

Internal P Loading: A Persistent Management Problem in Lake Recovery

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Phosphorus recycling between aquatic sediment and lake water

Internal phosphorus (P) loading is a term used to describe P movement and recycling between sediment in a lake and the water column. Phosphorus usually limits the growth of algae in freshwater systems and its enhanced availability via anthropogenic watershed runoff (i.e., external P loading) and internal P loading processes often leads to eutrophication and deterioration of ecosystem health such as frequent cyanobacterial blooms, dissolved oxygen depletion, poor water clarity, impaired fisheries, and declines in submersed aquatic plant communities that offer critical habitat for invertebrates and other biota. Since sediment P is ultimately derived from the watershed, land use practices that over-fertilize the soil and promote hydrological runoff can result in considerable deposition over decades and centuries of P-rich sediment in lake basins. Lakes are essentially traps for sediment and thus reflect the activities in its watershed. Internal P loading is, in essence, in-lake recycling of P that was derived from the watershed.

There are many mechanisms of internal P loading that can result in the movement of soluble P (i.e., the form of P that is readily assimilated by algae for growth) from sediment to the overlying water. The focus of this article will be on diffusion of P from the sediment porewater (i.e., interstitial water that surrounds sediment particles) directly into the water column (Figure 1). Rooted aquatic plants in the littoral can play an important role in promoting internal P loading by translocating P from the sediment into plant tissue during their growth phase, then releasing soluble P into the surrounding water during dieback. A myriad of aquatic invertebrates and

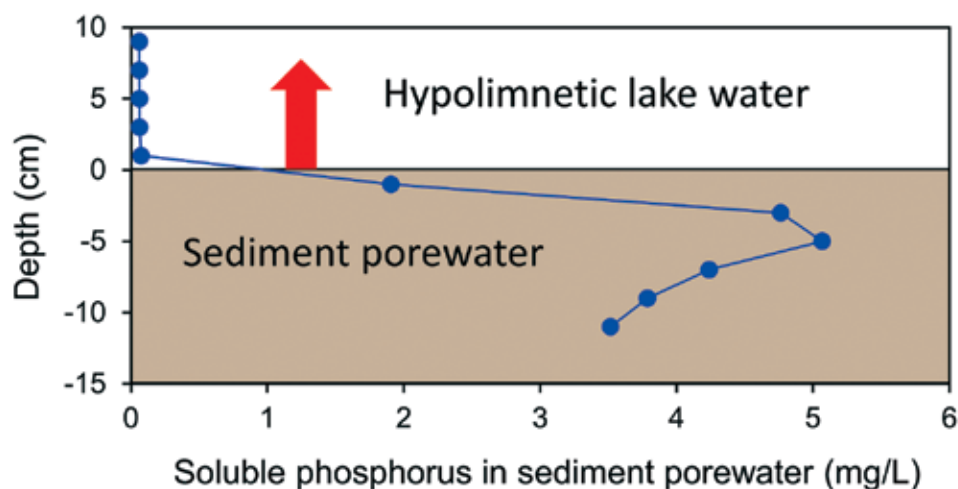


Figure 1. Variations in soluble phosphorus concentration (blue circles) in the overlying water and sediment porewater. The steep concentration differences at the sediment interface drive phosphorus diffusion toward the overlying water (direction of red arrow).

tubificid creatures inhabiting the sediment can cause internal P loading to the water by burrowing activities that mix sediment soluble P into the water. Benthic-feeding fish cause sediment disturbance and internal P loading on a larger scale. Finally, groundwater movement through P-rich sediments and wave-induced resuspension of sediment can result in transfer of soluble P from sediment to the water column for uptake by algae. P recycled to algae by any of these processes can become deposited back to the sediment in the form of algal remains or in fecal pellets from zooplankton or fish after being consumed.

Bacterial metabolism in the profundal and the role of iron reduction

Probably one of the most exciting areas of P recycling research, but a nemesis for lake managers, is internal P loading from the profundal sediment of

lakes by diffusive flux from porewater (Nürnberg 2009). As lakes stratify during the summer into an epilimnion and hypolimnion divided by a thermocline, ecosystem metabolism and nutrient cycling processes become separated spatially and vertically. Movement and exchanges between these stratified layers becomes difficult and requires much work in the form of wind and heat transfer. In the euphotic (region receiving sunlight in the epilimnion) zone, algal photosynthesis and dissolved oxygen production maintains an aerobic environment for zooplankton, invertebrates, and fish populations.

However, biota inhabiting the dark aphotic (region where sunlight penetration is zero) zone rapidly deplete dissolved oxygen reserves in the hypolimnion as stratification progresses. Because water exchanges between the two zones are restricted by density stratification, there

is little chance of dissolved oxygen replenishment and the hypolimnion becomes anoxic (i.e., devoid of oxygen).

However, life primarily in the form of bacteria thrives under anaerobic conditions in the hypolimnion. Instead of using oxygen as a final electron acceptor to release energy from organic matter (i.e., aerobic respiration), these organisms have evolved and adapted to use other electron acceptors such as nitrate (denitrification), manganese, iron, sulfate, and methane to survive and metabolize organic detritus (anaerobic respiration). Organic carbon produced in the euphotic zone rains downward into the hypolimnion and deposits onto profundal sediment as detritus, fueling anaerobic metabolism, which results in oxidation of organic matter to CO_2 (organic carbon loses an electron for energy production) with reduction (i.e., gains an electron) of an electron acceptor molecule other than oxygen.

What does this have to do with internal P loading? Oxidation-reduction reactions during anaerobic metabolism at the sediment-water interface drive the recycling of important elements like soluble P and iron that are in a form that can be taken up by algae for growth. Mortimer (1941) synthesized a scenario through his pioneering research that has become an important standard in our understanding of internal P loading from profundal sediment. Under aerobic and oxygenated conditions, phosphate (PO_4^{3-}) is adsorbed or precipitated with ferric (Fe^{3+}) iron oxyhydroxides

($\text{Fe-OOH}\sim\text{P}$) in the surface sediment. Freshly precipitated Fe-OOH is initially a very low molecular weight colloid particle consisting of iron and hydroxyl ions that polymerize (form chains). When associated with Fe-OOH , PO_4^{3-} is mostly removed from recycling pathways and in a form that cannot be taken up by algae. As hypolimnetic dissolved oxygen becomes depleted, anaerobic bacteria can use Fe-OOH as an alternate electron acceptor to produce energy from organic detritus. The bond between Fe-OOH and PO_4^{3-} becomes broken by bacterially mediated reduction of Fe-OOH to soluble Fe^{2+} , resulting in the diffusion of Fe^{2+} and PO_4^{3-} into the sediment porewater and eventually into the anoxic hypolimnion.

Phosphorus exchanges between the hypolimnion and epilimnion

As summer progresses, the slow process of diffusion at the sediment-water interface can lead to the accumulation of considerable soluble PO_4^{3-} and Fe^{2+} in the anoxic hypolimnion (Figure 2). By the

end of summer stratification, soluble P concentrations may exceed 1 mg/L above the sediment surface with gradients of decreasing concentration extending up into the metalimnion. The availability of this hypolimnetic soluble P to algae residing in the epilimnion is dictated by several factors. Some algae and cyanobacteria can migrate vertically in the water column because they have flagella (a whip-like tail) or can regulate their buoyancy using gas vacuole structures within the cell. These features offer many competitive advantages including access to internal P loads by vertical migration into the upper hypolimnion. For instance, *Ceratium hirundinella* (a flagellated dinoflagellate) can migrate downward into the hypolimnion at night for nutrient uptake and then upward into the euphotic zone during the day for photosynthesis (Figure 3).

For other algae depending solely on water movement and turbulence to stay afloat in the euphotic zone, hypolimnetic soluble P must first become mixed into the epilimnion as PO_4^{3-} for uptake. Because density stratification is resistant to disruption and mixing, strong cold fronts, loss of heat from the lake's surface, and sustained winds are usually required for any chance of turbulence and entrainment

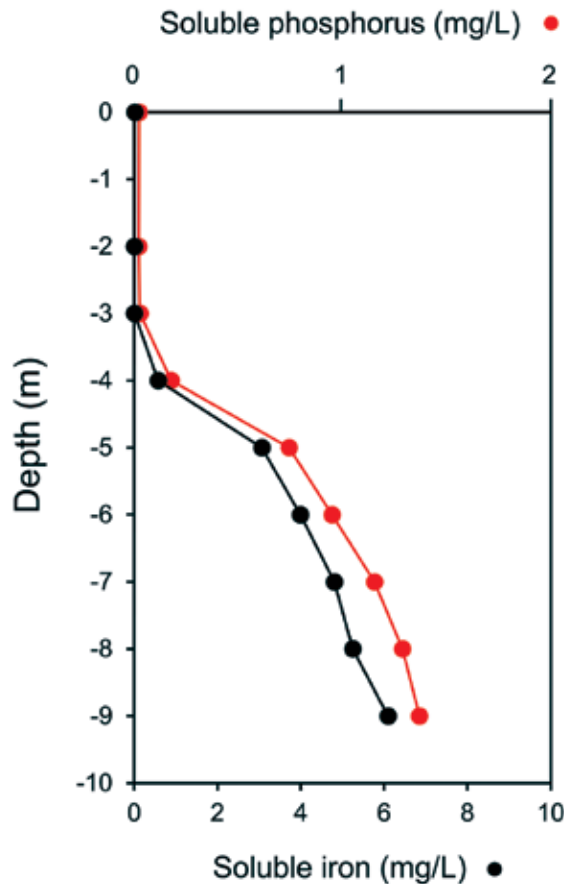


Figure 2. Vertical water column variations in soluble iron (black circles) and phosphorus (red circles) concentrations in Lake Desair, Wisconsin.

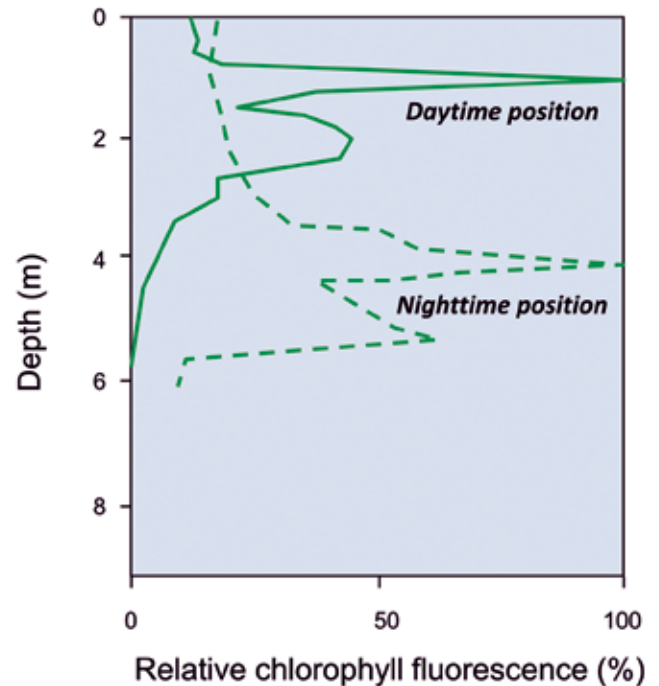


Figure 3. Daytime and nighttime depth position of a *Ceratium hirundinella* bloom in Eau Galle Reservoir, Wisconsin (modified from James et al. 1992).

of hypolimnetic soluble P into the surface waters. While water and nutrient exchanges can occur during summer stratification, cooling and heat loss is usually strongest during the fall and ultimately leads to complete water column mixing in a process known as autumnal overturn. During this event, hypolimnetic Fe^{2+} and PO_4^{3-} gradients become disturbed and both substances mix throughout the water column. In addition, dissolved oxygen mixes with and reoxygenates hypolimnetic water resulting in chemical oxidation of Fe^{2+} back to Fe-OOH and re-adsorption of PO_4^{3-} . Thus, the cycling of Fe from an oxidized state (Fe^{3+}) in the sediment to a reduced state (Fe^{2+}) in the anoxic hypolimnion back to an oxidized Fe-OOH colloidal precipitate during reoxygenation and eventual redeposition to the sediment is a process termed the Fe^{3+} – Fe^{2+} ferrous wheel (Campbell and Torgersen 1980).

Unfortunately for algae, chemical reaction to Fe-OOH sequesters PO_4^{3-} . The fate and availability of PO_4^{3-} after turnover events depends to a large extent on ratio of Fe^{2+} relative to PO_4^{3-} that previously accumulated in the anoxic hypolimnion. When there is sufficient Fe relative to P (“high” Fe:P ratio), most if not all of the PO_4^{3-} becomes coprecipitated or adsorbed to Fe-OOH during reaeration and deposits back to the sediment. The availability of PO_4^{3-} for algal uptake can be limited substantially under this scenario. An example of Fe – P interactions at a high Fe:P ratio is shown in Figure 4 for Lake Desair located in west-central Wisconsin. Although Fe and P concentrations were quite high in the hypolimnion as a result of internal P loading the Fe:P ratio was $> 5:1$ at the start of autumnal turnover suggesting adsorption of PO_4^{3-} and redeposition with little available PO_4^{3-} for uptake. Algal biomass, as chlorophyll, declined in late October as an apparent result of P-limitation of growth even though internal P loading was considerable.

In contrast, availability of profundal internal P loads to algae can be substantial when the Fe:P ratio is relatively low in the anoxic hypolimnion prior to reaeration. Incomplete binding and deposition of PO_4^{3-} by Fe-OOH can result in extensive and often toxic cyanobacterial blooms as PO_4^{3-} becomes entrained into the

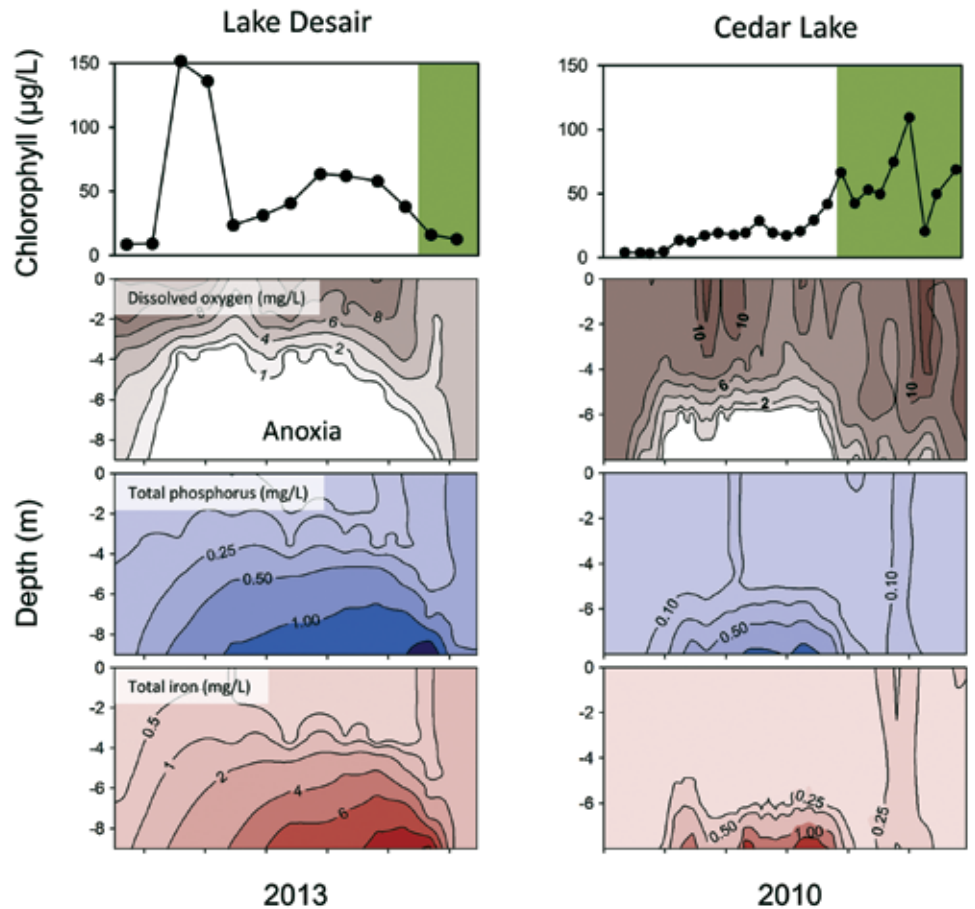


Figure 4. Seasonal variations in chlorophyll (upper panels) and contour profiles of dissolved oxygen, total phosphorus, and total iron versus depth in iron-rich (high Fe:P ratio) Lake Desair (left panels) and iron-poor (low Fe:P ratio) Cedar Lake (right panels; James et al. 2015). Chlorophyll concentration declined in Lake Desair while they increased in Cedar Lake during Autumnal turnover (green shaded areas).

surface waters and directly available for uptake and growth. Back at the sediment surface, Fe can become removed from recycling with PO_4^{3-} in the hypolimnion by reaction with sulfur to form inert and insoluble iron sulfide. Anaerobic bacteria residing in the sediment can promote FeS_x formation and burial by reducing sulfate to S (another metabolic reaction that releases energy from organic detritus). An example of Fe – P interactions at a low Fe:P ratio is shown in Figure 4 for Cedar Lake, Wisconsin (James et al. 2015). Although the sediment had very high Fe content, the buildup of Fe^{2+} in the anoxic hypolimnion was much less relative to PO_4^{3-} , resulting in an Fe:P ratio that was $\sim 1:1$. During and after Autumnal turnover and reoxygenation, chlorophyll concentrations reached seasonal peaks in conjunction with available PO_4^{3-} derived from sediment internal P loading.

Phosphorus management implications

Simply reducing watershed P loading to eutrophic lakes without also managing internal P loading may not be enough to reverse impaired water quality. Even though internal P loading is ultimately derived from the watershed, it can take years to decades to flush sediment P out of the system after watershed BMP implementation, resulting in delayed recovery and continued impairment. In addition, a symptom of decades of P retention as sediment in lakes is the buildup of a surface sediment P concentration bulge that is usually difficult to bury over time and persists as an important internal P source during hypolimnetic anoxia, stimulating and sustaining algal blooms despite other efforts of remediation (Figure 5). Unless controlled directly via P-adsorbing technologies such as aluminum salts, lanthanum-modified clays, or other

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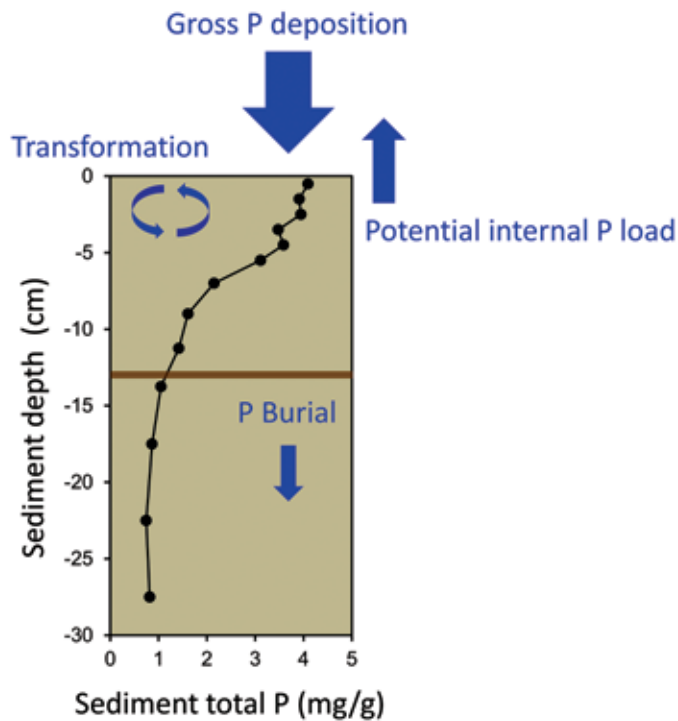


Figure 5. Variations in sediment total phosphorus concentration versus depth below the sediment-water interface. Development of a surface concentration peak in eutrophic lakes is a symptom of potential internal P loading from sediments (after Rydin et al. 2011).

measures, internal P loading from profundal sediments can provide a form of ecosystem feedback that maintains a eutrophic equilibrium that is resistant to management efforts.

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