Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for the Eastern Basin of Goose Lake, MN

Goose Lake, MN
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OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled anaerobic conditions and to quantify biologically-labile (i.e., subject to recycling) and refractory (i.e, more inert and subject to burial) P fractions for sediment collected in the eastern basin of Goose Lake, Chisago County, MN.

APPROACH

Laboratory-derived rates of P release from sediment under anaerobic conditions: Sediment cores were collected by Wenck Associates, Inc. from a centrally-located station in the eastern basin in August, 2014, for determination of rates of P release from sediment under anaerobic conditions. Cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling nitrogen (anaerobic conditions, 3 replicates) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment (mg/m^2 d) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Sediment chemistry: The upper 10-cm section of an additional sediment core was analyzed for moisture content (%), sediment density (g/cm^3), loss on ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, aluminum-bound P, calcium-bound P, labile and refractory organic P, total P, and total iron (Fe; all expressed at mg/g). A known volume of sediment was dried at 105 ^oC for determination of moisture content and sediment density and burned at 550 ^oC for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total P and Fe using standard methods (Anderson 1976, APHA 2005 method 4500 P.f., EPA method 3050B).

Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), sodium hydroxide-extractable P (i.e., aluminum-bound P), and hydrochloric acid-extractable P (i.e., calcium-bound P; Table 1). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P. Refractory organic P was estimated as the difference between total P and the sum of the other fractions.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that result in desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fractions represent redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The sum of redox-sensitive P and labile organic P collectively represent biologically-labile P. This fraction is generally active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound, calcium-bound, and refractory organic P fractions are more chemically inert and subject to burial rather than recycling.

RESULTS AND INTERPRETATION

P mass and concentration increased approximately linearly in the overlying water column of sediment systems maintained under anaerobic conditions (Figure 1). Linear increases in P concentration between day 2 and 11 were used in rate calculation. The mean P concentration maximum in the overlying water end of the incubation period was moderate at 0.362 mg/L (± 0.057 standard error; SE; Table 2). The mean rate of P release under anaerobic conditions was also moderate at 2.39 mg/m^2 d (± 0.28 SE; Table 1) but indicative of mesotrophic to eutrophic conditions (Nürnberg 1988). The anaerobic P release rate for the southern basin of Goose Lake was similar at 2.0 mg/m^2 d. Compared to other lakes in the region, the anaerobic P release rates for Goose Lake sediments fell below the 25% quartile (Figure 2).

Sediment moisture content was moderately high, while wet and dry bulk densities were low, suggesting flocculent sediment with high porosity (i.e., interstitial spaces for porewater; Table 3). Organic matter content was very high at ~45% (Table 3).

The sediment total P concentration was relatively high in eastern basin sediments (Table 4), and fell above the 75% quartile compared to other lakes in the region (Figure 3). Biologically-labile P (i.e., subject to recycling back to the overlying water column; loosely-bound P, iron-bound P, and labile organic P) accounted for ~47% of the sediment total P concentration (Table 4). Labile organic P was the dominant biologically-labile P fraction at ~ 50% (Figure 4 and Table 5). Loosely-bound and iron-bound P represented ~15% and 35% of the biologically-labile P, respectively (Figure 4 and Table 5). The loosely-bound P and labile organic P concentrations were high compared to other lakes in the region (Figure 3). In contrast, the iron-bound P concentration was at the median.

Biologically-refractory P (i.e., aluminum-bound, calcium-bound, and refractory organic P), which is more inert and subject to burial rather than recycling, accounted for ~ 53% of the sediment total P (Table 4). Calcium-bound P dominated the biologically-refractory P pool at ~58% (Figure 4 and Table 5). In addition, the concentration of calcium-bound P was very high relative to other lakes in the region (Figure 3). Aluminum-bound P and refractory organic P each represented ~ 21% of the biologically-refractory P (Figure 4 and Table 5). Generally, Al-P and Ca-P minerals have low solubility products and do not contribute substantially to diffusive P flux from sediment. Total P and concentrations of biologically-labile and refractory P fractions were similar to those measured in the southern basin of Goose Lake.

The total Fe concentration was moderately high at ~ 23 mg/g resulting in a moderately high Fe:P ratio of 15:1 (Table 6). Ratios greater than 10:1 to 15:1 have been associated with regulation of P release from sediments under oxic (aerobic) conditions due to efficient binding of P onto iron oxyhydroxides in the sediment oxic microzone (Jensen et al. 1992). Complete binding efficiency for P at these higher relative concentrations of Fe are suggested explanations for patterns reported by Jensen et al. At lower Fe:P ratios, Fe binding sites become increasingly saturated with P, allowing for diffusion of excess porewater P into the overlying water column, even in the presence of a sediment oxic microzone.

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Table 1. Sediment sequential phosphorus (P) fractionation scheme, extractants used, and definitions of recycling potential.

Variable	Extractant	Recycling Potential
Loosely-bound P	1 M Ammonium Chloride	Biologically labile; Soluble P in interstitial water and adsorbed to $CaCO_3$; Recycled via direct diffusion, eH and pH reactions, and equilibrium processes
Iron-bound P	0.11 M Sodium Bicarbonate-dithionate	Biologically labile; P adsorbed to iron oxyhydroxides (Fe(OOH); Recycled via eH and pH reactions and equilibrium processes
Labile organic P	Persulfate digestion of the NaOH extraction	Biologically labile; Recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells
Aluminum-bound P	0.1 N Sodium Hydroxide	Biologically refractory; Al-P minerals with a low solubility product
Calcium-bound P	0.5 N Hydrochloric Acid	Biologically refractory; Represents Ca-P minerals such as apatite with a low solubility product
Refractory organic P	Determined by subtraction of other forms from total P	Biologically refractory; Organic P that isresistant to bacterial breakdown

Table 2. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under aerobic and anaerobic conditions for sediments collected in the eastern basin of Goose Lake.

Station	Diffusive P Flux	
	Anaerobic	
	($mg\ m^{-2}\ d^{-1}$)	(mg/L)
East basin	2.39 (0.28)	0.362 (0.057)

Table 3. Textural characteristics for sediments collected in the eastern basin of Goose Lake.

Station	Moisture Content (%)	Wet Bulk Density (g/cm^3)	Dry Bulk Density (g/cm^3)	Loss-on-ignition (%)
East basin	93.6	1.022	0.066	44.9

Table 4. Concentrations of sediment total phosphorus (P), redox-sensitive P (Redox P; the sum of the loosely-bound and iron-bound P fraction), biologically-labile P (Bio-labile P; the sum of redox-P and labile organic P), and refractory P (the sum of the aluminum-bound, calcium-bound, and refractory organic P fractions) for sediments collected in the eastern basin of Goose Lake. DW = dry mass.

Station	Total P	Redox P		Bio-labile P		Refractory P	
	(mg/g DW)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)
East basin	1.503	0.352	23.4%	0.704	46.8%	0.798	53.1%

Table 5. Concentrations of biologically labile and refractory P for sediments collected in Goose Lake. DW = dry mass, FW = fresh mass.

Station	Redox-sensitive and biologically labile P				Refractory P		
	Loosely-bound P (mg/g DW)	Iron-bound P (mg/g DW)	Iron-bound P (ug/g FW)	Labile organic P (mg/g DW)	Aluminum-bound P (mg/g DW)	Calcium-bound P (mg/g DW)	Refractory organic P (mg/g DW)
East basin	0.108	0.244	15	0.352	0.165	0.46	0.173

Table 6. Concentrations of sediment total iron (Fe) and the Fe:P ratio for sediments collected in the eastern basin of Goose Lake. DW = dry mass.

Station	Total Fe (mg/g DW)	Fe:P
East basin	22.90	15.2

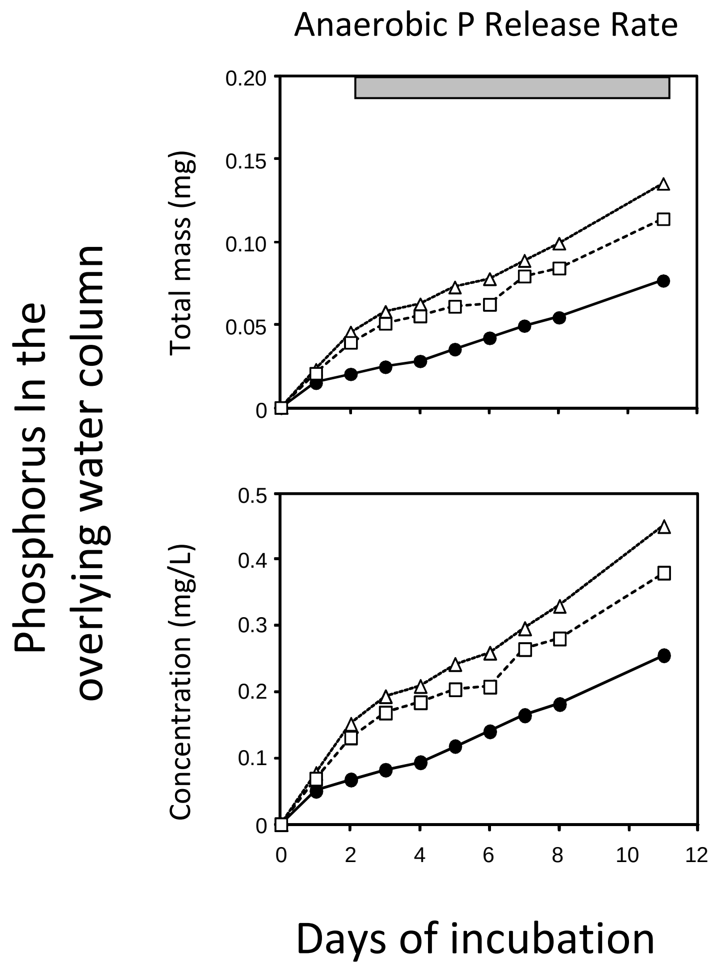

Figure 1. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anaerobic conditions versus time for sediment cores collected in the eastern basin of Goose Lake. Gray horizontal bar denotes the time period used for rate estimation.

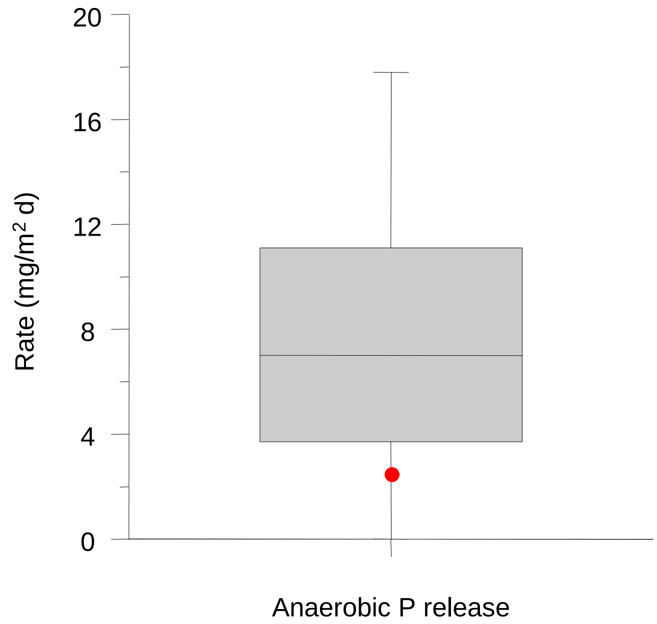

Figure 2. Box and whisker plot comparing the anaerobic phosphorus (P) release rate measured for the eastern basin of Goose Lake (red circle) with statistical ranges for other lakes in Minnesota.

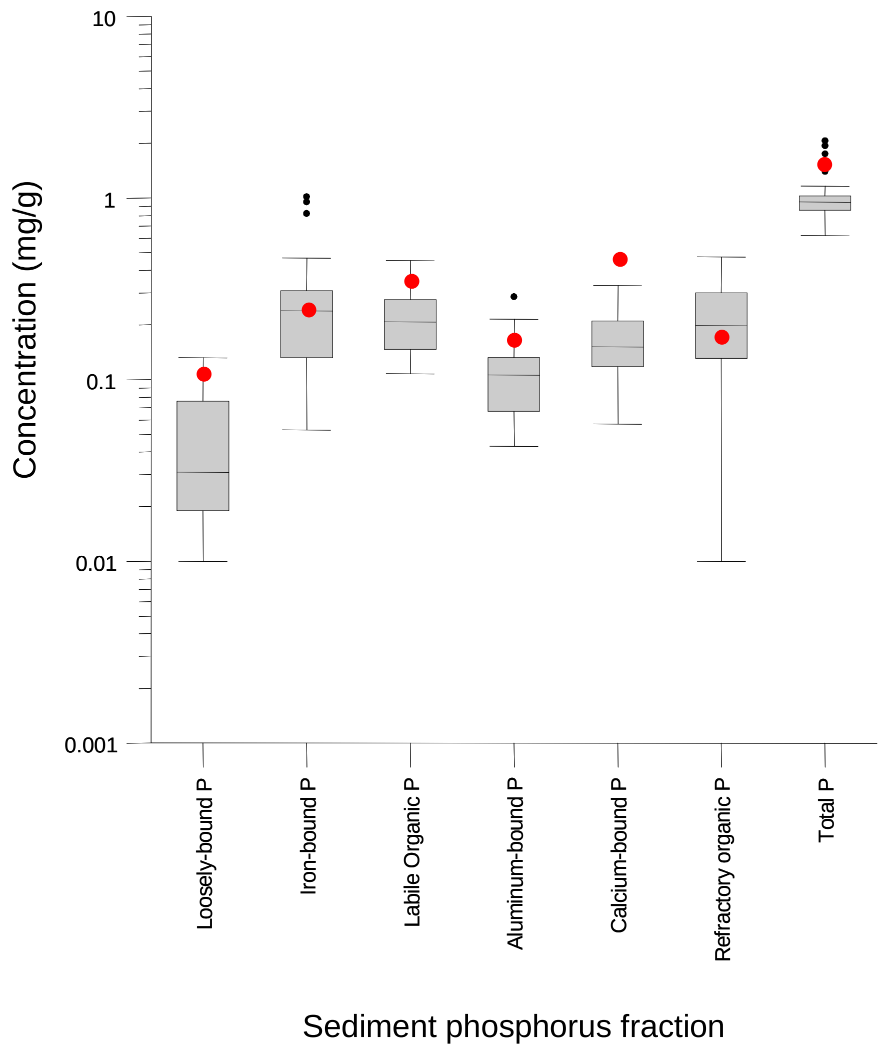

Figure 3. Box and whisker plots comparing various sediment phosphorus (P) fractions measured for sediment collected in the eastern basin of Goose Lake, MN, with statistical ranges for other lakes in Minnesota. Loosely-bound, iron-bound, and labile organic P are biologically-labile (i.e., subject to recycling) and aluminum-bound, calcium-bound, and refractory organic P are more are more inert to transformation (i.e., subject to burial). Please note the logarithmic scale.

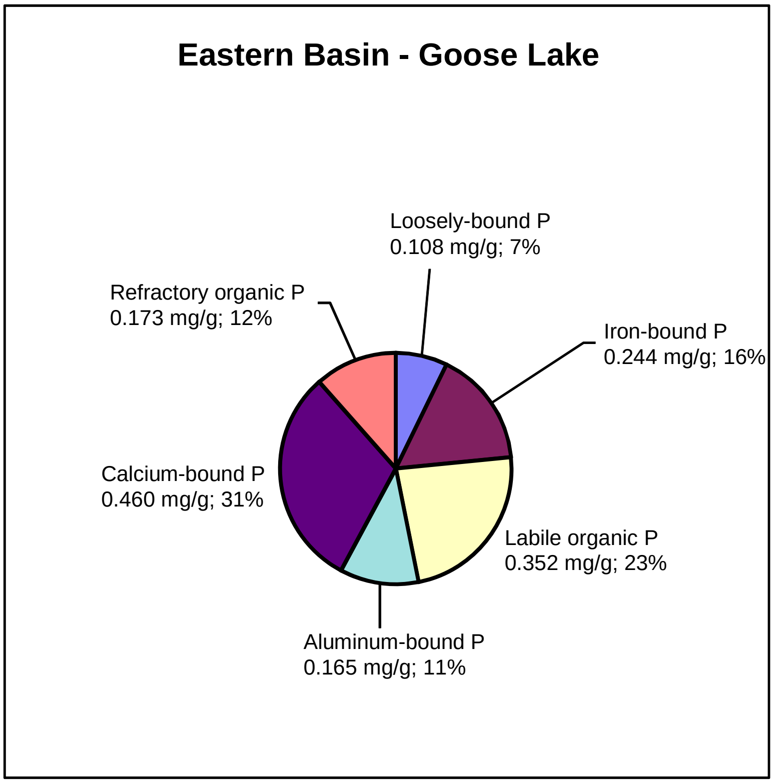

Figure 4. Composition of biologically-labile phosphorus (P) in the upper 10-cm surface sediment layer of the eastern basin of Goose Lake. Loosely-bound, iron-bound, and labile organic P are biologically reactive (i.e., subject to recycling). Values next to each label represent concentration ($mg \cdot g^{-1}$) and percent of the biologically-labile P concentration, respectively.