IRON REDUCTION AND PHOSPHORUS RELEASE FROM LAKE SEDIMENTS AND BT HORIZON SOIL: INCUBATION STUDIES TO EXPLORE PHOSPHORUS CYCLING

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Abstract. Sediment from two Georgia Piedmont impoundments and soil from the Georgia Piedmont Bt horizon were incubated with an easily consumable organic carbon substrate in an anaerobic environment to observe iron reduction and phosphorus release. 97% of porewater iron in the Bt horizon soil, 96% of porewater iron in Lake Lanier sediments, and 93% of porewater iron in Lake Oglethorpe sediments was reduced to a soluble form during anaerobic incubation. Phosphorus release followed a similar trend with 83% of total P in Bt horizon porewaters, 77% of total P in Lake Lanier sediment porewater, and 61% of total P in Lake Oglethorpe sediment porewater solubilized. The iron reduction and phosphorus release observed in soil from the Bt horizon collected in the Piedmont region of Georgia indicates that phosphorus transported to Piedmont impoundments may be made biologically available through iron reduction in the sediments. The smaller percentage of P and Fe solubilized in Lake Oglethorpe sediments may indicate that there is less reducible iron in these sediments, and that less P is directly adsorbed or bound to oxidized iron and thus less available for release upon iron reduction. We discuss the implications this work has on lake and watershed management practices in the Georgia Piedmont.

INTRODUCTION

The scientific basis for the conventional paradigm of phosphorus (P) cycling in lakes was developed with data primarily from north-temperate systems (Hutchinson 1957, Rodhe 1969, Carlson 1977). This paradigm involves the sinking of inorganic particulates and organic material from the surface (epilimnetic) waters to the hypolimnetic waters of lakes during summer stratification. The depletion of oxygen and anoxic respiration in the hypolimnion creates reducing conditions in the buffered waters of north-temperate lakes. As iron-phosphorus compounds are reduced and organic matter is decomposed in the anoxic hypolimnion, there is a steady increase in DIP (dissolved inorganic phosphorus) which is circulated to the lake at fall mixis (Hutchinson 1957; Wetzel 2001). This phosphorus cycling paradigm does not adequately address the role of abundant oxidized iron in surface water and sediments that is found in Southeastern Piedmont impoundments (Parker and Rasmussen 2001; Mayhew et al. 2001).

The chemistry of the conventional phosphorus cycling paradigm is true for lakes and impoundments in the Georgia Piedmont, i.e., inorganic and organic P are delivered to the waterbody; particulates sink to the hypolimnetic waters and sediments of lakes during summer stratification; the depletion of oxygen in the sediments and hypolimnetic waters leads to anoxic respiration; and oxidized metals which are used as electron acceptors when carbon is consumed by metal reducing bacteria are reduced. We rarely see elevated P at mixis in Georgia Piedmont impoundments, however, most likely due to the large amounts of oxidized iron that are supplied to these waterbodies via sediment loading. Oxidized iron in the soil and sediments of Georgia Piedmont impoundments have a high capacity for adsorbing phosphate (see Parker and Beck 2003), and thus we hypothesize that the lack of P release at mixis is due to the abundant supply of oxidized iron in these systems (see Parker and Rasmussen 2001). The work presented here explores the conditions that could lead to P release from the sediments of Georgia Piedmont impoundments and thus lead to water quality degradation.

The life cycle of a natural lake ecosystem is thought to progress from an oligotrophic to eutrophic state over long periods of time (hundreds to thousands of years) (Margalef 1968; Lampert and Sommer 1997). Lakes formed by impounding rivers or streams have characteristics of both natural lakes and flowing waters. The life cycle of these man-made lakes or impoundments is thought to generally follow a trajectory similar to natural lakes. However, the higher loading rates of sediment, nutrients, and organic matter frequently shorten the time needed for impoundments to progress from oligotrophic to eutrophic (Thornton et al. 1990). Natural lake ecosystems and their surrounding watershed tend to develop simultaneously, e.g., following glacial or oceanic retreat, whereas impoundments generally are constructed in areas where the surrounding watershed has already developed in the ecosystem sense (alia Odum 1969). Hence, the loading of organic matter into impoundments occurs at much greater rates on a shorter time scale than those of natural lake systems.

Organic matter loading and consumption is important to phosphorus cycling. Consumption of organic matter by metal reducing bacteria in the sediments and hypolimnetic waters leads to reduction of iron and hence release of phosphate from oxidized iron-phosphate complexes. Accordingly, microbial activity in the sediments plays an important role in carbon degradation and nutrient regeneration and cycling. Sediments with large amounts of organic substances and an abundant supply of oxidants will support a large population of metal reducing bacteria and will thus have greater release of sorbed or complexed anions, such as phosphate, at mixis. The study presented here describes experimental work to help define the conditions that would lead to substantial reduction of oxidized metals in the sediments and hypolimnia, and thus lead to release of sorbed phosphate. We also discuss management actions that need to be considered to prevent water quality degradation that might occur as a result of organic carbon consumption in anaerobic sediments and hypolimnetic waters.

METHODS

Sediment from Lake Lanier (Flat Creek or Flowery Branch), Lake Oglethorpe, and Bt horizon soil from the Georgia Piedmont were incubated with sucrose to determine the differences in sediment characteristics and the differences in potential phosphate release from each of the sediments. Surficial sediments were collected from Lake Lanier and Lake Oglethorpe with an Eckman dredge. An Eckman dredge was used rather than a sediment corer due to the difficulties of retrieving sediment from Lake Lanier with a corer. Bt horizon soil was collected from an exposed soil horizon at the University of Georgia's Whitehall Forest. 250 - 300 g of wet sediment from Lake Lanier, and Lake Oglethorpe, and Bt soil wet with Lake Lanier hypolimnetic water were added to each of three incubation chambers in an oxygen-free environment (N_2 filled Coy chamber). Hypolimnetic water from Lake Lanier was added to each chamber for a final volume of approximately 600 mL in each chamber. Five grams of sucrose was added to each of the nine incubation chambers to provide an easily consumable organic carbon substrate. An N_2 head was maintained through constant flow of N_2 into each chamber during the twelve week incubation. Sediments were stirred daily.

Porewaters were sampled at the end of the incubation to measure iron reduction and phosphate release from the sediments and soil. Porewaters were sampled just above the sediment-water interface in the chambers through an airstone used as a prefiltration device. Unfiltered and filtered samples were collected for elemental analyses. Filtered samples were pushed through a 0.22 µm Millipore cellulose nitrate syringe filter. The samples were analyzed in a twenty element sweep using an inductively coupled argon plasma (ICAP) Thermo Jarrell-Ash 965 elemental analyzer. Unfiltered samples represent the porewater total element concentrations; samples filtered through a 0.22 µm filter comprised the dissolved or soluble fraction.

Percentage of released phosphorus, iron, and manganese were calculated by difference between the unfiltered and filtered samples. Porewaters were also sampled for volatile fatty acid analyses to determine metabolic products produced during incubation. Total organic carbon (TOC) in the sediments was measured before and after incubation to determine if the added substrate was consumed. ANOVA tests were performed to identify significant differences between sample groups.

RESULTS

TOC measurements indicated that most of the organic carbon added as sucrose was consumed. There was no measurable carbon in the Bt soil after incubation. The percentage of organic carbon in the sediments from both Lake Lanier and Lake Oglethorpe was slightly elevated after incubation.

88-97% of porewater iron was soluble, as was 55-88% of porewater phosphorus (Table 1). A greater percentage of phosphorus was released from Bt horizon soil and Lake Lanier sediments than from Lake Oglethorpe sediments. >90% of the manganese was soluble in porewaters from all chambers, indicating that iron reduction had proceeded in all chambers. Percentage of soluble porewater iron and phosphorus were significantly different between sediment types at the $P < 0.10$ level.

DISCUSSION

The Bt horizon soil and Lake Lanier sediments had the greatest percentage of iron and phosphorus solubilized. A lower percentage of the total iron was dissolved in the incubations of Lake Oglethorpe sediments. A smaller percentage of the total P was dissolved in Lake Oglethorpe sediments, indicating that less of the phosphorus in these sediments is complexed with easily reducible iron. It may be that much of the reducible iron and complexed phosphate in these sediments was previously processed and thus is less available for solublization than the potentially less processed iron and phosphate in Lake Lanier sediments (Aller 1998).

Lake Oglethorpe has a greater watershed load to lake volume ratio than Lake Lanier. The load of organic carbon to Lake Oglethorpe is also greater, due to land application of livestock waste and the higher percentage of livestock in the watershed. The higher watershed loading coupled with shallower maximum depth, and the strength and extent of stratification and hypolimnetic anoxia in Lake Oglethorpe (Parker 1995) allow for greater processing and cycling of inorganic and organic particles. The strong thermocline and chemocline established early in the summer season in Lake Oglethorpe create a metalimnetic plate that effectively separates surface and bottom waters. Wind mixing of surface waters allows for extensive processing of surficial inorganic and organic particles, thus the particles reaching the sediment in Lake Oglethorpe are likely processed in the surficial waters. The shorter period of stratification, and the relatively weaker metalimnetic plate in most of Lake Lanier allow for more rapid settling, and thus less processing of organic and inorganic particles in the surface waters.

The iron reduction and phosphorus release observed in soil from the Bt horizon collected in the Piedmont region of Georgia demonstrates that phosphorus bound to Bt soil and transported to Piedmont impoundments may be made biologically available through iron reduction in the sediments. The high binding capacity of Bt soil (see Parker and Beck 2003) and the high iron content of Lake Lanier sediments indicates that much of the phosphorus in these sediments may be available for release as organic carbon is delivered to the sediments and oxidized iron is reduced during carbon consumption by metal-reducing bacteria. The higher percentage of soluble phosphate released from Lanier sediments than from Oglethorpe sediments supports the hypothesis that Lake Lanier is in an earlier development stage (sensu Odum 1969) than Lake Oglethorpe.

Table 1. Total and soluble Fe, P, and Mn expresssed as ppm in porewaters of sediment and soil anaerobic incubations with percent total in soluble form. Differences in group means ($P < 0.10$) identified by *.

Sample	Fe			P			Mn		
	Total	Soluble		Total	Soluble		Total	Soluble	
	ppm		%	ppm		%	ppm		%
Bt Soil	1563	1551	99*	6.99	6.14	87.9*	9.94	9.86	99.1
Bt Soil	1663	1592	96	8.19	6.38	77.9	9.87	9.46	95.8
Lanier	1294	1257	97*	6.50	5.36	82.4*	33.3	32.5	97.6
Lanier	1391	1334	96	7.95	5.72	71.9	33.7	32.3	95.8
Oglethorpe	1406	1322	94*	8.19	5.84	71.3*	47.7	44.3	92.9
Oglethorpe	1261	1183	94	7.59	4.40	57.9	38.8	36.7	94.6
Oglethorpe	1437	1306	91	10.12	5.60	55.3	44.7	42.3	94.6

Conditions that might lead to more rapid development of Lake Lanier as a lake ecosystem, i.e., increases in organic carbon input through increased wastewater effluent, and or decreases in oxidized iron input by reduction in sediment loading could lead to increased iron reduction in the sediments and thus an increased release of phosphorus to the surface waters.

The management of the Lake Lanier watershed should be carefully considered to balance the water quality needs of the impoundment with the potential effects of management actions on the cycling of phosphorus in this system. In Lake Lanier the reduction of sediment loading with its delivery of oxidized iron, could cause proportionally greater delivery of organic carbon to the sediments and thus result in an increase in iron reduction and phosphorus release from the sediments and bottom waters. It is imperative that the full impact of management actions be considered before they are implemented.

LITERATURE CITED

Aller, R. C. 1998. Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors. Marine Chemistry 61: 143-155.

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361-368.

Hutchinson, G. E. 1957. *A Treatise on Limnology, Volume 1*. John Wiley & Sons, New York.

Lampert, W. and U. Sommer. 1997. *Limnoecology: The ecology of lakes and streams*. Oxford University Press, New York.

Margalef, R. 1968. *Perspectives in Ecological Theory*. University of Chicago Press. Chicago, IL.

Mayhew, M., T. Rasmussen, and A. Parker. 2001. Phosphorus binding by colloidal iron in the Southeastern Piedmont: Implications for point and non-point sources of phosphorus. *Proceedings of the 2001 Georgia Water Resources Conference*, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, GA.

Odum, E. P. 1969. Strategy of ecosystem development. Science 164 (3877): 262-270.

Parker, A. K. 1995. Phytoplankton seasonal succession in a warm-monomictic lake (Lake Oglethorpe, GA). M.S. Thesis. University of Georgia.

Parker, A. K. and M. B. Beck. 2003. The role of transported sediment in the cycling of phosphate in Georgia Piedmont impoundments. Proceedings of the 2003 Georgia Water Resources Conference, held April 21-23, 2001, at The University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Parker, A. K. and T. C. Rasmussen. 2001. Phosphorus cycling in Southeastern Piedmont lakes: an alternative pathway. Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at The University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Reservoir Limnology: ecological perspectives. 1990. K. W. Thornton, B. L. Kimmel, F. E. Payne, eds. J. Wiley & Sons, New York.

Rodhe, W. 1969. Crystallization of eutrophication concepts in northern Europe. *In* Eutrophication: Causes, Consequences, Correctives. National Acad. Sci., Washington, DC.

Wetzel, Robert G. 2001. *Limnology: Lake and River Ecosystems.* Academic Press, San Diego, CA.