Phosphorus removal by ponds receiving polluted water from non-point sources

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Abstract

Phosphorus discharged into the water column of lakes, streams, reservoirs, and ponds is either assimilated by algae or retained by the sediment. A laboratory study was conducted using intact sediment-water columns obtained from three ponds to measure their capacity to assimilate P. Phosphorus retention by these systems was determined at two P levels (2 and 10 mg P L⁻¹ or equivalent to an area loading of 26 and 130 µg cm⁻²). The potential P removal rates were 20.4, 28.8 and 30.8 µg P cm⁻² day⁻¹ for PSF (pond adjacent to septic fields), P(J(pond adjacent to a pasture), and PAF (pond adjacent to agricultural farm land), respectively. Longer residence time was needed for P removal at high P loading (10 mg P L⁻¹) than at low P loading (2 mg P L⁻¹). At high P loading, 76–82% of the floodwater P was removed within 10 days. All sediments showed a greater sorption capacity under reduced conditions than under oxidized conditions. At the P levels evaluated, pond sediments functioned as net sinks for water column P.

Introduction

Wetland soils and shallow reservoirs and ponds have been used to reduce the nutrient levels of wastewater effluents (Turner et al. 1976, Boyt et al. 1977, Tilton and Kadlec 1979, Reddy and Graetz 1981). Phosphorus removal by shallow ponds or reservoirs is dependent on the concentration of soluble P in the water discharged into ponds, the concentration of soluble P in the overlying water column of the pond or reservoir, pH, the interstitial P concentration of the underlying sediment, adsorption/desorption characteristics of the sediments, and numerous other factors, such as light, temperature, available N, and organic carbon (Bostrom et al. 1982). Sediments in ponds or reservoirs may serve as a P source or sink, but the factors that control the direction of P flux between sediments and overlying water have not been clearly identified or quantified.

Phosphate adsorption-desorption by the sediment is dependent on ambient pH, porewater P concentration, presence of competing ions and redox potential (Taylor and Kunishi 1971, Li et al. 1972, Kuo and Lotse 1974). Wetland soils and pond sediments are characterized by two distinct soil horizons: aerobic (oxidized) soil at the mudwater interface and an underlying anaerobic (reduced) soil. The oxidized layer is differentiated by a reddish brown color developed as a result of ferric iron (Patrick and Mahapatra 1968). Patrick and Khalid (1974) showed that P retention was greater under anaerobic conditions than aerobic conditions in soils with high levels of P additions. Phosphorus retention under anaerobic conditions was
attributed to sorption on amorphous ferrous hydroxide.

In this experiment, we hypothesized that sediments rich in iron would function as effective sinks for P from overlying water. The objectives of the investigation were to determine: 1) the P removal capacity of shallow ponds receiving runoff water from septic tanks and agricultural and pasture lands, and 2) the P adsorption characteristics of underlying sediments under oxidized and reduced conditions.

Materials and methods

Site description

Three ponds used in the study are located in Greensboro, North Carolina, USA. The pond adjacent to septic fields (PSF) received discharges from faulty septic systems. The watershed, with 6 to 8% slope, was covered with fescue grass (Festuca sp.) and had three soil types: Enon fine sandy loam (fine, mixed thermic Ultic Hapludalf); Helena-Sedgefield sandy loam (Clayey, mixed Aquic Hapludult); and Iredell fine sandy loam (fine, montmorillonitic Thermic Typic Hapludalf). The pond surface area was 7376 m² with a mean water depth of 6.1 m. No management practices were administered on this watershed.

The pond adjacent to a pasture (PP) had a surface area of 9547 m² and a mean water depth of 5.5 m. This pond received runoff and seepage from 50 beef cattle (Bos taurus) and 20 dairy cattle from March through November. The watershed was covered with fescue grass and clover (Trifolium sp.) and had 6 to 10% slope. The grazing area was comprised of Enon fine sandy loam and Mecklenburg clay loam (fine, mixed Thermic Ultic Hapludalf).

The third pond (surface area = 7038 m²) adjacent to agricultural farm land (PAF) received runoff and drainage from cropped land. The mean water depth of the pond was 4.6 m. The land was in a corn (Zea mays) – soybean (Glycine max) rotation and bare-fallowed November through February. The slope was 5 to 7% with Enon sandy loam and Mecklenburg clay loam soil.

Sampling and analyses

Triplicate bulk sediment samples (30 cm depth) were collected from each pond in March, 1986. Particle size was determined by the hydrometer method (Gee and Bauder 1982). A 2.5 g sediment sample was shaken for 5 min in 25 mL acid solution (0.05 N HCl + 0.025 N H₂SO₄) and suspensions were filtered. The filtered solutions were analyzed for soluble reactive P (SRP) according to Murphy and Riley (1962) and for Al, Fe and Mn by atomic absorption spectrophotometry. Sediment and water pH were measured with an Acumet pH meter. Organic carbon in the sediment was determined by ashing according to Jackson (1965).

Phosphorus removal

Polyvinyl chloride pipes (5 cm ID X 60 cm length) were driven 30 cm deep into the sediment, then withdrawn from the pond after closing the column bottom with a rubber stopper. Duplicate sediment columns were collected from three locations within each pond. Thus, 18 columns were obtained (6 from each pond) and transported to the laboratory. The water above the sediment in each of the columns was replaced with 255 mL (13 cm depth) of floodwater obtained from the respective ponds. All columns were equilibrated for one day. Then, overlying floodwater was spiked with KH₂PO₄ to obtain two final concentrations: 2 mg P L⁻¹ (9 columns, three from each pond) and 10 mg P L⁻¹ (9 columns, three from each pond). On an area basis these loading rates were 26 and 130 μg P cm⁻². In a separate experiment, floodwater samples (without sediment) were also spiked and incubated under the same conditions; each treatment was replicated three times. All columns were incubated in the dark at 28°C for 20 days. A 2 mL sample of floodwater was removed from each column after 0, 1, 3, 5, 10, 15 and 20 days of incubation and analyzed for SRP.
Phosphorus adsorption

Under aerobic conditions, 1 g (oven-dry basis) of sediment (in duplicate) and 20 mL of phosphate solution (in 0.01 M CaCl₂) in known initial concentrations ranging from 0 to 50 mg L⁻¹ plus 3 drops of toluene were added to 50 mL centrifuge tubes and equilibrated under continuous shaking for 24 hr. Under anaerobic conditions, 10 mL distilled water was added to 1 g (oven-dry basis) of sediment and incubated under N₂ atmosphere for two weeks. Following incubation, the floodwater was removed under N₂ atmosphere and treated with phosphate solutions with initial concentrations ranging from 0 to 50 mg L⁻¹. The centrifuge tubes containing the sediment-water complex were purged with N₂ and equilibrated under continuous shaking for 24 hr. After equilibration, both aerobic and anaerobic sediment solutions were centrifuged at 2500 rpm for 15 min. The supernatant liquid was then filtered through 0.45 μm membrane filters. Anaerobic filtrations were performed under oxygen-free conditions. All filtered solutions were analyzed for SRP.

<table>
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<tr>
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<tr>
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<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>Mn</td>
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Fig. 1. Disappearance of floodwater P in the sediment-water columns obtained from three ponds (PSF = pond adjacent to septic fields; PAF = pond adjacent to agricultural farm land; PP = pond adjacent to a pasture).

Results and discussion

Selected characteristics of the pond sediments are presented in Table 1. The sediment pH ranged from 6.0 to 6.6. The PAF sediment had more clay and less sand than the PSF and PP sediments. Water and Mehlich I extractable P was higher in PP than in PSF and PAF sediments, whereas 0.01 M CaCl₂ extractable P was higher in PAF sediment. Higher concentrations of Mehlich I Mn were observed in PAF sediment than in PSF and PP sediments. The concentration of Al was low in all sediments.

Phosphorus was lost rapidly from the floodwater in all systems (Fig. 1). At high P loading (10 mg P L⁻¹), floodwater P reached negligible levels after 15 days, while at low P loading (2 mg P L⁻¹), negligible amounts were found after 5 days. These data indicate that at high P loading, the loss of P in floodwater was due to diffusion of P into the sediment underlying the floodwater. At high P loading, longer residence time was needed for P removal. No significant changes in P concentration were noted when floodwater was incubated without sediment.
Fig. 2. Phosphorus adsorption characteristics of sediments under oxidized (aerobic) and reduced (anaerobic) conditions: (a) PSF = pond adjacent to septic fields, (b) PAF = pond adjacent to agricultural farmland, (c) PP = pond adjacent to a pasture.

After the first day at high P loading, floodwater P concentration decreased from 10 mg P L\(^{-1}\) to 4.8, 5.4 and 6.0 in PP, PAF and PSF sediment columns, respectively. At high P loading, about 76–82% of floodwater P was removed within 10 days of incubation. At low P loading (2 mg P L\(^{-1}\)), floodwater P was removed rapidly, with reductions of 77, 73 and 25% after one day incubation for PSF, PP and PAF sediment-water columns, respectively. Potential P removal rates for these sediment columns were 20.4 ± 1.6, 28.8 ± 5.4 and 30.8 ± 3.0 µg cm\(^{-2}\) day\(^{-1}\) for PSF, PP and PAF. The SRP concentration selected for spiking in the floodwater was comparable to those observed under field conditions. In a one year study, Reddy et al. (1986) measured SRP concentrations in the water column of these ponds to be in the range of 1.8–5.3 mg L\(^{-1}\). At these concentrations, it is likely the sediments are functioning as net sinks for water column P. The mechanisms of P removal in this system were (1) diffusion from floodwater into underlying sediment, and (2) P adsorption by the sediment.

Phosphorus adsorption isotherms were used to assess the capacity of the sediment columns to remove floodwater P. All sediments showed higher adsorption under reduced conditions than oxidized conditions (Fig. 2a–c). Pond sediments contained appreciable amounts of P in labile forms (Table 2) as determined by P released into solution in the treatments where no external P was added. This high labile P in pond sediments was due to high P loadings (SRP concentrations in the pond water were in the range of 1.8–5.3 mg P L\(^{-1}\)), resulting in a high equilibrium P concentration (EPC) in the sediment. The EPC is defined as the concentration of P in solution where adsorption equals desorption (Logan, 1982). The ratio between P sorbed and P in solution represents phosphate adsorption coefficient or phosphate buffering capacity of soils with the units of L kg\(^{-1}\) (Mansell and Selim, 1982; Fig. 2a–c). The slopes of linear regression lines were

<table>
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<th>Sediment</th>
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<tr>
<td></td>
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<td>at 1000 mg P kg(^{-1}) added</td>
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<td></td>
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</tr>
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higher under reduced conditions than oxidized conditions. For example, the PP sediments had a P buffering capacity of about 20 fold higher under reduced conditions than under oxidized conditions.

The amount of P retained by the sediment at a high P level (1000 mg P kg⁻¹) is shown in Table 2. In PP sediments, about 15% of added P was retained under aerobic conditions compared to 78% under anaerobic conditions. The ratio of reduced/oxidized for P sorption capacity was 1.8, 1.2 and 5.3 for PSF, PAF and PP sediments, respectively (Table 2).

Sediments used in the study were high in Fe (Mehlich I extractable Fe = 381–444 mg kg⁻¹) and low in Al, indicating the role of Fe in P retention by the sediment. The transformation of ferric oxyhydroxide (Fe(OH)₃) to ferrous hydroxide (Fe(OH)₂) in biologically active sediment can result in more sorption sites, resulting in greater P retention under anaerobic conditions (Khalid et al. 1977). It is also likely that under anaerobic conditions, soil pH tends to approach neutrality (Ponnampерuma 1972), thus use of 0.01 M CaCl₂ in determining P sorption can result in precipitation of P as calcium phosphate. In recent laboratory experiments (O. Olila and K.R. Reddy, unpublished results, University of Florida) using flooded Crowley silt loam soil, more P was lost from soil solutions containing 0.01 M CaCl₂ than 0.03 M KCl, suggesting the possibility of precipitation with Ca.

Patrick and Khalid (1974) suggested that under reduced conditions, reduction of ferric oxyhydroxide to more soluble and highly dispersed ‘gel’ like material increases the reactivity and surface area of reduced iron (ferrous) compounds. This results in greater sorption and complexation under reduced conditions. Under reduced conditions, up to 800 mg P kg⁻¹ was retained by all three sediments, while under oxidized conditions, maximum retention was 140, 460, and 630 mg kg⁻¹, for PP, PSF, and PAF sediments, respectively (Fig. 2a–c).

It is well established that pond sediments are generally characterized by two distinct horizons: surface oxidized sediment layer at the sediment-water interface and an underlying reduced sediment layer (Reddy and Patrick 1984). The thickness of this oxidized layer is inversely related to the organic matter content at the sediment-water interface. This oxidized layer can function as a sink for P diffusing from the water column and for soluble P diffusing from the reduced soil layer to the oxidized soil layer.

In conclusion, the results presented in this study suggest that sediments in these ponds are functioning as sinks for floodwater P. Phosphorus adsorption in these sediments is governed by amorphous ferrous hydroxide, with greater P retention under reduced conditions than oxidized conditions. Apart from P retention by sediment, assimilation of P by microorganisms, algae and aquatic plants needs to be considered when evaluating capacity of these ponds to retain external sources of P.

References

Patrick, W.H., Jr. and Khalid, R.A. 1974. Phosphorus release and sorp-