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Phosphorus mobility among sediments, water and cyanobacteria enhanced by cyanobacteria blooms in eutrophic Lake Dianchi

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ABSTRACT

This study was focused on the phosphorus mobility among sediments, water and cyanobacteria in eutrophic Lake Dianchi. Four conditions lake water, water and algae, water and sediments, and three objects together were conducted to investigate the effects of cyanobacteria growth on the migration and transformation of phosphorus. Results showed a persistent correlation between the development of cyanobacterial blooms and the increase of soluble reactive phosphorus (SRP) in the lake water under the condition of three objects together. Time-course assays measuring different forms of phosphorus in sediments indicated that inorganic phosphorus (IP) and NaOH-P were relatively more easier to migrate out of sediment to the water and cyanobacteria. Further studies on phosphorus mobility showed that up to 70.2% of the released phosphorus could be absorbed by cyanobacteria, indicating that sediment is a major source of phosphorus when external loading is reduced. Time-course assays also showed that the development of cyanobacterial blooms promoted an increase in pH and a decrease in the redox potential of the lake water. The structure of the microbial communities in sediments was also significantly changed, revealed a great impaction of cyanobacterial blooms on the microbial communities in sediments, which may contribute to phosphorus release. Our study simulated the cyanobacterial blooms of Lake Dianchi and revealed that the cyanobacterial blooms is a driving force for phosphorus mobility among sediments, water and cyanobacteria. The outbreak of algal blooms caused deterioration in water quality. The P in the sediments represented a significant supply for the growth of cyanobacteria.

1. Introduction

Eutrophication and harmful algal blooms are global environmental problems causing by increasing anthropogenic nutrient inputs (Abell et al., 2010; Paerl, 1988; Qin et al., 2010; Smith et al., 1999). Phosphorus (P), needed for nucleic acid synthesis and energy transfer, is one of the key limiting nutrients that contributes to trophic state of a water body and restricts the growth of freshwater algae (Lewis et al., 2011; Schelske, 2009; Schindle, 1974; Sterner, 2008). Numerous of studies focused on algal blooms and water qualities have revealed that growth of algal blooms in eutrophic lakes were often coincident with an increase of P in the water (Osgood, 1988; Pettersson et al., 1993).

As a reservoir for external P and a source of internal P, lake sediments play an important role in P cycles that involve physical, chemical, and biological processes (Christophoridis and Fytianos, 2006; Gachter et al., 1988; Golterman, 2001; Schauser et al., 2006; Tornblom and Rydin, 1998; Xie and Xie, 2002). Although much effort has been made to reduce the external loading of P in lakes, P release from the sediments may act in so intense and persistent manner that it prevents the improvement of water quality (Sondergaard et al., 2003). It is reported that release of P from anoxic sediments in the hypolimnion of a eutrophic reservoir could affect epilimnetic nutrient concentrations (Nikolai and Dzialowski, 2014). Sediment-based P release becomes a major source of water quality deterioration when external loading is reduced (House and Denison, 2002).

On the other hand, many studies revealed that algal blooms have positive feedback on releasing of P from sediment. Enclosure experiment conducted in the hypereutrophic subtropical Lake Donghu showed that dissolved phosphorus released from sediment to lake water could be enhanced by algal blooms (Xie et al., 2003). Therefore, P cycling among the water, sediment and algal blooms became an important research topic.

Cyanobacteria are important primary producers in aquatic

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ecosystems (Conley et al., 2009). Harmful growth of cyanobacteria blooms in eutrophic lakes is often found to be coincident with an increase of P in the water column (Osgood, 1988; Pettersson et al., 1993; Xie and Xie, 2002). Previous studies showed that phosphorus forms were different in Dian Lake between April (before the cyanobacteria bloom) and August (outbreak of the cyanobacteria bloom) (Hu et al., 2007). In order to quantitatively elucidate the P cycling among the water, sediment and cyanobacteria blooms, we collected samples from Dian Lake and conducted a controlled simulation experiment. The objective of this study was to answer the following questions: (1) Does the utilization of P by cyanobacterial blooms drive the migration of bioavailable P? (2) If so, what is the quantitative relationship between phosphorus in the cyanobacteria, the water, and the sediment.

2. Materials and methods

2.1. Experimental design

Lake Dianchi (24° 40′–25° 02′ N, 102° 36′–103° 40′ E) is a plateau lake located in Kunming City, the capital of Yunnan province. Lake Dian chi covers an area of 330 km^2, with a mean depth of 5 m and surface elevation of 1886 m. The area used to be known as the "Pearl of the Highland" because of its picturesque scenery. However, Lake Dianchi is now one of China's most serious cases of freshwater lake eutrophication. It has been seriously contaminated with various pollutants, and approximately 90% of Kunming City's wastewater is been poured into the lake. Currently, cyanobacterial blooms occur annually over the whole lake (Huang et al., 2014).

Based on our unpublished data from monitoring the entire Dianchi Lake, we found a location that had high nutrients concentrations in the surface sediments and low nutrients in the overlying water column. The sediment sampling location was in the middle of Lake Dianchi near Guanyin Mountain (24° 50.010′ N, 102° 42.323′ E), an area that had little cyanobacteria in the overlying water. On July 3, 2015, before cyanobacterial blooms, the top 15 cm of the sediment was collected using a sediment core sampler (Perrson MY-052, Mingyu Technology). Several samples were taken from each position and the sampling procedure was repeated several times. After homogenization, all samples were kept in the portable refrigerator and delivered to the laboratory immediately. In addition, all the environmental factors of interest were recorded at the scene.

Four conditions were set for the control experiment. The first (W), included only lake water, and represented the blank control group. The second condition (AW), was 24 L of lake water inoculated with *Microcystis aeruginosa* (biomass assessment indicators, $OD_{680} = 0.02$), representing the driving potential of cyanobacterial blooms but not including a sediment supply. The third condition (SW), included sediments plus 24 L of lake water, representing the absence of cyanobacterial blooms. The fourth condition (SWA) was sediments plus 24 L of lake water inoculated with cyanobacteria ($OD_{680} = 0.02$), representing the general situation of the lakes. SWA and AW showed that the existence of sediments contributed to the growth of cyanobacteria. SWA represented the combined effect of lake water and sediments, which promoted cyanobacterial growth, while AW represented the effect of lake water alone. The influence of the sediment was reflected in the difference between the results from SWA and from AW. All the large simulation reactors (22 cm high, 40 × 50 cm) were made from polymethyl methacrylate, and were placed in a light incubator. The temperature was controlled at 25 °C. The ratio of light to dark was 12: 12 h, with light provided from 8:00 a.m. to 8:00 p.m. every day. The light intensity was 25,000 lux. In the incubation experiments, 500 g of fresh sediment was spread evenly into the bottom of the simulation reactors. Then 24 L of filtered lake water was added to each container as slowly as possible to minimize suspension of sediments. After 24 h, living *Microcystis aeruginosa* that had been starved (no-phosphorus starvation medium) for two days was added to the lake water ($OD_{680} = 0.02$). The base of each reactor formed a 2000 cm^2 rectangle, containing a 3-cm layer of sediment below 12 cm of water, to simulate the depth ratio of sediment to water in Lake Dianchi (4:1). The bottom of the reactors was shaded with black material to block external light.

The overlying water samples and pore water samples were collected with special sampling apparatus (Rhizons MOM) from the water column 1 cm above, and from 1 cm below, the solid/liquid interface. Three water samples were collected each time, and these were taken every two days. Transparent film was used to cover the top of the equipments to prevent evaporation. The sediment samples were collected using a modified pipetting device. We sampled the sediment 2-cm deep on Days 0, 3, 5, 9, 11, 15, 21, 25 and 29. To make sure the sediment samples were homogeneous, nine samples of sediment at different sites were collected and mixed on each sampling occasion. On Day 1, 5, 9, 15, 21 and 29, a 0.5-cm sample of surface sediment was collected and stored in a freezer at −80 °C for later microbe analysis. Throughout the process, all samples were kept stationary. The large capacity reactor and light incubator allowed environmental factors to be set (e.g., temperature, light, dissolved oxygen, etc.), which controlled the release of phosphorus from the sediment. When the temperature, light, and oxygen were controlled, the pH and redox potential were the most important environmental factors. These were detected in situ using a Multi-Parameter Water Quality Instrument (YSI6600, USA). The pH and redox potential of the overlying water were measured 1 cm above the sediments. The pH and redox potential of the pore water were monitored after pore water samples were collected using a Rhizons MOM. When observed, small numbers of zooplankton were removed by pipetting to avoid potential effects on cyanobacterial recruitment.

2.2. Analytical methods

For water samples, the SRP concentration was determined using the molybdenum blue method, after filtering through a 0.45-mm membrane. The TP concentration was analyzed using the molybdenum blue colorimetric method after digestion with $K_2S_2O_8$ to orthophosphate.

For sediment samples, the pretreatment methods included freeze drying for five days and grinding through a 100-mesh sieve. Then the sediments were sampled using SMT methods (Ruban et al., 2001). It was determined that the following five forms of phosphorus were present: total P, inorganic P (IP), organic P (OP), NaOH-P (Fe/Al–P, P bound to Al, Fe, and Mn oxides and hydroxides), and HCl-P (Ca–P, P associated with apatite). The P concentration in the filtrate was analyzed using the molybdenum blue method.

For algal samples, the concentration of chlorophyll *a* (Chl-a) was measured using Winterma's method (Winterma and Demots, 1965). The intracellular total dissolved phosphorus (intracellular TDP) concentration was analyzed using the molybdenum blue method. This was done after digestion of a clean, centrifuged sample of algae with $K_2S_2O_8$. The relationship between the Chl-a and SRP in the overlying water was analyzed using Statistic Package for Social Science software.

The mobility mechanisms for phosphorus under the four conditions (intracellular phosphorus, the overlying water, the pore water, and the sediment) were summarized by the differential integral method. This method is based on changes in the phosphorus concentration over the whole cyanobacterial bloom cycle from occurrence to disappearance. The accumulation of phosphorus was

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