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Nitrogen exchange across the sediment-water interface after dredging: The influence of contaminated riverine suspended particulate matter☆

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ABSTRACT

Dredging has been widely implemented in shallow lakes to reduce internal nitrogen (N) loading. The suspended particulate matter (SPM) coming from polluted rivers usually contains high levels of N and ultimately deposits on the dredged sediment surfaces near the river mouth. To study the influence of the riverine SPM on N exchange across the sediment-water interface (SWI) after dredging, a 360-day experiment was carried out comparing un-dredged and dredged sediments from Lake Chaohu, China. Dredged treatments showed a significant increase ($p < 0.01$) in total N concentrations in the sediments, while the deposition of SPM had little influence on labile NH_4^+-N concentrations. In addition, NH_4^+-N concentrations in pore-water and NH_4^+-N fluxes were significantly lower in dredged than in un-dredged sediments, despite the deposition of SPM. The oxygen production rates and the oxygen penetration depth in the dredged sediments were both higher than those in the un-dredged sediments. The increase of *Nitrospira* in dredged sediments was consistent with their decreased NH_4^+-N concentrations and fluxes across the SWI. Therefore, the oxidizing condition, increased oxygen production/consumption rates and *Nitrospira* relative abundance across the SWI were believed to be correlated with the low N exchange rates in dredged sediments. Dredging for reducing internal N loading in a river mouth area is therefore feasible, although the influence of the riverine SPM should be taken into account when aiming to achieve a long-term internal N loading reduction.

1. Introduction

Nitrogen (N) is suggested to be one of the limiting elements for eutrophication and phytoplankton growth (Conley et al., 2009; Howarth and Marino, 2006). A previous study in Lake Taihu, China (Xu et al., 2010) revealed it was the primary regulator of phytoplankton growth during algal blooming seasons. In aquatic environments, excessive N is usually concentrated in the suspended particulate matter (SPM) due to plankton debris (Suzumura et al., 2004). Most SPM is deposited on the sediment, which becomes the internal source of N (Fan et al., 2002; Nowlin et al., 2005), and this increased N loading in the sediment promotes the growth of harmful algae and aggravates algal blooms (Orihel et al., 2013). Therefore, controlling and reducing internal N loading is crucial for managing lakes' eutrophication.

Several techniques, including capping (Huang et al., 2011; Pan et al., 2012), phytoremediation (Gu et al., 2016; Toyama et al., 2016), and environmental dredging (Liu et al., 2015, 2016b), have been evaluated and applied to reduce internal N loading. Despite the controversy around its positive and negative effects (Annadotter et al., 1999; Zhong et al., 2010), environmental dredging is still widely used to reduce internal N loading, as it is an efficient way to remove contaminated sediment from lakes. Dredging has been implemented in various eutrophic lakes in China, including the highly concerning Lake Taihu (Cao et al., 2007; Liu et al., 2016b), Lake Chaohu (Kong et al., 2013; Liu et al., 2015), and Lake Dianchi (Sha et al., 2012). Our previous studies in Lake Chaohu (Liu et al., 2015) and Lake Taihu (Liu et al., 2016b) revealed

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that environmental dredging (under appropriate depth) effectively controlled internal N release from the sediment. However, the remarkable increase in internal N loading after dredging with time was also depressing (Liu et al., 2016b). The reduction in external pollution loading after dredging was likely contributed to the control of internal N and phosphorus (P) loading (Liu et al., 2016b; Ruley and Rusch, 2004). Our previous study focusing on internal P loading after dredging (Liu et al., 2016a) showed that contaminated riverine SPM played a key role in increasing internal P loading after dredging. In other words, contaminated riverine SPM might be a key external pollution element affecting dredging outcomes. However, there is limited information whether SPM significantly affects the post-dredging exchange of N across the sediment-water interface (SWI) similar to that observed for P, or not.

The present study investigated the post-dredging exchanges of N across the SWI under the influence of the riverine SPM for one year, and compared the exchanges of N with those of P in our previous work (Liu et al., 2016a). Ammonium was the element of primary concern because it can be directly used by harmful algae such as cyanobacteria (Glibert et al., 2016), which is the major algal species that causes harmful algal blooms in the large and shallow Lake Taihu and Lake Chaohu (Jiang et al., 2014; Xu et al., 2013). In addition, ammonium is toxic to some aquatic macroinvertebrates (Ankley et al., 1990; Frazier et al., 1996). A river mouth area in Lake Chaohu was chosen as the study site considering its serious pollution status (Zhang et al., 2015) and high sedimentation rate (Tu et al., 1991). Our study was supposed to reveal the relationship between the post-dredging exchanges of N across the SWI and the riverine SPM and to compare it with that of P. Useful information was supposed to be provided for improving environmental dredging projects in similar areas.

2. Materials and methods

2.1. Field sampling

The study area was located at the northwestern bay of Lake Chaohu, which is the fifth largest shallow lake in China and has been subject to hyper-eutrophication for the past decades (Shang and Shang, 2005). The chosen area is most seriously polluted across the entire lake, due to the inflowing urban rivers (Liu et al., 2012), and its sedimentation rate (about 6 mm yr^{-1}) is also the highest (Tu et al., 1991). In January 2014, 150 sediment cores were collected *in situ* from one of the most seriously polluted sites within the study area (31°42′4.76″N and 117°21′43.49″E; Fig. S1) (Liu et al., 2015) using a gravity corer (110 mm diameter × 500 mm length; Rigo Co., Ltd., Saitama, Japan). Given the serious pollution status of the Nanfei River, SPM was monthly sampled at its mouth (31°41′43.88″N and 117°24′19.24″E; Fig. S1), from January 2014 to December 2014, using five 16-channel sediment traps (110 mm diameter × 350 mm length). The collected SPM (Fig. S2) was mixed and preserved in Teflon® bottles at 4 °C and immediately taken to the laboratory where experiments started within 4 h.

2.2. Experimental design

Simulated dredging at 25 cm depth was immediately performed once the cores arrived at the laboratory. According to our previous study (Liu et al., 2015), the internal N loading in the study area was mostly reduced at this dredging depth. Six treatments were implemented during the experiment: (1) U, un-dredged sediment with no addition of SPM; (2) U + DP, un-dredged sediment with the addition of sterile SPM; (3) U + FP, un-dredged sediment with the addition of non-sterile SPM; (4) D, dredged sediment with no addition of SPM; (5) D + DP, dredged sediment with the addition of sterile SPM; and (6) D + FP, dredged sediment with the addition of non-sterile SPM. All of the sediment columns were collected from the same site (section 2.1). Therefore, the starting concentrations of nitrogen and other compounds in the sediment and pore-water of the un-dredged and dredged columns were nearly the same, which can be found in our previous work in the study area (Liu et al., 2015). Fresh SPM was dried at 60 °C for 24 h and then sterilized at 121 °C for 30 min to obtain sterile SPM. Non-sterile and sterile SPM were separately mixed with lake water, and then added to sediment columns according to the monthly sedimentation rate of the area (Tu et al., 1991). All sediment columns were incubated in a water tank filled with *in situ* lake water at ambient temperature. The depth of the overlying water above the sediment was about 70 cm. The water in the tank was replaced with *in situ* lake water monthly. Simultaneously, the collected SPM was added to the column monthly, following the *in situ* sedimentation rate (about 6 mm yr^{-1}) of the studied area (Tu et al., 1991). The pore-water and sediment samples were collected monthly during the experiment. Part of the surface sediment was preserved at −80 °C for DNA extraction on days 0, 90, 180, 270, and 360. In addition, the oxygen profiles across the SWI were also analyzed monthly. Triplicate samples (columns) were collected for each treatment monthly for the experiment. Further details on the experimental conditions can be found on our previous study considering P post-dredging exchanges across SWI (Liu et al., 2016a).

2.3. Chemical and microbial analysis

Total nitrogen (TN) and labile ammonium (NH_4^+-N) in the sediment were extracted using alkaline potassium persulfate (ChineseEPA, 2002) and potassium chloride (Shannon et al., 2011), respectively, and then analyzed with a UV–VIS spectrophotometer (Shimadzu UV-2550, Kyoto, Japan). Total organic carbon (TOC) in the sediment was analyzed using the potassium dichromate volumetric method (ChineseEPA, 2002). The oxygen production/consumption rate (OPR) across the SWI was analyzed, as oxygen consumption across the SWI might accelerate NH_4^+-N dissolution (Brandes and Devol, 1997). A microprofiling system (Unisense, Aarhus, Denmark) with a vertical resolution of 0.05 mm was used to analyze the oxygen distribution across the SWI. According to Rasmussen and Jorgensen (1992), the OPR was calculated based on zero-order kinetics:

$$R = D_s \frac{d^2C}{d^2z} \tag{1}$$

where R stands for OPR (μmol m^{-3} s^{-1}), C stands for oxygen concentration (μmol L^{-1}), z stands for sediment depth, and D_s is the diffusion coefficient of oxygen across the SWI (m^2 s^{-1}). D_s is related to the porosity (φ) of the sediment and was calculated according to the follow formula (Berner, 1980; Boudreau, 1996):

$$D_s = \frac{D_0}{1 - 2\ln\varphi} \tag{2}$$

where D_0 is the theoretical oxygen diffusion coefficient across the SWI, which is related to the temperature (Boudreau, 1997; Schulz and Zabel, 2000).

The profile of NH_4^+-N in the pore water was obtained using mini-peepers with a vertical resolution of 4 mm (Ding et al., 2010). Each peeper had 30 vertically arranged dialysis cells (3 cm length × 0.25 cm width × 0.2. cm thickness), with 0.15 cm space between them (Fig. S3). The content of NH_4^+-N in the pore water was analyzed using Nessler's reagent method (ChineseEPA, 2002). A microtiter plate reader (Biotek Epoch, Winooski, VT, USA) with a

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