DEDICATION

We dedicate this book to the memory of Dr. Karl Havens, most recently the Director of the Florida Sea Grant College Program and Professor in the Department of Fisheries and Aquatic Sciences at the University of Florida School of Forest Resources and Conservation. Al had the privilege of working with Karl from 1993 to 2001 at the South Florida Water Management District. Karl was an incredibly focused, insightful, and respected scientist. His clarity of thought was a wonder to behold, and truly delightful to see in action. The aquatic science community suffers a huge loss with his passing. May his memory serve as a blessing.
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Macronutrients, such as phosphorus, nitrogen, and potassium, are essential for life on this planet. Yet, in too high a quantity, they can cause profound environmental problems. Phosphorus, in particular, presents a unique case. It is a critical component of the high-energy compounds ATP and ADP, as well as nucleic acids, several essential co-enzymes, and cell membranes. Yet, its bioavailability under natural conditions is low, resulting in phosphorus limitation of plant growth in most freshwater ecosystems. Humans have altered these systems, however. Excess application of fertilizer, beyond the natural assimilative capacity of our ecosystems, has resulted in the eutrophication of the planet's lakes, wetlands, and streams, resulting in the proliferation of algal blooms, and subsequent conditions of depleted dissolved oxygen in the water column. Over decades, if not centuries, this phosphorus has accumulated in lake sediments (as well as catchment soils), creating a “legacy” of phosphorus. This accumulated reservoir of phosphorus is being released into the water column in lakes throughout the world (internal phosphorus loading, as opposed to phosphorus entering from the catchment, which is external phosphorus loading), resulting in noxious algal blooms and threatening the water supply of many millions of people. In addition, because internal phosphorus loading can persist for long periods of time, it can counterbalance the anticipated benefits of control measures taken to reduce phosphorus inputs from the catchment. In total, the impacts of internal phosphorus loading can result in impaired water bodies, economic impacts to local communities due to health issues, loss of tourism, and depressed civic pride.

There is a pressing need for better understanding of internal phosphorus loading on a global basis. The content provided in this book aligns with the Global Partnership on Nutrient Management (GPNM), which was launched during the 17th session of the UN Commission on Sustainable Development in 2009 as a global partnership of governments, policy makers, industry, the scientific community, civil society organizations, and UN agencies with UNEP providing the Secretariat. More recently, the 4th session of the UN Environment Assembly in March 2019 adopted a landmark resolution on Sustainable Nitrogen Management, which was followed by the Colombo Declaration in October 2019 marking the launch of a UN Global Campaign on Sustainable Nitrogen Management. It is my hope that the information contained in Internal Phosphorus Loading in Lakes: Causes, Case Studies, and Management will help raise the profile of phosphorus and lead to wiser management strategies of this very important element and, in turn, result in cleaner fresh waters, healthier people, and invigorated economies.

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Among his awards are Phi Beta Kappa; the 2017 Award of Excellence from the National Garden Clubs; the U.S. Army Corps of Engineers Outstanding Planning Achievement Award; the Joan Hodges Queneau Palladium Medal from the National Audubon Society; Paul Harris Fellow; Keiser Distinguished Lecturer in Life Sciences from Ohio Northern University; and the Patricia B. Johnson Award for Leadership and Innovative Grantmaking from the Community Foundation for Muskegon County.

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Section I

Introduction to and Overview of Internal Phosphorus Loading
CHAPTER 1

WHAT IS INTERNAL PHOSPHORUS LOADING AND WHY DOES IT OCCUR?

Alan D. Steinman and Bryan M. Spears

Abstract

Lake eutrophication is a global problem that is being exacerbated by climate change, excess nutrient runoff, and land-use alterations. While nutrient inputs to lakes from surrounding watersheds (external loading) have historically received considerable attention, phosphorus inputs (along with other elements) that are generated from within the lake have received far less attention until recently. But there is growing recognition and evidence that impairments that are created from phosphorus sources within lakes are a global phenomenon. Despite this awareness, there is still uncertainty regarding some of its most fundamental characteristics, including: (1) the definition of internal phosphorus loading; (2) the most appropriate way to measure it; (3) how to predict where, when, and how long it will occur; and (4) how to control or manage it. In this chapter, we briefly introduce the concept of internal phosphorus loading, provide an overview of various causes for this phenomenon, and set the stage for the remaining chapters of this book.

We have divided this book into three main parts: Part 1 is an overview of the internal phosphorus loading concept; Part 2 includes case studies from iconic lakes throughout the world; and Part 3 explains the integration and synthesis of the information that has been generated. Our ultimate goals for the book are to increase awareness of internal loading, compare and contrast internal loading from lakes around the world, and identify emerging themes regarding what drives internal loading along with which measures are best suited to manage or limit its impacts.

Keywords: Internal phosphorus loading; lake eutrophication; case studies; integration, and synthesis.

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1.1 INTRODUCTION

1.1.1 Definitions

Internal phosphorus (P) loading can be generically considered as all physical, chemical, and biological processes by which P is mobilized and translocated from the benthic environment. Other definitions exist for internal P loading; for example, Hupfer and Reitzel (see Chapter 2) explain why the term internal loading should be used only in cases where sediments are a net source of P at time scales of one or more years. Orihel et al. (2017) recognized that operational definitions of internal loading have not been consistent, which has resulted in confusion and ambiguity as to what is meant by the term. They qualified their definition, restricting it to P leaving the sediment that reaches the overlying water column, given the management concern regarding the influence of P on algal blooms and also excluding groundwater-driven P moving through the sediment matrix. Our approach in this book is to be less prescriptive, recognizing that users will define internal P loading based on their needs and objectives (see Chapter 2); however, it is important to recognize that internal loading defies one universal definition (cf. Orihel et al. 2017). Hence, it is critical that when authors use the term, they define their explicit intent.

1.1.2 History

Our understanding of internal P loading is grounded in a hypothesis proposed over 75 years ago by Mortimer (1941), who described the redox-mediated exchange of dissolved substances across the sediment-water interface in Esthwaite Water (UK). As oxygen and other electron donors become depleted, compounds that bind P (predominantly iron, i.e., Fe-P) become chemically reduced, releasing P and allowing it to diffuse into the overlying water. This hypothesis has been modified over the years as researchers examined the mechanisms associated with Mortimer’s original ideas. Since the 1980s, a few seminal papers have refined our understanding of the physical, chemical, and biological processes driving Mortimer’s central hypothesis. For example, Gächter et al. (1988), Boström et al. (1988), and Golterman et al. (2001) showed the pivotal role of the microbial community in driving phosphorus remineralization and subsequent redox chemistry in bed sediments.

The late 1980s can be considered the springboard of contemporary internal loading research, and we review a collection of seminal works below, including some significant recent contributions. Sas (1989; 826 citations as of 25 July 2019) produced the first comprehensive collection of case studies, from which he proposed a set of general principles governing internal loading in lakes, especially those recovering from catchment nutrient loading. Three distinct phases of recovery were defined relative to catchment nutrient load reduction: pre-management, a transient recovery phase, and a new steady-state. Using case studies with long-term monitoring data, differences were demonstrated in the functioning of shallow versus deep lakes through these phases. In shallow lakes, internal loading was initiated generally following a reduction in catchment loading; the length of the transient period was several years or longer in lakes where the average sediment P concentration in the upper 15 cm exceeded 1 mg g\(^{-1}\) dw. In these shallow lakes, catchment nutrient load reduction triggered a change in functioning where sediments became a source of phosphorus, with net annual sediment P release being common. However, in deep lakes where sediment P concentrations were generally low, net annual sediment P retention was common regardless of catchment load. This detailed analysis of long-term changes in sediment processes and the mass balance modeling approach produced from these studies, demonstrated the critical role that internal loading can play.
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in driving ecological structure and function at the ecosystem scale—and confirmed the problem to be globally relevant.

Sas’ analyses were further developed by Nürnberg (1984 and 1988; 679 collective citations as of 25 July 2019) in two important papers relating internal P load to sediment P content and composition, providing a novel and simple predictive approach and characterizing increasing sediment P fluxes with increasing total and reductant-soluble sediment P concentrations. Across 82 North American and European lakes, sediment P flux ranged from <1 mg P m$^{-2}$ d$^{-1}$ for oligotrophic sediments and up to 50 mg P m$^{-2}$ d$^{-1}$ for hypertrophic sediments.

Boström et al. (1988; 845 citations as of 25 July 2019) produced a complementary seminal work that outlined the complex pathways through which P was cycled between the sediment and the overlying water. This paper filled the gaps in process understanding and proposed key hypotheses that have shaped the research field. Specifically, the role of the microbial community in bed sediments was highlighted as a critical pathway for P, a hypothesis that even after 30 years, we are only just starting to address comprehensively given the development of powerful chemical and molecular analytical approaches. Pettersen et al. (1988; 192 citations as of 25 July 2019) produced a comprehensive description of the chemical pathways and constraints on P cycling, demonstrating the power of previously proposed techniques that were designed to operationally define sediment P (such as Psenner et al. 1988; 304 citations as of 25 July 2019). With modifications (e.g., Hupfer et al. 1995; 336 citations as of 25 July 2019), this fractionation approach is still in use today.

In the early 2000s, research moved toward testing the hypotheses of the 1980s. Søndergaard et al. (2003; 1144 citations as of 25 July 2019) demonstrated the power of long-term monitoring data in providing general understanding of internal loading and its drivers using data from Danish lakes. This work characterized the typical bell curve pattern in lakes dominated by internal loading where P is released to the water column during periods of low catchment loading. This work was followed by a global scale analysis of whole lake responses to reduced catchment P loading across 35 lakes with long-term data, demonstrating that internal loading could prolong recovery for years—or even decades—especially in shallow lakes (Jeppesen et al. 2005; 968 citations as of 25 July 2019). This work also highlighted the importance of climate change in future regulation of internal loading, which remains a knowledge gap in the field. More recently, the concept of legacy phosphorus has been developed, allowing the effects of internal loading to be placed into the context of catchment phosphorus recovery times, potentially reaching centuries or possibly millennia (Sharpley et al. 2013; 421 citations as of 25 July 2019). Collectively, the 10 papers that were previously cited represent an essential reading list for any researcher who may consider entering the field. They have amassed nearly 5000 citations and continue to influence the research field. It has not escaped our attention that most of these studies focus primarily on data from lakes in North America and Europe, highlighting the need to expand the study of internal P loading to lakes that are located on other parts of the globe.

This body of work advanced Mortimer’s seminal geochemical P pump hypothesis and confirmed that the liberation of P from bed sediments to bottom waters could drive ecosystem scale responses, and is governed by a complex mosaic of physical, biological, and chemical processes. It also suggested that this process is globally relevant. However, the extent to which these processes respond to environmental change—including anthropogenic changes in land use, invasive species, and climate, as well as the influence of latitude and longitude—remains unclear. Muddying the waters further, we still lack robust operational classifications for internal loading and its processes, even though the field has made impressive advances in detection (see Chapter 2), modeling (see Chapter 3), prediction (see Chapter 4), and control (see Chapter 5) in recent years.
1.1.3 Why Phosphorus?

Our focus on P is driven by a number of factors. First, historically, P has been considered the primary nutrient limiting autotrophic production in freshwater ecosystems, given its limited bioavailability in nature (Schindler 1977; Hecky and Kilham 1988; Hudson et al. 2000; but see upcoming text). Second, P concentrations in healthy plants are relatively low, usually ranging from 0.1 to 0.8% of dry mass (Raven et al. 1981), although P is essential for growth. Some of the more important functions played by P in plants and animals include being a structural component of high-energy phosphate compounds (e.g., ADP and ATP), nucleic acids, several essential coenzymes, and cell membrane constituents (phospholipids), as well as being involved in the phosphorylation of sugars. Third, most of the sediment P that is the source of internal loading ultimately comes from the watershed, so the question of how best to manage P—in the watershed or in the lake—is a fertile area of debate with significant economic, societal, and ecological implications (Sharples et al. 2013; Osgood 2017; Steinman et al. 2018a). Despite concerns of a global phosphorus shortage (Cordell and White 2011), the mass of P stockpiled in freshwater ecosystems as a result of anthropogenic activities continues to grow at a rate of about 5.0 Tg P yr$^{-1}$ (Beusen et al. 2016).

While many lakes certainly are limited by phosphorus alone (cf. Paterson et al. 2011; Schindler et al. 2016), that paradigm has come into question in recent years, as nitrogen (N) has been found to be either the limiting or co-limiting (with P) nutrient in some lakes (Elser et al. 1990; Leavitt et al. 2006; Conley et al. 2009; Paerl and Scott 2010; Paerl et al. 2016; Steinman et al. 2016). Excess internal P loading can lead to N limitation in lakes (Ding et al. 2018); this type of secondary N limitation may be mitigated by controlling internal P loading. Internal nitrogen loading has received relatively little attention compared to P, although release of ammonia has certainly been documented (Beutel 2006). Internal processes of N and P cycling in lakes should not be considered decoupled, although the mechanisms by which they interact are not yet fully understood. Indeed, nitrate is an important precursor to Fe in the redox series, and nitrate losses in bottom waters are expected to occur more rapidly through denitrification in warmer lakes, leading to a higher likelihood of internal loading (Weyhenmeyer et al. 2007).

1.2 CAUSES OF INTERNAL P LOADING

Internal P loading is measurable only when sediment phosphorus release exceeds sediment phosphorus retention. Both release and retention can occur simultaneously in lakes, but P accumulation in the water column along with the attendant management concerns, emerge only when release exceeds retention. The factors driving internal P loading can be partitioned into biological, chemical, and physical mechanisms (see Figure 1.1)—although nature rarely behaves so simplistically. Hence, although we use these three categories, in reality they often interact, resulting in outcomes that may not align with predictions or preconceptions.

1.2.1 Biological Causes

Bioturbation is perhaps the best known biological mechanism for P release from sediments (cf. Mermillod-Blondin and Rosenberg 2006; Roskosch et al. 2012; Höller et al. 2015; Nogaro et al. 2016). The most common bioturbators in eutrophic lakes are usually chironomid larvae and tubificid oligochaetes. Chironomid larvae can form u-shaped tubes in the sediment; pumping of water at the sediment-water interface can flush nutrients out of the tubes and into the overlying water column (Hansen et al. 1997), although the amount of P that is released is influenced by sediment properties
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(Nogaro and Steinman 2014). In contrast, oligochaetes ingest sediment at depth and egest fecal pellets at the sediment surface; hence, while they can stimulate solute exchange between sediment and water via their constructed galleries, their bioirrigation activity is limited in comparison with chironomid larvae (Svensson et al. 2001). Certain species of benthic fish, such as ruffe and gizzard shad (Kelly et al. 2018), as well as crayfish (Ottolenghi et al. 2002) and mussels (Nogaro and Steinman 2014; Chen et al. 2016a), also are known to disturb sediments and result in P movement from sediments to the water column, although some nutrients may derive from fish excretion and not from internal loading, sensu lato (Vanni 2002; Tarvainen et al. 2005; Schaus et al. 2010).

Another biologically mediated mechanism by which P can be moved from the sediment to the water column is vertical transport. Tang et al. (2017) showed that *Chaoborus* larvae, through both oxygen demand from sediment and the water column as well as nutrient excretion, enhance internal nutrient loading in lakes. In addition, Xie et al. (2003a, b) found that *Microcystis* blooms can be responsible for internal P loading, through either mineralization of decaying cells or by inducing a massive release of P from the sediment, perhaps due to either seasonal migration or high pH caused by intense algal photosynthesis, revealing the tight linkage between biology and chemistry in driving internal P loading (cf. Katsev 2017). Benthic algae and macrophytes also can play important roles in the movement of P; both groups of autotrophs can release P as they senesce and mineralize (Paalme et al. 2002; Higgins et al. 2008; Gao et al. 2013; Zhu et al. 2013). Macrophytes can also help prevent sediment resuspension by serving as a physical barrier to diffuse wind-wave action (Horppila and Nurminen 2003), although under dense canopies, internal loading can be enhanced via both anaerobic and aerobic diffusive flux pathways (Frodge and Pauley 1991). For benthivorous fish, where most data are available for carp, densities in excess of a 200 kg ha$^{-1}$ to 700 kg ha$^{-1}$ threshold result in increased turbidity and internal loading in shallow lakes (Williams and Moss 2003). Several chapters in this book highlight the fact that in certain lakes, sediment resuspension accounts for the majority of internal P loading (see Chapters 7 and 18).

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**Figure 1.1** Schematic diagram of different mechanisms responsible for internal P loading in lakes. Figure credit: Emily Kindervater.
Although inferred in earlier models as a major conduit of organic-P turnover in sediments that is ultimately driving internal loading in lakes, the role of the microbial community has remained a black box, until recently. We now know that microbial communities are capable of performing a range of functions that are designed to access P from inorganic and organic P compounds; this access can fuel both microbial production and the remineralization of relatively refractory and complex P compounds, thereby forming an important link with the well-described inorganic P cycle (Vila-Costa et al. 2013). Although the lake bed has been demonstrated as a major site of these biochemical pathways at the whole-lake scale (Reitzel et al. 2012), much remains to be learned of the environmental cues driving underlying processes, of the importance of microbial community succession for functional performance, and of the sensitivity of these processes to environmental change.

1.2.2 Chemical Causes

The best known chemically driven mechanism for P release derives from redox reactions that release P from iron hydoxides (Mortimer 1941). However, as thoroughly reviewed by Orihel et al. (2017) and Katsev (2017), there are many other mechanisms besides iron cycling to account for P diffusion from sediment porewater, including desorption, dissolution, mineralization, exudate excretion, and dissociation. These processes are dealt with in more detail in the following chapters of this book, as well as in the two prior citations.

1.2.3 Physical Causes

Disturbance is related to resuspension of sediment particles, which can be due to either physical forces such as wind-wave action or biological activity (Havens 1991; Steinman et al. 2006; Thomas and Schallenberg 2008; Tammeorg et al. 2013; Chen et al. 2016b; Chao et al. 2017; Matisoff et al. 2017). Bioturbation is often included as a physical process, but it also can be attributed to biotic activity (see Section 1.2.1), given that both sediment-dwelling organisms and sediment-surface feeders are responsible for solute or particle transport into the water column (cf. Vanni 2002; Mermillod-Blondin and Rosenberg 2006).

These complex biogeochemical processes interact and combine to govern the connection between the benthos and water column, the net effects of which can result in hysteresis in ecosystem scale responses to catchment and internal loading variation. These interactions make up the building blocks of ecological resilience theory in shallow lakes (Scheffer et al. 2004) and have been used to produce process models capable of predicting large-scale ecological responses to nutrient loading and climate change in some of the world’s largest lakes (e.g., Taihu, China; Janssen et al. 2017).

Carey and Rydin (2011), based on a meta-analysis of sediment burial patterns of P in lakes around the world, found that the sediment total P (TP) concentrations changed with depth and that the shape of these distributions varied with lake trophic state; this suggested that lake sediment TP profiles may be indicative of nascent eutrophication. Using their database and adding data from lake studies conducted by the authors, we examined relations between water column and sediment P. We did not focus on the role of sediment depth in our analysis, which was one of the key findings in Carey and Rydin (2011). We used the same approach as Carey and Rydin for water column TP, averaging as many samples as available in the year that sediments were sampled for TP and separating lakes into three trophic states based on water column TP concentration (oligotrophic: < 10 µg/L; mesotrophic: 10–30 µg/L; and eutrophic: > 30 µg/L). There was high variance in the relationships in all trophic levels, resulting in low predictive ability (see Figure 1.2). It is likely that variance would be reduced if we used mobile sediment P instead of sediment TP because the more stable sediment P fractions
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will not be contributing to water column TP (see Chapter 9). Nonetheless, the relationships varied among trophic state, revealing a slightly positive slope between sediment TP and log water-column TP for oligotrophic lakes, a slightly negative slope for mesotrophic lakes, and a stronger positive slope for eutrophic lakes. From a management perspective, water depth should also be taken into consideration since recent studies have shown that the influence of water depth on lake water quality will vary based on trophic state: oligotrophic lakes get clearer when lake levels decline but more turbid when lake levels rise, with the opposite pattern for eutrophic lakes (Ji and Havens 2019; Lisi and Hein 2019).

1.3 CONTROL AND MANAGEMENT

Cataloging the mechanisms of internal P loading is more than an academic exercise because effective control and management is absolutely dependent on knowing the source. One theme that emerges from the case studies that are described in the following chapters is the need for lake-specific analyses to determine the best management strategy; a one-size-fits-all approach is doomed to failure (see Chapter 5). Biomanipulation involving the removal of benthivorous fish will be an expensive and ineffective strategy if the P source is diffusive flux from the sediment; conversely, a chemical inactivation treatment will have limited benefit if the main P source from the watershed is not addressed.

The influence of internal P loading is likely to become more important in the future for several reasons. First, a warming climate is resulting in warming lake temperatures (O’Reilly et al. 2015).
As lakes warm, stratification intensifies resulting in a greater chance for hypoxia/anoxia to form in the hypolimnion, thereby driving P desorption from Fe hydroxides and more P diffusion from sediments. Second, continued population growth is creating pressure on agricultural production. This intensification is resulting in greater P runoff around the world (Macintosh et al. 2018), which ultimately finds its way to lake sediments, setting the stage for future internal loading.

Like much of limnology, most studies of internal loading have occurred in North America and Europe. However, it is likely that the problem is of a global nature, and we have attempted to demonstrate that with select case studies. As we identify best practices for measuring (see Chapters 2 and 3), understanding (see Chapter 4), and managing (see Chapter 5) internal phosphorus loading, we also explore the most effective societal and scientific approaches to address this phenomenon. Our objective is to present a comprehensive account of the research field, focussing on identifying drivers of variation in internal loading over the longer term and synthesising evidence across the peer-reviewed literature and from some of the world’s most iconic long-term monitoring programs that are centred on lakes, their ecology, and their vital role in society.

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1.5 REFERENCES

Beusen, AH; Bouwman, AF; Van Beek, LP; Mogollón, JM; and Middelburg, JJ. 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences. 13:2441–2451.


Chen, M; Ding, S; Liu, L; Xu, D; Gong, M; Tang, H; and Zhang, C. 2016a. Kinetics of phosphorus release from sediments and its relationship with iron speciation influenced by the mussel (Corbicula fluminea) bioturbation. Sci Total Environ. 542:833–840.


Conley, DJ; Paerl, HW; Howarth, RW; Boesche, DF; Seitzinger, SP; Havens, KE; Lancelot, C; and Likens, GE. 2009. Controlling eutrophication: nitrogen and phosphorus. Science. 323:1014–1015.


Ding, S; Chen, M; Gong, M; Fan, X; Qin, B; Xu, H; Gao, S; Jin, Z; Tsang, DC; and Zhang, C. 2018. Internal phosphorus loading from sediments causes seasonal nitrogen limitation for harmful algal blooms. Sci Total Environ. 625:872–884.


Hölker, F; Vanni, MJ; Kuiper, JJ; Meile, C; Grossart, HP; Stief, P; Adrian, R; Lorke, A; Dellwig, O; Brand, A; et al. 2015. Tube-dwelling invertebrates: tiny ecosystem engineers have large effects in lake ecosystems. Ecol Monogr. 85:333–351.


Jeppesen, E; Søndergaard, M; Jensen, JP; Havens, K; Anneville, O; Carvalho, L; Coveney, MF; Deneke, R; Dokulil, MT; Toy, B; et al. 2005. Lake responses to reduced nutrient loading—an analysis of contemporary long-term data from 35 case studies. Freshwat Biol. 50:1747–1771.


Kelly, PT; González, MJ; Renwick, WH; and Vanni, MJ. 2018. Increased light availability and nutrient cycling by fish provide resilience against reversing eutrophication in an agriculturally impacted reservoir. Limnol Oceanogr. 63:2647–60.


Macintosh, KA; Mayer, BK; McDowell, RW; Powers, SM; Baker, LA; Boyer, TH; and Rittmann, BE. 2018. Managing diffuse phosphorus at the sources versus at the sink. Environ Sci Technol. In Press.


Nogaro, G; Harris, AM; and Steinman, AD. 2016. Alum application, invertebrate bioturbation, and sediment characteristics interact to affect phosphorus exchange in eutrophic ecosystems. Freshwater Science. 35:597–610.


O'Reilly, CM; Sharma, S; Gray, DK; Hampton, SE; Read, JS; Rowley, RJ; Schneider, P; Lenters, JD; McIntyre, PB; Kraemer, BM; et al. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys Res Lett. 42:10–773.

Orihel, DM; Baulch, HM; Casson, NJ; North, RL; Parsons, CT; Seckar, DC; and Venkiteswaran, JJ. 2017. Internal phosphorus loading in Canadian fresh waters: a critical review and data analysis. Can J Fish Aquat Sci. 74:2005–2029.


Paerl, HW; Scott, JT; McCarthy, MJ; Newell, SE; Gardner, WS; Havens, KE; and Hoffman, DK; Wilhelm, SW; and Wurtz, WA. 2016. It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environ Sci Tech. 50:10805–10813.


Schau, MH; Godwin, W; Battoe, L; Coveney, M; Lowe, E; Roth, R; Hawkins, C; Vindigni, M; Weinberg, C; and Zimmerman, A. 2010. Impact of the removal of gizzard shad (Dorosoma cepedianum) on nutrient cycles in Lake Apopka, Florida. Freshw Biol. 55:2401–2413.


Schindler, DW; Carpenter, SR; Chapra, SC; Hecky, RE; and Orihel, DM. 2016. Reducing phosphorus to curb lake eutrophication is a success. Environ Sci Tech. 50:8923–8929.


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Tammeorg, O; Niemistö, J; Möls, T; Laugaste, R; Panksep, K; and Kangur, K. 2013. Wind-induced sediment resuspension as a potential factor sustaining eutrophication in large and shallow Lake Peipsi. Aquat Sci. 75:559–570.


Weyhenmeyer, GA; Jeppesen, E; Adrian, R; Arvola, L; Blenckner, T; Jankowski, T; Jennings, E; Noges, P; Noges, T; and Straile D. 2007. Nitrate-depleted conditions on the increase in shallow northern European lakes. Limnol Oceanogr. 52:1346–1353.


Zhu, M; Zhu, G; Zhao, L; Yao, X; Zhang, Y; Gao, G; and Qin, B. 2013. Influence of algal bloom degradation on nutrient release at the sediment–water interface in Lake Taihu, China. Environ Sci Poll Res. 20:1803–1811.