in algal biomass in our experiment could be partly due to insufficiency of nutrients in maintaining large amount of algal biomass. The experiments were conducted in 1-L bioassay bottles with no other nutrients addition. So, the nutrients could be exhausted even before the end of the study. The nutrients therefore were supplied only by the sediments and the degradation of particulate matter. However, comparison of the algal community composition in the Filtered group (new community) and Non-filtered group (resident community) revealed high community similarity suggesting that sediment resuspension did not significantly change algal community structure.

Conclusion

Sediment resuspension is an important phenomenon in Lake Taihu. Our results have important implications for the long-term management of river outlets in the western region of the shallow lake since they are located in a wind divergence zone making them vulnerable to wind-induced mixing. Resuspended sediments contribute to nutrient release allowing algae growth. Further, they could also bring algae in the sediments back into water column, causing the algal biomass increase and an onset of new blooms. However, sediment resuspension had no significant effect on the algal community composition. Episodic sediment resuspension could compel the algae to adjust to maintain the algal photosynthetic activities. So, in the end of experiment, our research did not find that episodic sediment resuspension decreased the photosynthetic activities. Our research results highlight the importance of sediment resuspension in long-term management goals and restoration efforts for these types of ecosystems. Specifically, when external nutrient loads are reduced, the internal reservoir in the sediments could be cycled back into the water column during resuspension events inducing high algal biomass for a long period.

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