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RESEARCH ARTICLE

Phosphorus released from sediment of Dianchi Lake and its effect on growth of *Microcystis aeruginosa*

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Abstract Phosphorus stored in lake sediments is an inner nutrient source and can be released into overlying water to exacerbate algal blooms. A simulated microcosm of Dianchi Lake was built to investigate phosphorus release from sediments to overlying water and its effect on the growth of *Microcystis aeruginosa*. The sediments of Dianchi Lake had a total phosphorus (TP) content of 1.7–1.8 mg g^{-1} with Ca bound phosphorus (Ca-P, 50–54 %) and organic phosphorus (Org-P, 28–32 %) as the main fractions. The sediments released 8 % of TP into the overlying water with Fe/Al bound phosphorus (Fe/Al-P, 26 %) and Org-P (65 %) being the main fractions released. The phosphorus concentration of the overlying water increased from 0.14–0.16 to 0.28–0.33 mg L^{-1}. The biomass density of *M. aeruginosa* was positively correlated ($R^2 = 0.825$) with the concentration of orthophosphate, which was the predominant bioavailable phosphorus fraction for algal growth. Org-P can be partly utilized by *M. aeruginosa* but will not cause a bloom. A good understanding of the geochemical cycles of phosphorus is needed for regulating phosphorus release from sediments and thereby reducing the risk of cyanobacterial blooms.

Keywords Phosphorus release · Dianchi Lake · Sediment · *Microcystis aeruginosa*

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Introduction

Eutrophication is a phenomenon arising from the excessive input of inorganic nutrients such as nitrogen and phosphorus into natural aquatic ecosystems leading to the overgrowth of phytoplankton, death of aquatic organisms, and deterioration of surface water quality (Cai et al. 2013; Smith and Schindler 2009). Worldwide, eutrophication of freshwater aquatic ecosystems has resulted in the reduction of biodiversity and ecosystem functions and deterioration of surface water quality (Renuka et al. 2015).

As a consequence, combating eutrophication by controlling the external nutrient input is increasingly being included in water policy regulations. Among the various nutrient elements, phosphorus is usually the limiting element in most aquatic ecosystems. Reducing phosphorus levels in aquatic systems is therefore the highest priority in combating eutrophication (Lewis et al. 2011; Wang et al. 2006).

Sediment in a lake acts as an internal phosphorus source in addition to being a phosphorus sink (Wang et al. 2006). In other words, even when the external phosphorus input is under control, release of internal phosphorus accumulated in the sediment can be a significant phosphorus source and prolong the eutrophic status of a lake (Wu et al. 2011; Zhu et al. 2013). Phosphorus can be released through many physical, chemical, and biological processes, such as ligand exchange mechanisms, mineralization, and release from living cells (Christophoridis and Fytianos 2006). Moreover, many factors can drive phosphorus release into the overlying water, such as temperature, redox condition, dissolved oxygen, pH, and hydraulic conditions of the lake (Dittrich et al. 2013).

Phosphorus exists in the sediments in various chemical forms, such as inorganic phosphorus associated with Fe-, Al-, and Ca-oxides and hydroxides or clay minerals, and organic phosphorus compounds (Dittrich et al. 2013; Zan et al.

2011). However, each phosphorus fraction contributes differently to the internal loading and not all fractions can be released from the sediments and assimilated by phytoplankton (Gao et al. 2005; Wang et al. 2006). For instance, Ca bound phosphorus (Ca-P) is usually not available for assimilation by the phytoplankton (Andrieux-Loyer and Aminot 2001) while bioavailable organic phosphorus only accounted for 12.1–27.2 % of total organic phosphorus in the sediments of Dianchi Lake, China (Zhu et al. 2013). Thus, to assess the eutrophication and algal bloom risks in a lake, it is necessary to know the content and bioavailability of different phosphorus fractions.

Dianchi Lake is located in the downstream area of Kunming, Yunnan, China. It is the sink for wastewater from Kunming (40 % of the total wastewater loadings from non-point sources) and is one of the most severely eutrophic lakes in China (Wu et al. 2010). There are several rivers flowing into the lake, but only one outlet, which induces a relatively long residence period of 3–8 years for the lake and exacerbates nutrient accumulation (Zhu et al. 2013). Although the external phosphorus input has been greatly reduced in recent decades, the water quality of Dianchi Lake has not significantly improved and cyanobacterial blooms still occur annually (Zhu et al. 2013). A previous investigation showed that about 70 % of phosphorus from external inputs settled at the bottom of Dianchi Lake and was stored in the sediment with a maximum phosphorus content of 6.66 g kg^{-1} (Gao et al. 2005). Before effective control measures can be applied, it is necessary to know and/or determine the various phosphorus fractions in the sediments and how these are released from Dianchi Lake (Zhu et al. 2013).

Cyanobacteria are the predominant phytoplankton in lakes (e.g., Chaohu Lake, Taihu Lake, and Dianchi Lake in China) with a contribution of 40–100 % to the total phytoplankton biomass, and cyanobacterial blooms have frequently occurred in these lakes (Chuai et al. 2011; Deng et al. 2007; Pan et al. 2006). For example, Chuai et al. (2011) reported that the cyanobacteria density reached as high as 8×10^7 cells L^{-1} in Taihu Lake, China. Among the various cyanobacterial species in eutrophic lakes, *Microcystis aeruginosa* is usually the dominant species (Pan et al. 2006). Therefore, it is important to know the effects of phosphorus released from lake sediment on the growth of *M. aeruginosa* to assess and subsequently prevent cyanobacterial blooms.

With this background, a simulated microcosm of Dianchi Lake was built in a water tank with the objectives (1) to investigate the release of different phosphorus fractions from sediment of Dianchi Lake into the overlying water, (2) to determine the effects of phosphorus released from sediment of Dianchi Lake on the growth of *M. aeruginosa*, and (3) to evaluate the utilization of organic phosphorus by *M. aeruginosa*.

Materials and methods

Simulated microcosm of Dianchi Lake for phosphorus release

To investigate the characteristics of phosphorus release from the sediment of Dianchi Lake, a eutrophic lake in Kunming, southwest China, a glass water tank (length 30 cm, width 20 cm, height 50 cm) was used to simulate the environment. Sediment collected from Dianchi Lake was put at the bottom of the water tank to a depth of 10 cm. Lake water from the top layer of Dianchi Lake (Table 1) was added to the water tank as overlying water with a depth of 32 cm. Cyanobacterium *M. aeruginosa* (purchased from Freshwater Algae Culture Collection at Institute of Hydrobiology, Chinese Academy of Sciences) from the exponential growth phase was then added to the water tank with initial biomass density, measured as Chl *a* equivalents, of 2 μg L^{-1}. The water tank was placed in outdoor conditions in Kunming, Yunnan, China, for 42 days from July to August, 2012. Concentrations of total phosphorus (TP), total dissolved phosphorus (TDP), orthophosphate, and algal biomass density were measured every 7 days. Water samples were collected from the top (0–5 cm under water) and the bottom (15–20 cm under water) of the overlying water. Distilled water was added every day to compensate for evaporation. Lake sediment samples were collected every 7 days to measure the contents of different phosphorus fractions: TP, exchangeable phosphorus (Ex-P), Fe/Al bound phosphorus (Fe/Al-P), Ca-P, and organic phosphorus (Org-P). All the analysis was done within 12 h after sampling.

Organic phosphorus and cyanobacterial growth experiment

To investigate the effects of different types of organic phosphorus on the growth of *M. aeruginosa*, indoor experiments were carried out in glass water tanks (length 30 cm, width 20 cm, height 20 cm). The culture media for the experiments were based on BG-11 medium, to which inorganic phosphorus was not added. ATP, β-glycerophosphate, and lecithin were individually used as the sole organic phosphorus source and the initial TP concentrations were set at 50, 25, 15, 10, 5, and 2.5 mg L^{-1}. The medium was added to the water tanks to a depth of 10 cm and *M. aeruginosa* from exponentially growing cultures was added to the medium with an initial biomass density, measured as Chl *a* equivalents, of 2 μg L^{-1}. This was done in triplicate. All simulated microcosms (water tanks) were kept at 22 °C with a light intensity of 2500 lx under a 14/10 h light/dark cycle in an incubator.

Table 1 Chemical characteristics of water from Dianchi Lake

	pH	TP (mg L^{-1})	TDP (mg L^{-1})	Orthophosphate (mg L^{-1})	TN (mg L^{-1})	NH_4^+-N (mg L^{-1})	COD (mg L^{-1})	DO (mg L^{-1})
Water	8.5	0.15	0.12	0.07	2.14	0.41	11.1	7.8

Water samples were collected every 5 days to measure TDP, orthophosphate, and Chl *a*. All analyses were done within 12 h after sampling.

Samples and analysis

TP of water samples was measured after digestion at 120 °C for 30 min with a spectrophotometer (UV-1800, Japan) at 700 nm following the molybdenum-antimony-spectrophotometric method (Wei et al. 2002). TDP of water was measured in the same way after filtering water samples through a 0.45-μm filter membrane. Orthophosphate was measured according to the molybdenum-antimony-spectrophotometric method without digestion (Wei et al. 2002).

For the sediment samples, TP was measured by burning 0.5 g sediment at 550 °C for 1 h and the phosphorus was extracted from the ash with 1 mol L^{-1} H_2SO_4 (20 mL) (Lu 2000). Thereafter, TP was measured in the same way as the water samples (Wei et al. 2002). Inorganic phosphorus was measured in the same way as the water samples after extraction from the sediment by 1 mol L^{-1} H_2SO_4 without burning (Lu 2000). Org-P was obtained by subtracting inorganic phosphorus from TP.

For measuring Ex-P, 0.5 g sediment was weighed into a 50-mL Falcon tube and 20 mL of 1 mol L^{-1} $MgCl_2$ was added. The sample was then shaken for 2 h at 30 °C in a water bath and centrifuged. The upper layer solution was used to measure TP in the same way as in the water samples. For measuring Fe/Al-P, 20 mL of 1 mol L^{-1} NaOH was added to the residue after extracting Ex-P and the sample was shaken for 12 h then centrifuged. The upper layer was used to measure TP in the same way as in the water samples. For Ca-P, the residue after extracting Fe/Al-P was washed with saturated NaCl and 20 mL of 1 mol L^{-1} H_2SO_4 was then added and the phosphorus measured after 12 h shaking.

Chl *a* was extracted with 90 % acetone after filtering 10-mL water through a 0.45-μm filter membrane and then measured on a spectrophotometer at 664.3 nm (Parsons and Strickland 1963).

Data analysis

A *t* test was used to compare the phosphorus concentrations of the top and bottom water layers of the simulated microcosm using SPSS 19.0. Correlation analyses were performed to investigate the correlations between different phosphorus forms and Chl *a*. Two-way ANOVA was employed to investigate the effects of organic phosphorus types and their initial concentrations on *M. aeruginosa* growth. The significance level was $p = 0.05$.

Results and discussion

Characteristics of phosphorus released from sediment

Phosphorus is stored in sediment in various forms (Wang et al. 2006). In this study, four phosphorus fractions were determined: the Ex-P, Fe/Al-P, Ca-P, and Org-P (Fig. 1). Generally, in the sediment of Dianchi Lake, Ca-P was the predominant fraction (50–54 %), Org-P was the second largest fraction (28–32 %), while Ex-P was the smallest fraction with a percentage of only 1.6–2.3 % (Fig. 1a).

Ex-P is the phosphorus adsorbed on the surface of sediments and the predominant fraction which can diffuse from sediment to water (Wu et al. 2011). In this study, the Ex-P content of the sediment was low (33–45 μg g^{-1}). On day 14, the maximal Ex-P content (45 μg g^{-1}) was observed and it then decreased from day 14 to 21 and remained at a relatively stable level of 35 μg g^{-1} (Fig. 1c). The fluctuation of Ex-P content in sediment must be due to hydraulic disturbance at the beginning of the experiment, because Ex-P is usually sensitive to the external environment, especially the interface conditions between sediment and the overlying water (Wu et al. 2011). Thus, phosphorus was accumulated in the sediment or diffused into water whenever there was hydraulic disturbance. Afterwards, phosphorus exchange between the sediment and overlying water reached a stable status or equilibrium.

Fe/Al-P represents phosphorus bound to Fe and Al oxides and is exchangeable with OH- and other inorganic phosphorus compounds, which are soluble in bases (Wu et al. 2011). Furthermore, Fe/Al-P can be used to evaluate algal available phosphorus, because it supports the growth of phytoplankton (Zhou et al. 2001). Fe/Al-P is also sensitive to external conditions, for example, a decrease in pH can induce the transformation of Fe/Al-P into overlying water and increase the dissolved phosphorus concentration (Andrieux-Loyer and Aminot 2001). At the beginning of this study, Fe/Al-P had a concentration of over 280 μg g^{-1} (Fig. 1d), then decreased gradually to 230 μg g^{-1} by day 35. The large decrease in Fe/

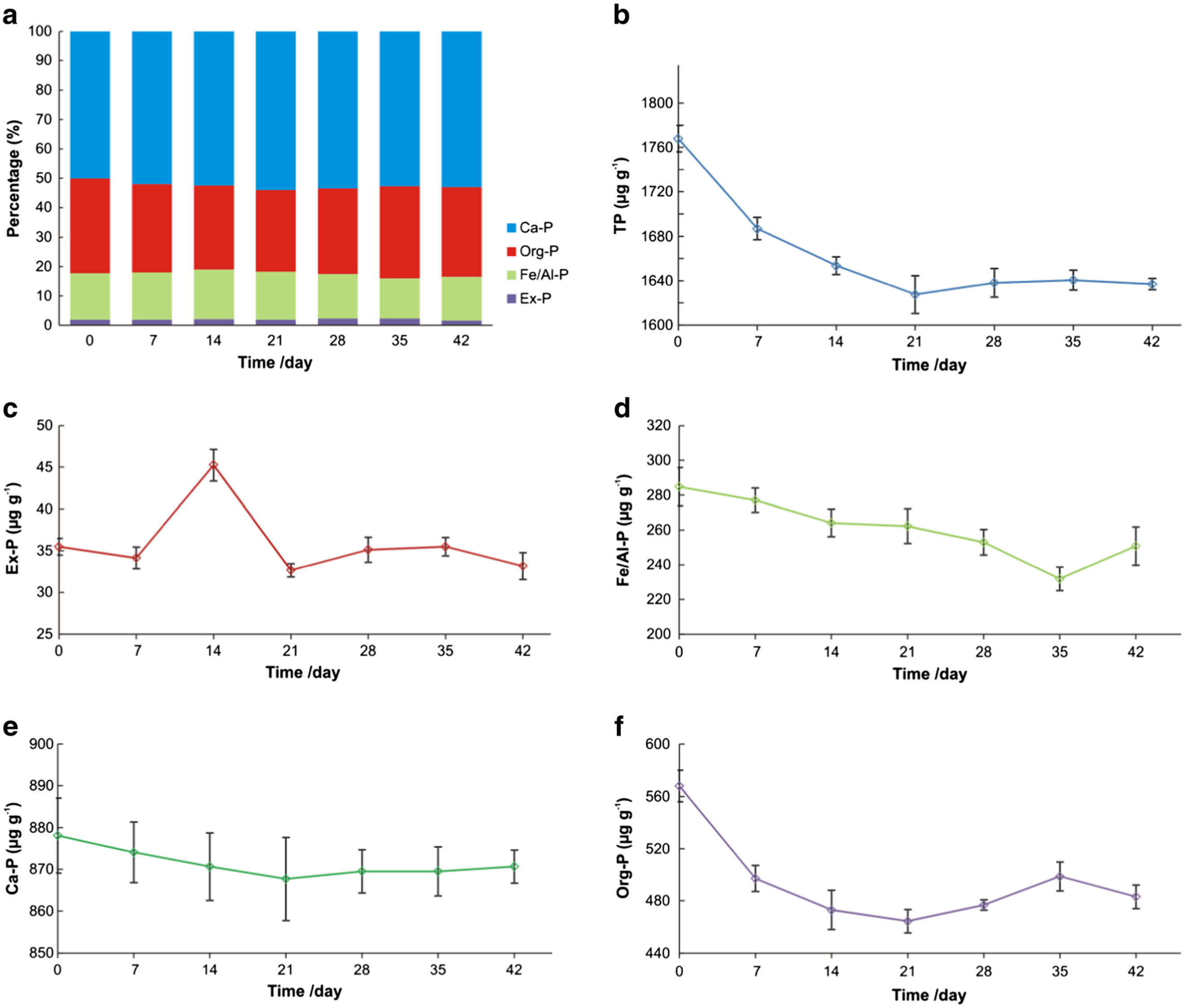

Fig. 1 **a** Changes in the percentages of exchangeable phosphorus (*Ex-P*), Fe/Al bound phosphorus (*Fe/Al-P*), organic phosphorus (*Org-P*), and Ca bound phosphorus (*Ca-P*) in total phosphorus (*TP*) of sediment over time. **b–f** Changes of TP, Ex-P, Fe/Al-P, Ca-P, and Org-P contents (μg g^{-1}) in lake sediment over time

Al-P content of the sediment indicated that Fe/Al-P was the main phosphorus fraction released from sediment into the overlying water column.

Ca-P is a relatively stable phosphorus fraction and can only be released under acidic conditions. Thus, Ca-P is usually not bioavailable for microorganisms and is usually confined to permanent burial within sediments (Andrieux-Loyer and Aminot 2001; Wu et al. 2011). In this study, Ca-P decreased slightly from 878 μg g^{-1} on day 0 to 869 μg g^{-1} by day 42. Ca-P can only dissolve in acidic water, but as the water of Dianchi Lake was usually alkaline, this water is not a preferred condition for the release of Ca-P (Fig. 1e).

Org-P can be partly utilized by microorganisms and directly affects the dissolved phosphorus levels in water for primary production (Wu et al. 2011; Zhu et al. 2013). In the sediments of Dianchi Lake, Org-P primarily originated from autochthonous sources (Zhu et al. 2013). Thus, although most Org-P was stable, the lake sediments would accumulate some bioavailable Org-P in the process of eutrophication. Furthermore, with greater phytoplankton biomass (or organic substances) accumulated in eutrophic lake sediments, activities of phosphatase (e.g., alkaline phosphatase) are usually greater in sediments (Zhang et al. 2007; Zhou et al. 2008). In this study, the Org-P decreased from 568 on day 0 to 464 μg g^{-1} by day 21, and then increased to 498 μg g^{-1} by day 35 (Fig. 1f). Therefore, the bioavailable Org-P must have been released into the overlying water when less orthophosphate was available.

Phosphorus in overlying water and growth of *M. aeruginosa*

In natural water bodies, TP, TDP, and orthophosphate are highly related to the growth of algae and other phytoplankton (Xu et al. 2010; Zhang et al. 2007). Accordingly, TP, TDP, and orthophosphate changes were monitored in this study (Fig. 2). Generally, the bottom layer of the simulated lake microcosm had significantly higher TP, TDP, and orthophosphate concentrations than the top layer (all $p < 0.05$, Fig. 2a–c). The water of Dianchi Lake had a TP concentration of 0.14–0.17 mg L^{-1} (day 0 in Fig. 2a) with dissolved phosphorus being the main phosphorus fraction (70–75 % of TP) (Fig. 2b). Moreover, due to the settlement of suspended phosphorus and the diffusion of phosphorus from the bottom (15–20 cm under water) to the top (0–5 cm) of the water column, the top water layer had lower phosphorus concentrations than the bottom layer.

Specifically, TP of the overlying water showed great increases in the first 7 days from 0.14 to 0.33 and 0.17 to 0.28 mg L^{-1} of the bottom and top layers, respectively (Fig. 2a). From day 7 to 14, TP of both the bottom and top layers decreased quickly to 0.15 and 0.13 mg L^{-1}, respectively. Then, the TP concentration stabilized at 0.15–0.17 and 0.11–0.13 mg L^{-1} in the top and bottom layers, respectively, until day 35. The TDP concentration showed a similar pattern to TP (Fig. 2b). From day 35 to 42, TP and TDP increased by 0.03–0.13 and 0.01–0.02 mg L^{-1}, respectively. In contrast to the increase in TP and TDP during the first 7 days, the orthophosphate concentration decreased from 0.080 to 0.055 and 0.053 to 0.015 mg L^{-1}, in the bottom and top layers, respectively (Fig. 2c). The orthophosphate must have been consumed by the growth of *M. aeruginosa* as orthophosphate is the predominant reactive phosphorus fraction which can be easily assimilated by algae (Jansson 1993; Jansson et al. 2012). Moreover, the top layer had a larger decrease in orthophosphate than the bottom layer, most probably because the photoautotrophic microorganisms exhibit phototaxis and moved to the surface of the water column (Liu et al. 2010). From day 35 to 42, an increase in orthophosphate concentration was observed in the bottom layer of the water tank. This increase was attributed to the death and settlement of algal cells, which release phosphorus into the water (Zeng et al. 2010).

The biomass density of *M. aeruginosa* greatly increased from 2 to 16 μg Chl *a* L^{-1} in the first 7 days and then further increased to 36 μg Chl *a* L^{-1} by day 21. After that, algal biomass density started to decrease (Fig. 2d). The Chl *a* change was in accordance with orthophosphate and TP changes (Fig. 2c), and a positive correlation was observed between orthophosphate concentration and Chl *a* ($R^2 = 0.825$). For instance, the growth of *M. aeruginosa* in the first 7 days consumed much orthophosphate and then induced the

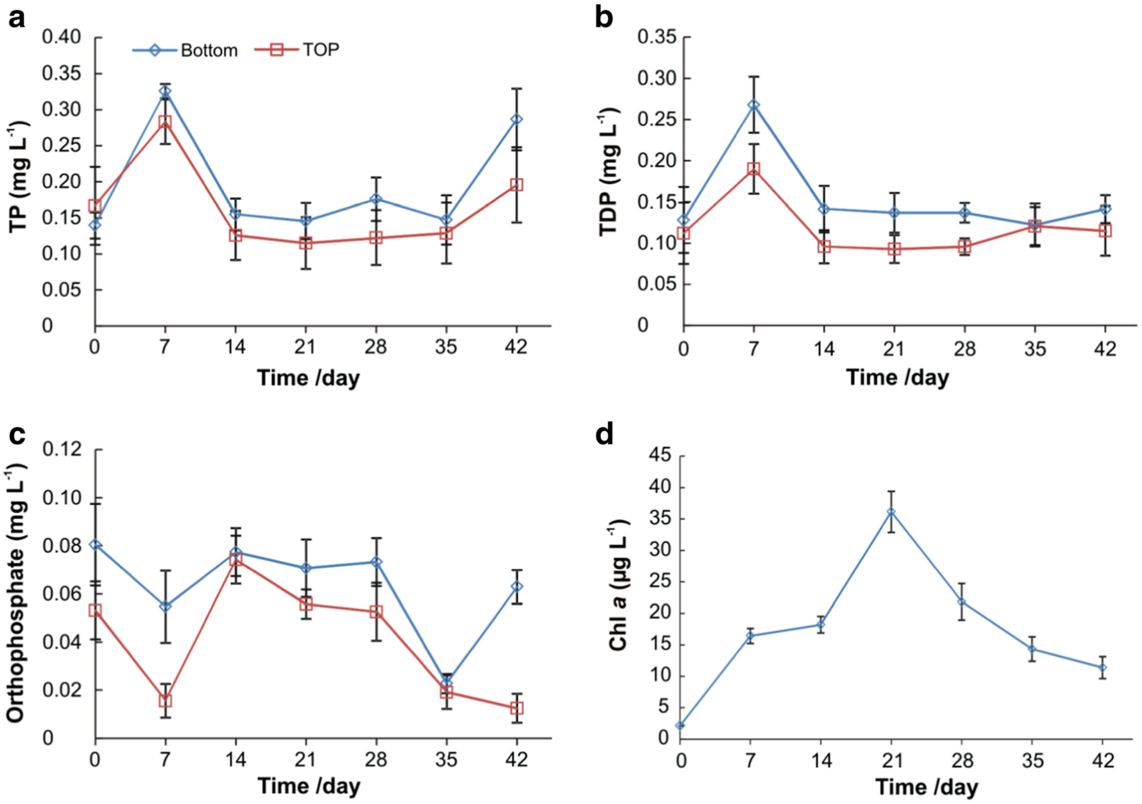

Fig. 2 **a–c** Changes in total phosphorus (*TP*), total dissolved phosphorus (*TDP*), and orthophosphate of the *top* and *bottom* overlying water of the simulated lake microcosm (water tanks) over time. **d** Chl *a* changes of *M. aeruginosa* in the water tank over time

transformation of dissolved phosphorus into orthophosphate. Accordingly, decreases in TP and TDP were observed from day 7 to 14.

Chl *a* had significant positive correlation with exchangeable phosphorus in the sediment ($p < 0.01$, Table 2). When there was a phosphorus concentration gradient, Ex-P automatically diffused into water and prompted the growth of *M. aeruginosa*. Ex-P, however, was not significantly correlated with TP or any other phosphorus fractions, most probably due to the properties of Ex-P, which are strongly dependent on the external environment (Jin et al. 2006). Therefore, the Ex-P of the sediment determines the algal growth of the lake.

Organic phosphorus and growth of *M. aeruginosa*

The decrease in TP was mainly caused by the decrease in organic phosphorus (73 %) (Fig. 1b, f). Therefore, in Dianchi Lake, the sediment Org-P must play a critical role in phosphorus release from sediment into water and then affected algal growth. Based on this observation, three types of organic phosphorus compounds (ATP, β-glycerophosphate, and lecithin) were used to investigate the effects of organic phosphorus on algal growth.

The groups with ATP and β-glycerophosphate as phosphorus sources had significantly higher TDP than those with lecithin ($p < 0.05$, Fig. 3a, d, g). For instance, group 1 with ATP or β-glycerophosphate had TDP concentrations of 49.6 and 49.8 mg L^{-1}, respectively, while that with lecithin only had 13.2 mg L^{-1}. In addition to a lower phosphorus content than ATP and β-glycerophosphate, lecithin is harder to dissolve in water. These two characteristics resulted in it having the lowest phosphorus concentration. However, both TDP and orthophosphate showed sharp decreases in all the groups, especially in the first 5 days.

Large increases in the biomass density of *M. aeruginosa* were observed in accordance with the changes in phosphorus levels (Fig. 3c, f, i). There were highly significant effects of organic phosphorus type (two-way ANOVA: $p < 0.001$) and their initial concentrations ($p < 0.001$) on the growth of *M. aeruginosa*. Furthermore, the interaction between organic phosphorus types and the initial concentrations was highly significant ($p < 0.001$). The post hoc Tukey test indicated that the effect of organic phosphorus type was most evident in the β-glycerophosphate-treated group, which had a higher Chl *a* concentration than the ATP- and lecithin-treated groups. For example, the Chl *a* concentration of group 1 in the β-glycerophosphate treatment reached 47.2 μg L^{-1} on day 10, while it was only 19.3 and 25.3 μg L^{-1} for the ATP- and lecithin-treated groups, respectively (Fig. 3c, f, i). The effect of initial phosphorus concentration was most evident for high initial phosphorus concentrations such as 50 and 25 mg L^{-1}, which induced significantly higher Chl *a* concentration of *M. aeruginosa* than low initial phosphorus concentrations (Fig. 3c, f, i). No significant differences (all $p > 0.05$) in Chl *a* concentration were detected between the low initial phosphorus concentrations of 2.5–15 mg L^{-1}, which was probably caused by the small difference in orthophosphate concentration (~1 mg L^{-1}). Again, it indicated that orthophosphate was the main bioavailable phosphorus fraction for algal growth (Wu et al. 2011). Furthermore, from day 15 to 20, the Chl *a* concentration decreased in most cases (Fig. 3c, f, i), which is likely due to the inhibition of *M. aeruginosab* growth by nutrient depletion and oxygen increase in the water (Zhao et al. 2012).

Relationships between phosphorus release from sediment and cyanobacterial blooms

As the phosphorus sink in Dianchi Lake, the sediment has accumulated a great amount of phosphorus (~1.8 mg g^{-1}, Fig. 1b). The sediment has become a phosphorus source and can release phosphorus into the overlying water under suitable conditions and prolong eutrophication. For example, changes in pH, dissolved oxygen, temperature, and hydraulic disturbance can all affect the phosphorus release process from sediment into overlying water (Jin et al. 2006; Kim et al. 2004; Qiu and McComb 1994).

Table 2 The correlation matrix between Chl *a* and different phosphorus fractions of the lake sediment

Correlation coefficient	TP	Ex-P	Fe/Al-P	Ca-P	Org-P	Chl *a*
TP	1.00					
Ex-P	0.03	1.00				
Fe/Al-P	0.77*	0.04	1.00			
Ca-P	0.97**	0.01	0.76*	1.00		
Org-P	0.94**	−0.10	0.52	0.91**	1.00	
Chl *a*	0.07	0.90**	0.32	0.05	−0.17	1.00

*$p < 0.05$, **$p < 0.01$

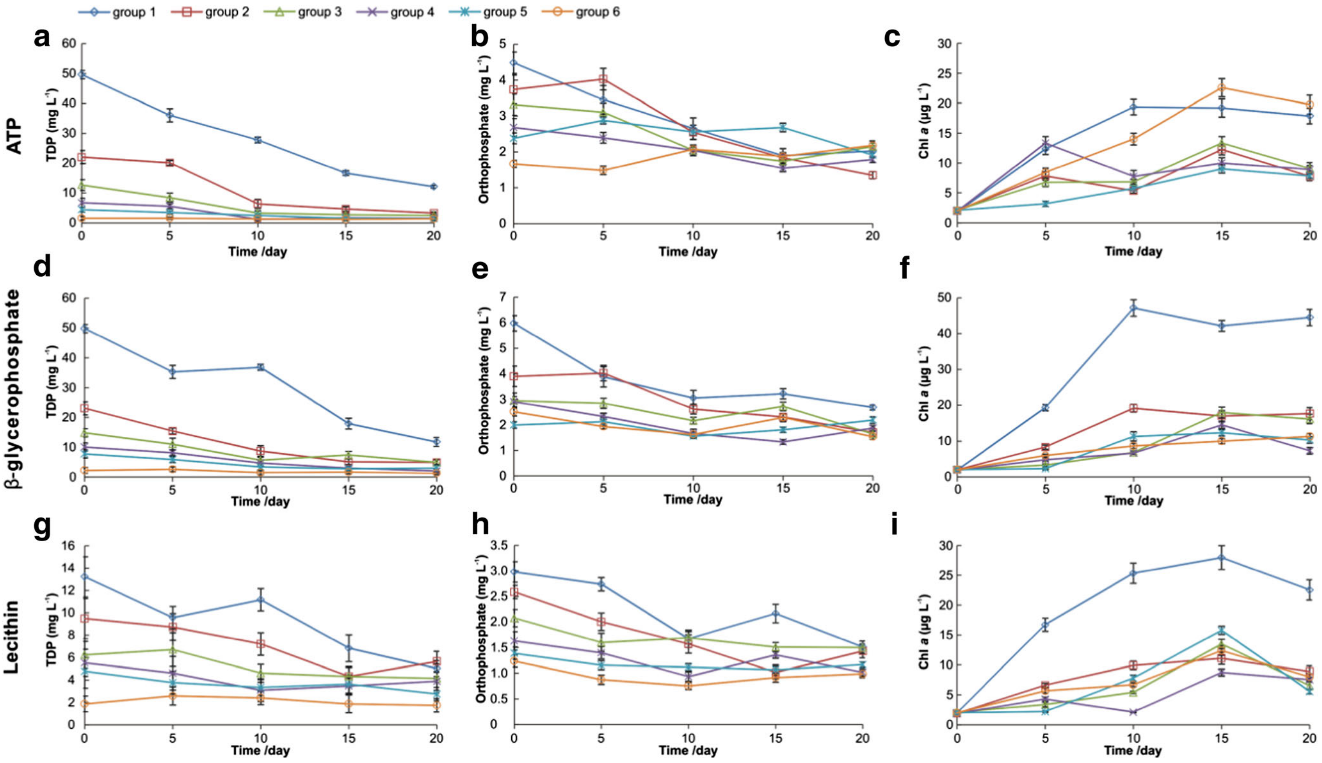

Fig. 3 **a**–**c** Changes in total dissolved phosphorus (*TDP*), orthophosphate, and Chl *a* in the water using ATP as phosphorus source. **d**–**f** Changes in total dissolved phosphorus (*TDP*), orthophosphate, and Chl *a* in the water using β-glycerophosphate as phosphorus source. **g**–**i** Changes in total dissolved phosphorus (*TDP*), orthophosphate, and Chl *a* in the water using lecithin as phosphorus source

In this simulated lake microcosm, all phosphorus fractions (except Ca-P) of the sediment in Dianchi Lake can be released into the overlying water and assimilated by algae. Release of phosphorus from sediment to the overlying water is a physical diffusion process from high to low concentration in the water column, resulting in a significantly higher phosphorus concentration in the bottom layer than the top. Among the various phosphorus fractions, Fe/Al bound phosphorus is the predominant fraction released from sediment into overlying water and had a positive, non-significant correlation ($R^2 = 0.32$) with Chl *a* concentration (Table 2).

Many organic phosphorus compounds, including ATP, ADP, CMP, UMP, glucose phosphates, and sodium glycerophosphate, are bioavailable and can be utilized by algae in the presence of alkaline phosphatase (Hong et al. 1995; Zhou et al. 2008). Moreover, the bacterium *Pseudomonas putida* can transform various phosphorus fractions into orthophosphate and enhance the growth of *M. aeruginosa* (Du et al. 2012). This study indicates that the utilization of organic phosphorus by *M. aeruginosa* is highly dependent on the amount of organic phosphorus transformed into orthophosphate. Thus, organic phosphorus is less likely to cause *M. aeruginosa* blooms. Therefore, the biogeochemical cycles of phosphorus are important nutrient self-regulating processes in eutrophic lakes (Zhu et al. 2013).

Conclusions

The sediment of Dianchi Lake has a TP content of 1.7–1.8 mg g^{-1} with Ca-P and Org-P as the predominant fractions with 50–54 and 28–32 %, respectively. The sediments released 8 % of TP into the overlying water with Fe/Al-P (26 %) and Org-P (65 %) being the main fractions released. The overlying water showed a phosphorus diffusion gradient with the bottom layer having higher phosphorus concentrations than the top layer. The biomass density of *M. aeruginosa* showed a positive correlation ($R^2 = 0.825$) with the orthophosphate concentration, indicating it is the most bioavailable phosphorus fraction for algal growth. Org-P can be partly utilized by *M. aeruginosa* depending on its transformation into orthophosphate. A good understanding of the biogeochemical cycles of different phosphorus fractions in lake sediments can help develop measures to minimize phosphorus release from lake sediment.

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