



Dynamics of particulate phosphorus in a shallow eutrophic lake



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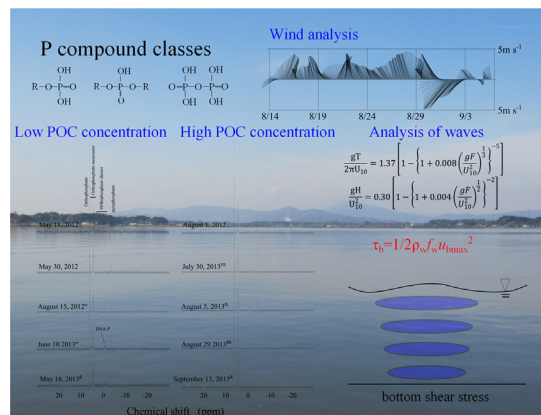
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HIGHLIGHTS

- Biogenic P affected the PP concentration more than did sediment resuspension.
- PP correlated with particulate organic carbon concentration but not wind velocity.
- Mononucleotides accounted for the largest P compound class of organic P in PP.

GRAPHICAL ABSTRACT



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ABSTRACT

We tested the hypothesis that in shallow, eutrophic Lake Kasumigaura, the concentration of particulate phosphorus (PP) is controlled by biogenic P (P in living or dead phytoplankton and bacterial cells), rather than by resuspension of inorganic P in sediment. Increases in wind velocity and turbidity were associated with bottom shear stress exceeding the critical value for the lake ($\tau_c = 0.15 \text{ N m}^{-2}$); this increased turbidity was due to sediment resuspension. However, concentrations of PP; HCl-extractable, reactive P in PP (P-rP); and HCl-extractable, non-reactive P in PP (P-nrP) were not correlated with wind velocity (PP vs. wind velocity: $r = 0.40$, $p > 0.05$). Rather, the P-nrP concentration accounted for approximately 79% of PP, and the concentrations of PP, P-rP, and P-nrP were correlated with the particulate organic carbon (POC) concentration (POC vs. PP: $r = 0.90$, $p < 0.01$; POC vs. P-rP: $r = 0.82$, $p < 0.01$; POC vs. P-nrP: $r = 0.86$, $p < 0.01$). In our ^{31}P nuclear magnetic resonance spectroscopy results, mononucleotides accounted for the largest proportion among the detected P compound classes. In addition, concentrations of mononucleotides, orthophosphate, and pyrophosphate were significantly higher in samples with high POC concentrations, whereas the DNA-P concentration was not. These results suggest that biogenic P affects PP concentrations more strongly than does sediment resuspension, and the production of biogenic P creates a pool of mononucleotides, a class of easily degradable P, even in shallow, eutrophic Lake Kasumigaura.

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1. Introduction

Typically, most phosphorus (P) in lakes is present as particulate forms adsorbed on minerals (Nöges et al., 1999; Selig et al., 2002) or included in phytoplankton and bacterial cells (Hupfer et al., 2004). Particulate P (PP) is often a source of dissolved P in lake water through degradation and release (Niemistö et al., 2011), thereby relieving the P limitation of phytoplankton (Currie and Kalff, 1984) and delaying the recovery of the lake from eutrophication (Søndergaard et al., 2005). In lakes, a variety of factors affect the PP concentration, such as bacterial and phytoplankton uptake (Currie and Kalff, 1984) and sediment resuspension, the latter especially where the water is shallow (Hamilton and Mitchell, 1997). Such processes that affect the PP concentration probably also alter P compound classes (e.g., orthophosphate monoesters and mineral-bound P), which in turn alter the mechanisms of the P supply to the water column [e.g., enzymatic hydrolysis (phosphomonoesterase for orthophosphate monoesters: Feuillade and Dorioz, 1992) and chemical adsorption and release of P on mineral particles due to pH changes (Shinohara and Isobe, 2012)]. To understand the P cycle in the water column, it is necessary to clarify (1) the processes that affect PP concentrations and (2) the resulting compositional changes in P compounds.

In deep water, where substantial sediment resuspension does not occur, microbial cells can be the major component of PP in the water column (e.g., Currie and Kalff, 1984). In such waters, the biogenic production of PP (biogenic P — defined as P in living and dead phytoplankton and bacteria) likely alters PP concentrations and the composition of P compounds. For example, phytoplankton, in particular cyanobacteria, synthesizes polyphosphate when they take up orthophosphate from the water column in excess of their metabolic needs (Kromkamp, 1987; Hupfer et al., 2007). Polyphosphate accounts for a significant proportion of P in the settling seston (Hupfer et al., 2004) and thus significantly affects the compound composition of PP. In contrast, traditional studies of shallow lakes have hypothesized that sediment resuspension is the major driving force affecting PP concentrations; wind-induced sediment resuspension increases PP concentrations in shallow lakes, and orthophosphate is adsorbed or released between the resuspended sediment and water column (Dapeng et al., 2011; Wang et al., 2015). If sediment resuspension is occurring, the inorganic P concentration in suspended particles in the lake water usually increases with wind velocity (Shinohara and Isobe, 2010) because the proportion of orthophosphate in bottom sediments is much higher than the proportion in suspended particles (Ishii et al., 2010).

Wind-induced sediment resuspension generally increases the PP concentration in shallow lakes, but even in a shallow lake, the P concentration does not always reflect the wind velocity (e.g., Lake Vest Stadil Fjord; Søndergaard et al., 2003). In such lakes, biogenic P might affect the concentrations and compositions of PP compounds substantially more than sediment resuspension. For example, in Lake Kasumigaura, a shallow and hypereutrophic lake in Japan, when phytoplankton production is high in summer (Tomioka et al., 2008, 2011), the proportion of organic P in PP is also greater than that of inorganic P (at the center of Lake Kasumigaura: orthophosphate and pyro/polyphosphate, 36.6%; orthophosphate monoesters and diesters, 63.4%; Shinohara et al., 2012). This result implies that most PP is composed of biogenic P through uptake of dissolved P by phytoplankton and bacteria rather than of inorganic P supplied by sediment resuspension. Such differences in the processes affecting the PP concentration, production of biogenic P or sediment resuspension, must be directly reflected in the compound composition of PP. Furthermore, detailed analysis of the compounds (classes) of PP can more specifically clarify the degradability of the PP. However, no information currently exists for Lake Kasumigaura about (1) whether sediment resuspension or biogenic production mainly accounts for the PP concentration; and (2) how the P compound composition is affected by the processes that affect the PP concentration.

The purpose of the current study was to answer these questions. To evaluate the effects of sediment resuspension, we first analyzed turbidity, recorded from July to September 2012. Because sediment resuspension can occur when the bottom shear stress caused by waves exceeds a critical shear stress value (e.g., Kleeberg et al., 2013), we analyzed turbidity and the bottom shear stress due to waves to ascertain whether waves induce sediment resuspension and turbidity in Lake Kasumigaura. We next analyzed HCl-extractable, reactive P (P-rP) and non-reactive P (P-nrP) concentrations in PP in summer (Aspila et al., 1976; Suzumura et al., 2004) and identified the factors affecting the concentrations [wind velocity, bottom shear stress, water temperature, pH, particulate organic nitrogen (PON), and particulate organic carbon (POC)]. Finally, P compound classes were more specifically identified by means of solution ^{31}P nuclear magnetic resonance (NMR) spectroscopy. Several operationally defined P fractions have been suggested to comprise PP in suspended particles [e.g., NaOH-extractable bioavailable P (Dorich et al., 1985) and sequential P extraction (Penn and Auer, 1997)]; previously used analysis techniques have identified mostly inorganic P, but the current study required identification of organic P compound classes. Not only does ^{31}P NMR distinguish P compound classes among inorganic (orthophosphate, pyrophosphate, and polyphosphate) and organic P compound classes (orthophosphate monoesters, orthophosphate diesters, and phosphonates; Cade-Menun and Preston, 1996; Cade-Menun et al., 2006), it also provides information on the degradability of PP. In Lake Kasumigaura, for example, ^{31}P NMR spectroscopy demonstrated that mononucleotides and pyrophosphate are degraded between surface water and sediment (Shinohara et al., 2012); that analysis also found that orthophosphate accounted for 74.4% of the extractable P in sediment. In this study, we compared the concentrations of the detected P compound classes along with the processes affecting the PP concentrations. We hypothesized that biogenic P in living or dead phytoplankton and bacterial cells controls the concentration of PP rather than inorganic P through sediment resuspension.

2. Methods

2.1. Lake Kasumigaura study site

Lake Kasumigaura is the second largest lake in Japan, with an area of 171 km², a mean depth of approximately 4 m, and a maximum depth of 7.4 m (Fig. 1). Because of extremely high loading of organic matter and nutrients, the lake is eutrophic; the annual mean concentrations of total nitrogen (TN) and total P (TP) in 2010 were 1.1 and 0.12 mg L⁻¹, respectively. These values are much higher than Japanese environmental water quality standards (TN < 0.4 mg L⁻¹ and TP < 0.03 mg L⁻¹). Surface sediment in Lake Kasumigaura includes a large proportion of orthophosphate, as shown by ^{31}P NMR spectroscopy (>65%; Shinohara et al., 2012; Fig. S1). Previously, this lake was brackish, but the intrusion of seawater has been blocked so that its water can be used for drinking water and agriculture. As a result, the lake water has been fresh since the 1960s.

We collected water samples at a single sampling point approximately 3 m away from the breakwater near our laboratory (Lake Kasumigaura Water Research Station) during the summers of 2012 and 2013. We selected this sampling station because it is located in the downwind region of typical winds above Lake Kasumigaura: east–northeast or south–southeast wind. Because of long fetch lengths, the wind often raises high waves at the station, so we regarded the location as appropriate for monitoring sediment resuspension by waves. Because spectral analysis showed that wind velocity at the sampling site has a 24-h period (Shinohara and Isobe, 2010, 2012) and wind velocity is strongest above Lake Kasumigaura during 15:00–18:00 local time (LT), we collected most water samples within that time period. In addition, we sometimes collected water samples in the morning (8:00 LT) or at noon (12:00 LT), when conditions were calm. The water depth at the sampling site was approximately

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