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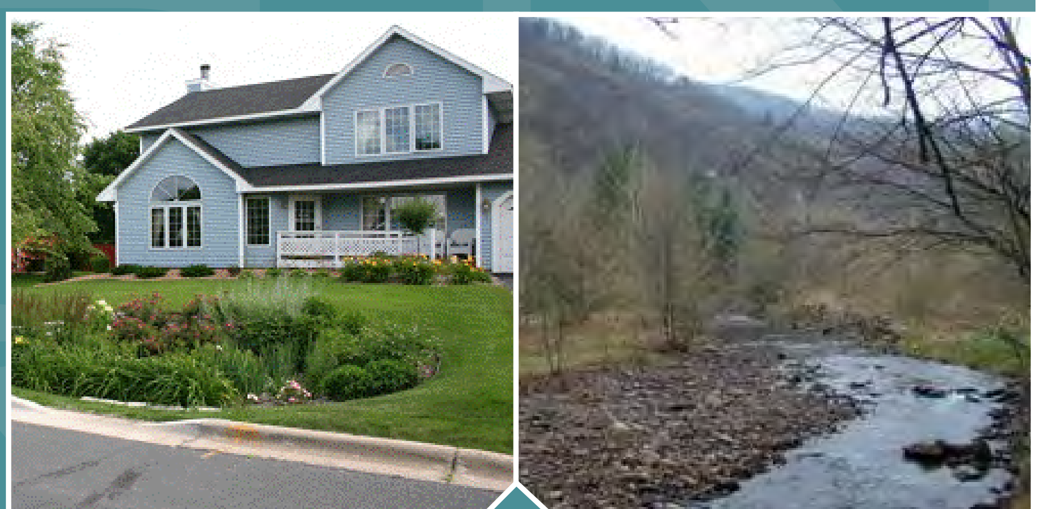
A Meta-Analysis of Phosphorous Attenuation in Best Management Practices (BMP) and Low Impact Development (LID) Practices in Urban and Agricultural Areas



Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

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Notice

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Contents

Notice ii
Abstract iv
Introduction and Objectives 1
Phosphorous as a pollutant 1
Phosphorus attenuation in the Environment 1
Phosphorus Biogeochemistry 2
Overview of water quality regulation in the United States 3
Mini-Review of P attenuation in urban BMPs and LIDs 5
Meta-analysis of Phosphorus Attenuation in BMPs and LID practices 6
Purpose of a Meta-analysis 6
Materials and Methods 7
Quality Metrics Used to Evaluate Data Inclusion 7
Results 8
Discussion 15
Future Research 18
Conclusions 19
Literature Cited 21

Table 1. Studies utilized as data sources for the Phosphorus Meta-Analysis 9
Table 2. P removal effectiveness (%) of Low Impact Development (LID) and Best Management Practices (BMPs) 11
Table 3. Comparison of P removal effectiveness (%) of Low Impact Development (LID) practices based on phosphorus type measured. 12

Figure 1. Comparison of phosphorus source 13
Figure 2. Relationship of P removal effectiveness 14

Abstract

While all living organisms require phosphorous to live and grow, adding too much phosphorus to the environment can cause unintended and undesirable effects, such as eutrophication of surface waters and harmful algal blooms. Urban and agricultural best management practice (BMP) and low impact development (LID) are often employed to improve water quality because of their ability to process and remove excess anthropogenic phosphorous (P) from surface and ground waters. Urban and agricultural BMPs and LIDs are land development approaches that attempt to mimic natural systems. The efficiency at which BMPs and LIDs remove P is not clearly understood because data that generalizes patterns of P removal across ecosystems and environmental conditions are not well synthesized. Here, we use existing scientific literature to conduct a meta-analysis to examine the capacity of various BMPs and LIDs to attenuate P. We identify patterns that are intended to inform resource managers about the most effective approaches for managing P. We found that P removal varies greatly among BMPs and local conditions such as soil type. We show the range of P removal effectiveness of a wide variety of BMPs and LIDs and identify processes that are contributing to P attenuation. We also describe an overview of the development of current federal water quality regulations contained in the Federal Code that have set the stage for implementing BMPs or LIDs in the context of managing water quality.

Introduction and Objectives

The goal of this report is to synthesize the existing scientific literature on the effectiveness of best management practices (BMP) and low impact development (LID) to improve water quality through their ability to process and remove excess anthropogenic phosphorous (P) from surface and ground waters. In urban settings, BMPs and LIDs are land development approaches that attempt to mimic natural systems in order to provide green space or to manage stormwater in urban or suburban environments (Passeport et al. 2013). In agricultural settings BMPs are primarily focused on incorporating natural features such as grass strips, riparian areas and wetlands to intercept runoff from the cultivated or agricultural managed areas as a means of attenuating anthropogenically derived nutrients and sediments. Specific techniques include, but are not limited to, constructing wetlands, green roofs, bioretention cells, planting riparian zones, restoring streams, and installing permeable pavement systems. BMPs and LIDs often are employed as nutrient management tools by resource management agencies by designing features that are intended to decrease the volume of stormwater runoff to drainage systems and streams by intercepting water, increasing infiltration, and/or disconnecting impervious surfaces from conventional stormwater networks. Despite significant research effort toward understanding the ecological functions of BMPs and LIDs, there remains no consensus for what constitutes optimal design to achieve maximum P removal effectiveness. The objective of this report is to identify patterns and trends of P attenuation reported in the published literature in order to provide guidance that will aid managers in making decisions about implementing BMPs and LIDs to better manage P as part of comprehensive watershed management plans.

Phosphorous as a pollutant

While all living organisms require P to live and grow, adding too much P to the environment can cause unintended and undesirable effects (Carpenter et al. 1998). Eutrophication occurs when excess P and/or nitrogen (N) is added to aquatic systems which stimulates the growth of algae which then die and decay, creating an over abundance of decomposing bacteria that consume the algae and, with it, the oxygen in the water, causing low-oxygen dead zones that suffocate aquatic life. Some of the algae that bloom during eutrophication are themselves toxic, producing harmful algal blooms (HABs) that can directly kill fish in the water or even livestock that drink the water.

Phosphorus attenuation in the Environment

There are two forms of P in the environment, organic and inorganic. Organic P (e.g., polyphosphate and organophosphate) is found as plant and animal biomass, metabolic waste (including sewage), and in pesticides (Carpenter et al. 1998). The main form of inorganic P is orthophosphate (PO_4^{-3}), a term used interchangeably with "phosphate" and with "reactive P", referring to the form of phosphorous that can be used directly by plants and microorganisms (USEPA 2012). Orthophosphate in the environment is derived from phosphate minerals (e.g. apatite minerals), fertilizers, detergents, and industrial chemicals.

Stormwater runoff and soil erosion are the main factors driving P transport. Phosphorus in the form of orthophosphate dissolved in stormwater (dissolved phosphate) and P associated with soil and/or organic matter (particulate phosphate) can be transported offsite and cause excess P to accumulate in the environment. However, under certain agricultural settings and biogeochemical conditions, orthophosphate can also be transported through the subsurface into groundwater (Domagalski and Johnson 2012). Particulate phosphate (PP) accounts for 75 to 90% of phosphate transported from cultivated land (Randall et al. 1998). Particulate phosphate is not immediately bioavailable but may become a source of orthophosphate that can dissolve when soil solution P levels are depleted. Dissolved phosphate (DP) is bioavailable and therefore, has the most immediate impact on aquatic systems. Phosphorus concentrations and loading are often monitored as total phosphorus (TP), a measure of both dissolved and particulate phosphate (USEPA 2012).

Phosphorus Biogeochemistry

P attenuation refers to the reduction in P concentration in water and soil through chemical and biological processes. Soil mineralogy and pH are important factors determining P attenuation in soil. Many soils bind tightly to large quantities of P, exchanging reactive soluble, forms for particulate, less bioavailable forms (Bohn et al. 1985). The chemical binding of P to soil particles (P sorption) occurs in the soil through fast and slow soil chemical reactions: 1. Fast reactions (about one day) include absorption and substitution between P and other anions (negatively charged molecules) on mineral surfaces; and 2. Slow reactions (several weeks or longer) include a complex combination of mineral dissolution and precipitation reactions between P and cations on the surface and within the inner-sphere of soil particles (Bohn et al. 1985). Phosphate reacts with Ca and Mg minerals as well as Al, Fe, and Mn oxide compounds in soil depending on soil pH (Bohn et al. 1985). At low pH, P forms poorly soluble Fe and Al compounds, at near neutral pH, P forms more soluble Ca and Mg compounds, and at higher pH, P forms poorly soluble Ca compounds (Bohn et al. 1985). Phosphate is most soluble in slightly acid to neutral pH soils. Under reducing conditions, P-Fe oxide compounds may dissolve, thereby releasing P (Denver et al. 2010).

Once soil P has reached its sorption capacity, excess P will dissolve, and then, can potentially be exported in water (Domagalski and Johnson 2012, Lucas and Greenway 2011). Phosphorus retention in BMPs is regulated by the equilibrium P concentration (EPC), the concentration at which P sorption equals desorption (Hoffmann et al. 2009). The EPC can dictate the soluble P concentration supported by soils (Indiati and Sharpley 1998). For instance, if the P concentration of the water entering is higher than EPC, soils will sorb P and be a P-sink. However, P will be released from soils if the P concentration entering is lower than EPC (Hoffmann et al. 2009). Mineralogy also influences EPC. EPC declines as the ratio of Al-oxides to Fe-oxides increases (Lucas and Greenway 2011).

Biological processes also play a role in P attenuation and release. Phosphorus is attenuated in soil through biological uptake. Bacteria, fungi, algae, and plants incorporate P into biomass (e.g., P is on average, 0.2% of plant dry weight (Bohn et al. 1985). However, plants vary in P demand and uptake effectiveness. Plants employ varied strategies to obtain the amount of P that they need to grow and thrive. Some of these strategies are: expansion of root network or root type to reach additional sources of P, chemical releases from the roots that increase solubility of soil bound P thus enhancing uptake, symbiotic interactions with fungi, bacteria, or other plants to provide bioavailable P in their root structure, and/or changing the way P is utilized (i.e. internal recycling of P, reduction of P loss from plant cells) to more efficiently recycle P when soil P is limited (Shen et al. 2011). Conversely, P is released from organic matter through decomposition. Decomposition rates depend on pH, litter quality (C:P:N), Ca content, redox potential, soil moisture, and temperature (Hoffmann et al. 2009).

Overview of water quality regulation in the United States

The United States Federal Government has been developing water quality regulations for the last 130 years. The first federal legislation was enacted by Congress in 1886 with the development of the River and Harbor Act and was subsequently re-codified in the Rivers and Harbors Act of 1899 (33USC407 1899) and represents the oldest Federal environmental law in the United States. Under this Act, the Federal Government gained authority to monitor, manage and regulate actions on the nation's rivers that would impact navigation. Under this Act, it became a misdemeanor to discharge refuse of any kind into navigable waters and tributaries of the United States without a permit. This section is also known as the Refuse Act which focused primarily on regulating impediments to navigation though the Act served indirectly to reduce water pollution.

Over the next half century, over 100 bills were brought forth in an attempt to address water pollution, but none of these bills were adopted. By 1948, urban growth and expanding industrialization brought on by World War II had created a situation where the amount and effects of uncontrolled pollution discharges were becoming problematic. The first legislation enacted by Congress to specifically empower the Federal Government to regulate water quality was passed in 1948 in the form of the Federal Water Pollution Control Act (FWPCA) (33U.S.C.1251-1376 1948). Although a step forward, this Act did not achieve the desired water quality goals because many legislators held that pollution control in water bodies was a responsibility of the States. Congress stated that the Act's purpose was to "provide a comprehensive program for preventing, abating and controlling water pollution". Congress reaffirmed that this policy was "to recognize, preserve, and protect the primary responsibilities and rights of States in controlling water pollution". As part of the compromise to get this bill passed, the Act requires the federal government to work cooperatively with states to develop plans to address water pollution. The Act relegated the federal authority to prepare pollution abatement plans and provide support to the states. The law did not specifically limit new sources of pollution, prohibit activities that caused pollution, or set standards to regulate pollutants from entering water bodies. This approach limited the enforcement authority of the federal government.

Over the next 14 years the FWPCA was amended six times. The 1956 amendment strengthens the federal authority to regulate pollution by no longer requiring States' consensus in order for the federal government to take actions to prevent and address pollution. The 1961 amendment gave authority to the Secretary of Health, Education and Welfare to develop research programs to evaluate the effects of pollution, identify potential treatment methods and evaluate water quality in the Great Lakes. Also, at the request of the States, the federal government was authorized to take steps to prevent pollution in navigable or interstate waters of the United States. In 1965, the FWPCA was amended to expand the federal role in pollution control by authorizing the development and establishment of water quality standards. The Clean Water Restoration Act of 1966 expanded on the previous amendments by establishing the federal government's authority to fine polluters for not filling out required reports, thus putting some "teeth" into the application of the FWPCA. With the development of standards in place, The Water Quality Improvement Act of 1970 expanded the federal role once again by establishing a State certification process to prevent water degradation below water quality standards. This Act requires that all States develop and implement a certification process for water quality. The federal government took on greater authority and thus responsibility for overseeing the Nation's streams and rivers. Along with this Act, the Environmental Protection Agency

(EPA) was created to become the lead federal agency responsible for the oversight and protection of the Nation's waters. With the creation of the EPA, the Federal Water Quality Administration, a part of the Department of Interior, was dissolved and all its functions, responsibilities and authorities were transferred to the EPA.

The FWPCA was amended in 1972 to include language stating that this Act was to "restore and maintain the chemical, physical and biological integrity of the nation's waters." The goal of this amendment was to provide water quality sufficient to protect fish, shellfish, wildlife and recreation ("fishable and swimmable"), eliminate discharge of large amounts of toxic substances into water, and eliminate additional pollutants into navigable waters of the US by 1985. This amendment made it illegal to discharge pollutants from a point source into waters of the US without a permit. The establishment of the National Pollutant Discharge Elimination System (NPDES) permit program made it mandatory for every point source discharger to obtain a discharge permit. It also required EPA to develop and implement technology-based effluent limitations into the NPDES permits. These amendments expanded the emphasis on water quality standards, made them applicable to interstate waters and required the permits to be consistent with state water quality standards. Additionally these amendments assigned authority to the Army Corps of Engineers to issue permits to dredge and fill in navigable waters. With the 1972 amendments, the FWPCA represented a significant expansion of the 1948 Act and became known from that point on as the Clean Water ACT (CWA). Contained within this amendment were the first efforts to evaluate the extent of non-point source pollution although little actual efforts were expended to implement any controls on non-point source pollutants.

The Water Quality Act of 1987 resulted in the adoption of new provisions for water quality standards in the CWA. One of the biggest concerns of Congress was that the States were relying by and large on narrative criteria to control toxics which left the actual amounts of toxics that could be discharged very non descript. To address this issue, Congress included section 303(c) (2) (B) in the amendments which required the development of numeric criteria for the discharge of toxic pollutants where they were likely to negatively affect the designated uses of those water bodies. These standards were still primarily for point source discharges and the development and adoption of these standards continues to be a long and arduous process. Still, the development of standards for non-point discharges was not made a priority focus and has languished far behind the development of standards for point source discharges.

Nonpoint source (NPS) water pollution regulations attempt to restrict and limit the amount of pollution entering the Nation's water bodies from diffuse effluent sources, primarily overland runoff and sub surface seepages from contaminated sources. NPS pollution originates primarily from urban/suburban or agricultural sources. NPS pollution may contain heavy metals, pathogens, nutrients, sediments, and organic contaminants. Addressing NPS is costly and difficult, as the origins of NPS pollution is often difficult to identify. Congress included section 208 of the CWA as a way to address the NPS problem (Szalay 2010). This section directed States and local governments to create management plans that would identify future waste treatment needs and also identify and control NPS pollution of water. This effort was focused at controlling both urban and agricultural derived NPS pollution. Currently 33 of the 50 States have water quality standards for nitrate, but not phosphorus for potable or drinking water sources as reported to EPA in the State Numeric Criteria Reports (USEPA 2013b). Additionally, there are ambient water quality criteria recommendations in place for lakes, reservoirs, rivers and streams of the US, with these criteria developed and applicable on a nutrient ecoregional distribution (USEPA 2013a). Section 208 did not provide an enforcement provision and primarily relied on federally funding these efforts in the hopes of getting the States to develop the control of NPS pollution. Lack of funding curtailed the section's objective. As part of the 1987 Water Quality Act, Congress included a section 319 directing States to identify waters that cannot meet water quality standards without control of NPS pollution. States must then develop BMPs designed to address these sources of impairment and an implementation plan to execute these practices (33U.S.C.1329 1948) (33U.S.C.1329 1948). States have the autonomy to choose from among various pollution control practices to remediate polluted waters. States have primarily taken the approach of adopting BMPs in both urban and agricultural settings. Low Impact Development (LID) often has been incorporated as part of the efforts to address the NPS pollution problem in the context of urban and suburban growth. It is these BMP and LID efforts under the broader umbrella of an approach called Green Infrastructure (GI) that represents the bulk of the efforts to control NPS pollution.

Mini-Review of P attenuation in urban BMPs and LIDs

A goal of Low Impact Development and Best Management Practice (LID/BMP) design is to alter hydrology of a site in order to reduce stormwater runoff (peak and volume), increase infiltration, groundwater recharge, protect streams, and/or remove pollutants to enhance water quality (Ahiablame et al. 2012). Examples of structural LID/BMP practices include: bioretention (rain garden), infiltration wells/trenches, stormwater wetlands, wet ponds, level spreaders, permeable pavements, swales, green roofs, vegetated filter/buffer strips, sand filters, smaller culverts, and water harvesting systems such as rain barrels/cisterns (Passeport et al. 2013). These practices promote infiltration, water residence, and increase subsequent pollutant biodegradation (Ahiablame et al. 2012). In contrast, conventional stormwater management systems route water offsite as fast as possible through conveyance structures that do not allow time for attenuation of pollutants like P (e.g., pipes and concrete channels, (Ahiablame et al. 2012).

Several LID/BMP practices promote processes that may improve P attenuation. Designs that sustain physical (settling and filtration), physicochemical (adsorption, precipitation, and ion exchange), and biological (plant and algal uptake) processes have the highest potential for P removal (Scholes et al. 2008). Key to the effectiveness of these processes on P removal is efficient contact ratios between stormwater and substrate/vegetation (Scholes et al. 2008). Scholes et al. (2008) suggested several BMP characteristics that influence P removal: dry/wet area volumes, stormwater retention times, flow attenuation, vegetation, presence of sorption sites and pore sizes of substrates, infiltration potential, and aerobic/anaerobic conditions.

Ahiablame et al. (2012) recently reviewed the effectiveness of LID practices on nutrient (N or P) removal, reviewing 250 published studies on bioretention, permeable pavements, green roofs and swale systems. However Ahiablame et al. (2012) only reported P removal data from 9 studies which showed a range of -3 to 99% P removal effectiveness in bioretention, permeable pavement, and swale systems (Ahiablame et al. 2012). Only one of these studies recorded a negative value, indicating P release. In contrast, Ahiablame et al. (2012) reported that green roofs did not retain any significant amount of P, but instead were a significant source of P. Ahiablame et al. (2012) did not provide information about the features, factors, or indicate processes that contributed to those P removal ranges. There is critical need to identify mechanisms of P removal and transformation LID/BMPs in order to better guide P management.

Meta-analysis of Phosphorus Attenuation in BMPs and LID practices

Purpose of a Meta-analysis

Meta-analysis is a powerful statistical tool to summarize, synthesize, and evaluate independent research studies in order to reach general conclusions. Meta-analysis allows data from multiple studies to be combined within a rigorous statistical framework that provides range and magnitude of effects, predictive relationships among factors, and measures of variability. Mayer et al. (2007) successfully used meta-analysis to determine riparian buffer characteristics associated with removal of nitrogen and identified considerations for future research. Our goal was to perform a meta-analysis of P attenuation in LID/BMPs in order to help identify the factors contributing to P attenuation and to provide ranges of P removal effectiveness among these practices.

In order to perform our meta-analysis, we obtained data about P removal in LID/BMPs from published literature. We performed an extensive literature search using Web of Knowledge, ScienceDirect, Google, Google Scholar, PubMed, and Cambridge Abstracts. We searched terms singly or in combination including: bioretention, buffer strips, filter, green roofs, permeable pavement, rain garden, riparian, BMP, green infrastructure, stormwater, P, phosphate, urban, removal, and LID. We limited search results to peer-reviewed studies with original data describing P removal effectiveness of LID/BMP practices. Papers that did not specifically measure P influent and effluent concentrations from LID/BMPs were excluded from the study.

We created an Access Database and extracted meta-data from the papers including study location, LID/BMP, source of P, vegetative cover type, P flow path distance, soil texture, P type, P inflow and outflow concentrations, and percent removal effectiveness ((inflow concentration – outflow concentration/inflow concentration) x 100). These data were used to identify ranges of P removal effectiveness. We also analyzed P removal effectiveness based on LID/BMP type, source of P, vegetative cover type, P flow path distance, soil texture, and P type measured (orthophosphate/phosphate or total P) using a non-parametric test (Kruskal-Wallis (K-W) one-way analysis of variance on ranks) with JMP v. 5.0.1a and model fitting with SigmaPlot 12.0.

Quality Metrics Used to Evaluate Data Inclusion

The data used in the meta-analysis was secondary data from the literature. No new data was generated in this project. To help ensure data quality, we used data that was from published papers that were subjected to a peer review process as part of the journal requirements. In an effort to evaluate/control data quality of literature sources used in this project, the papers must have used standard analytical methods (i.e., methods published and used by more than one author in a peer-reviewed journal); sampling methods and designs must include and identify P-inflow and outflow concentrations, P type, and P removal efficiency within that BMP/LID. Works that were included in this effort were from the primary literature and clearly stated the analytical methods used to produce the data, included pertinent project, site, and BMP LID characteristics (location, BMP LID type, width, soil texture, vegetation cover, flow path, etc.). To be included in the list of data sources, the data contained in the papers must be amenable to calculations of relative changes in phosphorus associated with the selected BMPs or LIDs as described in the papers. Ultimately the data used in this report is the product of the works of other researchers. It is strongly encouraged that the reader look at these works first hand before any subsequent analysis of the data or use of the data is done.

Results

We found 154 papers that included search terms but only 44 had information on P influent and effluent concentrations (Table 1). These 44 studies included 348 data examples of P removal effectiveness in biofilter, bioretention (including rain gardens), buffer strips, filter strips, filter systems, green roofs, permeable pavement systems, riparian buffers, and wetland BMPs. We noted that there is ambiguity throughout the literature regarding the definitions of buffer strips vs. riparian buffers, biofilters vs. bioretention, and other similar terms. Because there is no nomenclature guidance and because we did not want to misclassify or inadvertently lump BMP's or LID's, we took the original authors' classification at face value and retained the original categories as listed. Data came from eight countries: Australia (21% of data), Canada (18%), Denmark (3%), New Zealand (0.8%), The Netherlands (0.8%), United Kingdom (4%), and USA (52%). USA data came from eleven states: Midwest (12%), Northeast (16%), Northwest (0.5%), Southeast (70%), and the Southwest (1%). Phosphorus removal effectiveness ranged from -488% to 100% across all studies, however only 18% of all of the records showed P release from BMPs (i.e., a negative percentage of P removal).

The ranges of P removal effectiveness differed by LID/BMP type (Table 2). Phosphorus removal effectiveness differed among the 9 LID/BMP types (Kruskal-Wallis (K-W) one-way analysis of variance on ranks, $P < 0.0001$). Tukey HSD mean comparison showed that mean P removal effectiveness of Biofilter (76%) was significantly higher than Bioretention (18%), Buffer Strips (5%), Riparian Buffers (-2%), and Green Roofs (-20%). In addition, P removal in Filter Strips (47%) was significantly higher than Buffer Strips (5%), but no differences were found between any other practice types.

The percentage of data showing P release also varied by LID/BMP type: Biofilter (0% showed P release), Bioretention (23%), Buffer Strips (30%), Filter (0%), Filter Strips (12%), Green Roofs (100%), Permeable Pavement (0%), Riparian Buffer (30%), Wetland (38%). The variability was large across studies (Table 2). Highly engineered/controlled practices showed the lowest variability: Biofilter (CV=0.21), Filter (CV=0.24), and Permeable Pavement (CV=0.54); while practices that utilized and/or established vegetated strips showed the highest variability: Buffer Strips (CV=13.23), Riparian Buffer (CV=64.48).

Studies presented P removal effectiveness as either total phosphorus (DP + PP) or Orthophosphate (DP). There was no difference in P removal effectiveness across all studies by P type (K-W, $P = 0.85$). However, P type (TP or DP) had a significant effect on P removal effectiveness in Biofilters, Filter Strips, and Permeable Pavement. For Biofilter (K-W, $P = 0.01$) and Filter Strips (K-W, $P = 0.001$), mean P removal effectiveness was significantly higher for TP, and for Permeable Pavement (K-W, $P<0.0001$), mean P removal was significantly higher for Orthophosphate (Ortho-P, Table 3).

We also analyzed the fate and removal of P depending on source of P as either from stormwater (including natural concentrations from overland runoff) or from P concentrations prepared in the laboratory (synthetic). Across all mean P, removal effectiveness was significantly higher when P entered the BMP as a synthetic solution than as stormwater (52% versus 9% mean P removal effectiveness; K-W, $P <0.0001$). Among LID/BMP types, bioretention was most effective at removing P entering as synthetic solution (K-W, $P = 0.0025$), although student-t mean comparison was not significant (Figure 1). Phosphorus removal in Filter Strips differed between

Table 1. Studies utilized as data sources for the phosphorus meta-analysis

Publication	Biofilter	Bioretention	Buffer Strips	Filter	Filter Strips	Green Roofs	Permeable Pavement	Riparian Buffer	Wetland
Abu-Zreig et al. (2003)					X				
Barrett et al. (1998)					X				
Beecham et al. (2012)							X		
Berretta and Sansalone (2012)				X					
Bratieres et al. (2008)	X								
Carpenter, et al. (1998)		X							
Chapman and Horner (2010)		X							
Chaubey, et al. (1994)					X				
Chaubey, et al. (1995)					X				
Davis et al. (2001)		X							
Davis et al. (2006)		X							
Davis (2007)		X							
DeBusk and Wynn (2011)		X							
Deletic and Fletcher (2006)					X				
Dietz and Clausen (2005)		X							
Dillaha et al. (1989)					X				
Hathaway et al. (2008)						X			
Hatt et al. (2007)				X					
Hatt et al. (2009)		X							
Heinen et al. (2012)			X						
Hoffmann et al. (2012)									X
Hunt et al. 2006)		X							
Hunt et al. 2008)		X							
Istenic et al. (2012)				X					

Publication	Biofilter	Bioretention	Buffer Strips	Filter	Filter Strips	Green Roofs	Permeable Pavement	Riparian Buffer	Wetland
Kandasamy et al. (2008)				X					
Kohler et al. (2004)									X
Lee and Dunton (1999)					X				
Lowrance and Sheridan (2005)								X	
Lucas and Greenway (2011)		X							
Luell et al. (2011)		X							
Mankin et al. (2007)								X	
McKergow et al. (2006)								X	
Mothersill et al. (2000)		X							
O’Neill and Davis (2012 a,b)		X							
Parsons et al. (1994)					X				
Passeport et al. (2009)		X							
Schellinger and Clausen (1992)					X				
Schmitt et al. (1999)					X				
Sheppard et al. (2006)			X						
Srivastava et al. (1996)					X				
Tota-Maharaj et al. (2010)							X		
Wilcock et al. (2012)									X
Winston et al. (2011)					X				
Yong et al. (2011)							X		

Table 2. P removal effectiveness (%) of Low Impact Development (LID) and Best Management Practices (BMPs)

Practice Type	N	Mean	Median	CV	Minimum	Maximum
Biofilter	24	76	82	0.21	40	95
Bioretention	59	18	63	5.63	-443	98
Buffer Strips	47	5	14	13.23	-331	77
Filter	10	75	82	0.24	41	92
Filter Strips	138	47	60	1.14	-258	100
Green Roofs	8	-20	-20	-0.32	-27	-11
Permeable Pavement	33	49	34	0.54	17	93
Riparian Buffer	21	-2	46	64.48	-466	73
Wetland	8	25	40	3.3	-127	97
	348					

Table 3. Comparison of P removal effectiveness (%) of Low Impact Development (LID) and best management practices (BMPs) based on phosphorus type measured.

Practice Type	P Type	N	Mean	Median	CV	Minimum	Maximum
Biofilter							
	Ortho P	12	66	68	0.26	40	90
	Total P	12	85	84	0.07	77	95
		24					
Bioretention							
	Ortho P	23	32	76	3.82	-443	98
	Total P	36	9	40	9.48	-240	97
		59					
Buffer Strips							
	Ortho P	22	3	8	16.66	-160	76
	Total P	25	6	15	11.65	-331	77
		47					
Filter							
	Ortho P	3	89	90	0.04	85	92
	Total P	6	70	74	0.30	41	91
		9					
Filter Strips							
	Ortho P	52	21	43	3.56	-258	100
	Total P	86	63	65	0.38	-27	100
		138					
Green Roofs							
	Total P	8	-20	-20	-0.32	-27	-11
		8					
Permeable Pavement							
	Ortho P	12	79	82	0.14	60	93
	Total P	21	31	27	0.38	17	60
		33					
Riparian Buffer							
	Ortho P	4	-59	-24	-2.07	-233	48
	Total P	17	11	53	11.16	-466	73
		21					
Wetland							
	Total P	8	25	40	3.30	-127	97
Total Count		348					

stormwater and synthetic sources (K-W, $P = 0.06$, synthetic 53% versus stormwater 24%) (Figure 1).

The mean influent concentration entering BMPs differed between those using synthetic (4.59 mg/L) solutions and those using stormwater (0.701 mg/L). Phosphorus influent concentration explained a small but significant portion of the variance in BMP P removal effectiveness ($R^2 = 0.03$, $P = 0.02$, $N = 168$; Model $y = ax^b$). That is, P removal effectiveness tended to increase with increased P influent concentration. There was an even stronger relationship between P influent concentration and P removal effectiveness for Permeable Pavement ($R^2=0.82$, $P <0.001$, $N = 33$; Model $y = ax^b$), and Filter Strips ($R^2=0.22$, $P =0.03$, $N = 21$; Model $y = ax^b$ (Figure 2). The model was chosen based on Mayer et al (2007).

We recorded the distance that influent P flowed to the outlet as P path distance. This is height, length, or width between input source and outlet collection port reported by author. Phosphorus path distance explained a significant portion of the variance in Permeable Pavement P removal effectiveness ($R^2 = 0.90$, $P < 0.0001$, $N = 27$; Model $y = ax^b$), but not for any other practice. For Permeable Pavement, P influent concentration and P path distance was significantly correlated ($R^2 = 0.78$, $P < 0.0001$, $N = 27$; Model $y = y_0 + ax$).

Soil texture also influenced P removal effectiveness. Across all practices, soil texture had a significant effect on P removal

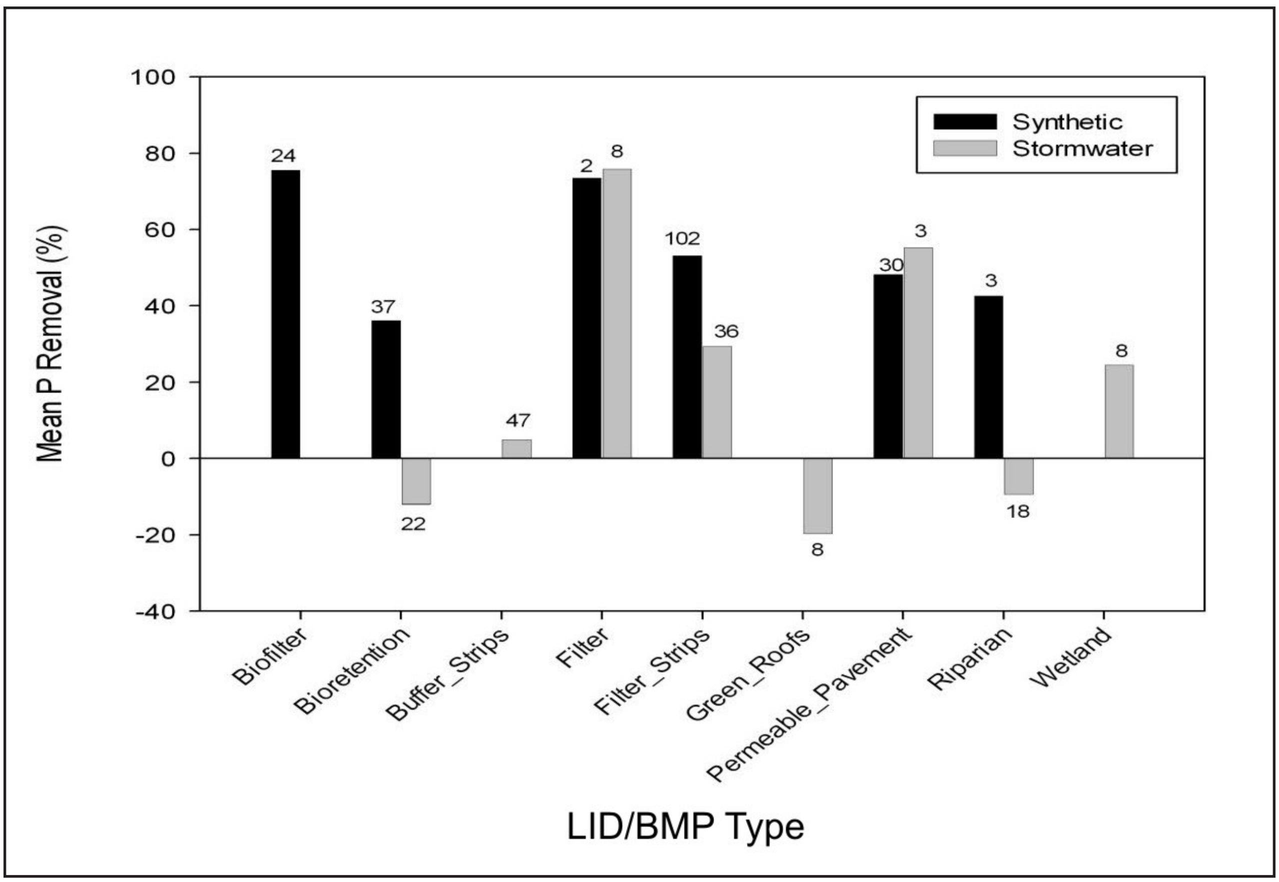

Figure 1. *Comparison of phosphorus source (synthetic or stormwater) on mean P removal effectiveness (%) of Low Impact Development (LID) and Best Management Practices (BMPs). Numbers on top of bars are the number of measurements associated with the mean.*

effectiveness (K-W, P = < 0.0001), but Tukey HSD mean comparisons showed only silt loam (52% mean P removal effectiveness) as significantly higher than clay soil texture (2%) and no other significant differences among soil texture means. When looking at individual practices separately only Filter Strips P removal effectiveness showed a response to soil texture (K-W, P = 0.012). Tukey HSD mean comparisons showed that silty clay loam (63% mean P removal effectiveness) and silt loam (53%), had significantly higher P removal effectiveness than loam soil texture (-39%) in filter strips.

Vegetation cover type showed no effect on P removal effectiveness across all LID/BMP types. (K-W, P = 0.115). Furthermore, vegetation type had no effect within any LID/BMP type.

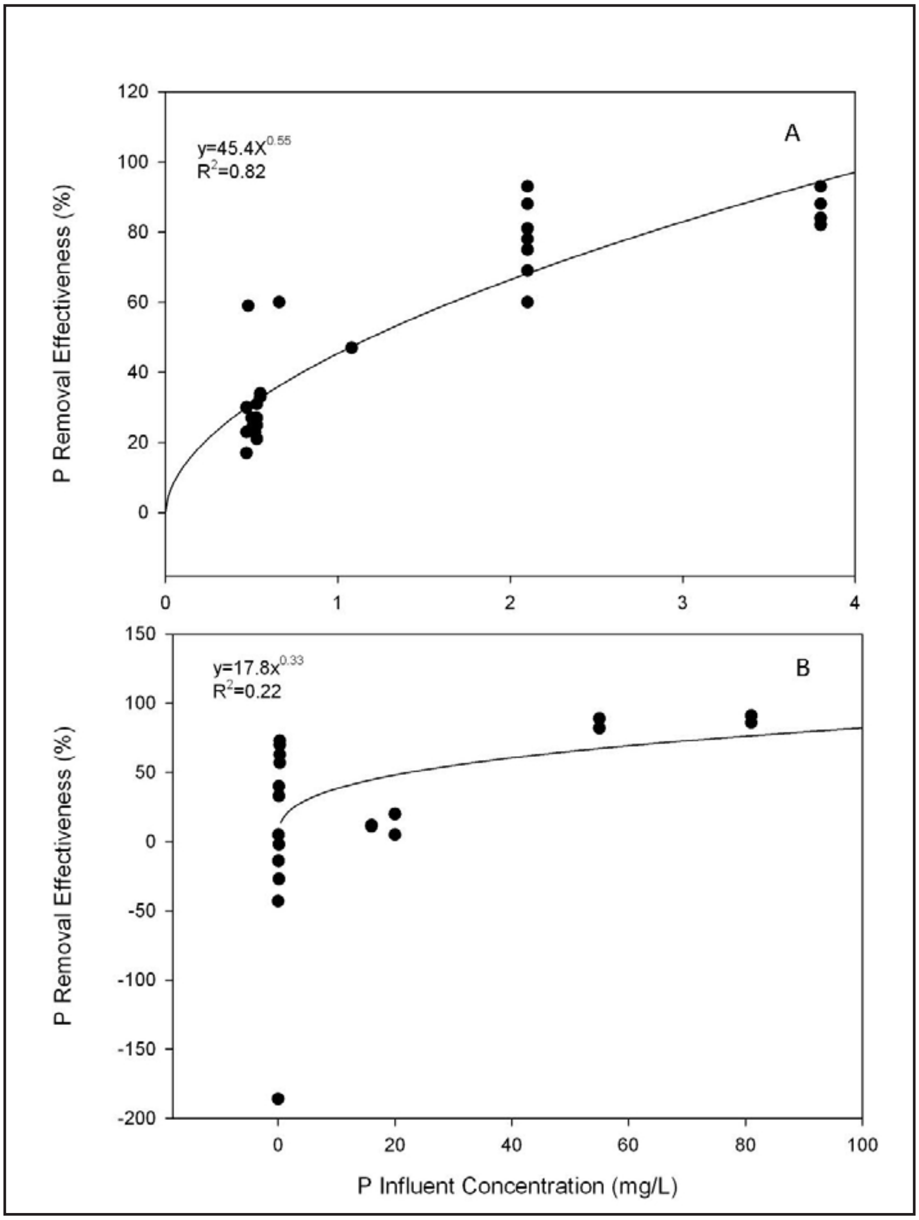

Figure 2. *Relationship of P removal effectiveness (%) to P influent concentration in A. Permeable Pavement, and B. Filter Strips. Lines are fitted to model $y = ax^b$. Fit to model is significant ($P < 0.05$).*

This report is the first meta-analysis of P removal effectiveness of urban LIDs and BMPs that identifies factors and processes that affect P attenuation. We report P removal effectiveness from a larger variety of LID and BMPs and larger number of studies than recent reviews (Ahiablame et al. 2012). However, the limited sample size of some LID/BMP types, large variability across studies, and limited geographic distribution restricts interpretation to broad patterns and general processes. Our goal was to show the range of P removal effectiveness of LID/BMPs and identify processes that are contributing to P attenuation and/or P release. We found that P type (TP or DP), P source (synthetic or stormwater), P influent concentration, P path distance, and soil texture influenced P removal effectiveness.

Unlike Ahiablame et al. (2012) who only reported P ranges from nine papers, we found that most LID and BMPs show both substantial P attenuation and P release. The ranges of P removal effectiveness were large with high variability. Single practices (e.g., bioretention) employed a wide range of designs with different dimensions, media characteristics and vegetation types, as well as different conditions including P type, P source, and P influent concentrations. Practices that were specifically designed to adsorb and filter pollutants (Permeable Pavement, Filters, and Biofilters) are the only practices in the meta-analysis that attenuated P without showing any P release and had lower removal variability among studies.

The P removal effectiveness differed depending on the type of P measured. Total P removal was higher in Biofilter and Filter Strips than DP. Phosphorus removal in Permeable Pavements was significantly higher for DP than TP, suggesting the relative importance of different processes in these practices such as filtration and settling for Biofilter and Filter Strips and absorption for Permeable Pavement (Scholes et al. 2008). Our analysis suggests that the type of P measured may dramatically alter the interpretation of the effectiveness of P removal reported for BMP/LID practices.

Phosphorus source and influent P concentration entering the BMP/LID practices affected overall P removal effectiveness. Phosphorus entering as stormwater resulted in lower P removal effectiveness than P entering as synthetic solutions. The main difference between P sources is the P influent concentration; the mean P influent concentration of synthetic P solutions was over 6 times larger than the mean P concentrations added as stormwater in these studies. Therefore, it is likely that the effect of P source is a function of P influent concentration. We found a significant positive relationship between influent P concentration and P removal effectiveness, a result consistent with other studies. In a study of filter materials, Cucarella and Renman (2009) also found that P removal effectiveness increased with higher initial P concentrations, with maximum P sorption occurring at the highest initial P concentration. Rosenquist et al. (2010) found that P removal is dependent on and directly correlated with the concentration gradient present between solution and adsorbed P. They suggested that P removal during a given event is likely dependent on previous P loadings of the media and concentration of P influent. Their research predicted several potential P removal outcomes related to P concentration gradient: 1) Less P removal may occur for lower influent concentration than for higher influent concentrations; 2) For equivalent influent P concentrations, P removal in a BMP will likely decrease with fewer available sorption sites; 3) BMP substrates will likely slowly gain additional concentration gradient after P diffuses into media micropores; 4) Phosphorus removal effectiveness may be increased by increasing influent concentration, through the addition of more sorption sites, or by harvesting P from substrate.

Phosphorus content of the media/soil may also affect P removal effectiveness. Several studies showed that the initial P content of the BMP/LID practice media is critical to P removal performance (Davis et al. 2009, Hunt et al. 2006, McKergow et al. 2006). These studies looked at media P retention index (the ratio of P adsorbed in the solution to the concentration of P remaining in solution at equilibrium) of soil to explain differential P removal performance. Hunt et al. (2006) stated that a high P index in bioretention media (indicating that the media was saturated with P) was the reason that the BMP was unable to sorb P from stormwater. However, out of the 44 papers that we reviewed, only three included a measure of P index.

Phosphorus path distance was not a clear indicator of P removal effectiveness in this meta-analysis. While hydraulic pathways of P influent within BMP/LID practices are important to increase contact time between influent and substrate and therefore absorption, settling, and filtration processes (Scholes et al. 2008), the distance between influent source and outlet sampling port (P path distance) did not influence P removal effectiveness. The exception is in Permeable Pavement, but in this case P path distance was correlated with P influent concentration confounding the result. Phosphorus path distance alone may not properly indicate dry and wet area/volumes stormwater retention and drain down times, or hydraulics/flow attenuation processes important for P retention (Scholes et al. 2008). Phosphorus retention may increase with riparian buffer width due to longer transport pathways that allow more time for retention or dilution (Schmitt et al., 1999), however, sediment removal efficiency (and, therefore, particulate P removal) is dependent upon slope; slopes greater than 10% result in decreased P retention (Zhang et al. 2010). In a review of riparian buffer characteristics on P removal, Zhang et al. (2010) found a positive curvilinear (asymptotic) relationship of P removal efficiency (%) with riparian buffer width and that, about 35% of the variance in efficiency depends on width alone. Nearly 100% of P is removed in buffers >20 m wide (Zhang et al. 2010). Sheppard et al. (2006) suggested vegetated buffer strips be 10 to 90 m wide, and Davis et al. (2009) suggested that bioretention media depth be 0.75 m in order to optimize P removal. Similarly, wider buffers more efficiently remove nitrogen (Mayer et al. 2007; Zhang et al. 2010), but unlike P, ground water flow paths dictate efficient nitrogen removal (Mayer et al. 2007). Although P may be efficiently retained in buffer zones, remobilization of dissolved reactive P may occur thereby creating source zones for P depending on the degree of P saturation, soil type, and size of buffer area compared to the source area (Dillaha et al., 1989; Lee et al. 1989; Uusi-Kämppä, 2005;).

Soil texture affected P removal effectiveness. For instance, loamy sand, sandy loam, and loam soil textures are recommended in bioretention specifications in order to allow high infiltration rates and because soils with clay content >30% can lead to failure of the BMP (Davis et al. 2009). Our meta-analysis also found that media with a coarser texture had higher mean P removal effectiveness compared to finer clay materials. Others have shown that clay materials may provide more P-sorption sites but coarser materials may provide better hydraulic conditions to support absorption, settling, and filtration processes (Hoffmann et al. 2009, Scholes et al. 2008). In a review of P removal, Zhang et al. (2010) did not find an effect of soil type on P; however, evidence from others showed higher retention of total P and dissolved P in sandy soils than in silty clay soils (Magette et al., 1989; Schwer and Clausen, 1989).

Vegetation cover type played no role

in P removal effectiveness. Our meta-analysis showed no difference on P removal effectiveness among BMP/LID practices that had grass, forbs, trees or were bare. Hoffmann et al. (2009) and Zhang et al. (2010) reported better P retention with trees or shrubs compared to grass. However, some authors suggest that the benefit of vegetation may be in the increased infiltration and sedimentation due to improved soil structure and soil permeability related to plant roots (Davis et al. 2009, Sheppard et al. 2006). Lucas and Greenway (2011) found that P retention by barren media eventually becomes exhausted due to long-term exposure of P, but vegetation delays P saturation by extending P sorption capacity.

Future Research

Phosphorus removal effectiveness is determined by design features that support effective absorption, filtration, settling, and biological processes (Scholes et al. 2008). However, most studies do not record the meta-data that will help identify which processes are at work and design parameters that can improve P removal effectiveness. For instance, P removal effectiveness of a material is closely related to material Al, Fe, Ca content and pH (Cucarella and Renman 2009). However, only four authors included in our study reported any information about mineralogy and only six authors reported pH. Reporting essential information about mineralogy and pH will allow for better estimates of P removal effectiveness. We support the Davis et al. (2009) conclusion that BMP/LID research needs to clearly identify fill media composition, media depth and geometry (perimeter area, surface area, media volume, and perimeter area to surface area ratio); drainage configuration, and vegetation rooting types and depths. In addition, reporting local hydrology, such as magnitude and duration of storms/flooding, residence times, and sediment deposition rates (Hoffmann et al. 2009) are critical to understand P removal processes in LID/BMPs.

BMP’s and LID’s show varying effectiveness at removing P. Our data show that there is no single best practice but rather a suite of practices that may work better under one circumstance or another. Multiple considerations need to be taken into account prior to selection of BMP/LID approach such as the form of P in the water stream, source of P, soil texture, slope, and available area for BMP/LID placement. The presence of other stressors may impact the effectiveness of some approaches. For example, N removal and P removal may at times be at odds with one another because conditions (e.g. low dissolved oxygen, reducing conditions) that are prime for fostering denitrification, a natural microbial process that consumes nitrate nitrogen, may lead to conditions that cause an increase in P flux. Another consideration is the potential for a BMP/LID to provide stacked benefits in addition to P removal such as flood and sediment control, increased water infiltration, or increased aesthetics. Resource managers may need to weigh trade-offs in the efficiency of a practice to remove P with the efficacy of that practice to provide other benefits.

Costs associated with various BMPs/LIDs were not considered here but, of course, drive many resource management decisions. A thorough cost-benefit analysis would further improve the decision making process for selecting effective practices. While engineered approaches may be effective and demonstrate lower variability in ranges of effectiveness, maintaining and protecting existing natural buffers, riparian zone, and wetlands may be far cheaper in the long-run than constructing BMPs/LIDs that may or may not emulate those natural features. Furthermore, the longevity of engineered practices has not been assessed. The costs of practices must be amortized over the expected functional life of the BMP/LID.

Improved understanding of the importance of historic land use practices is emerging as a key to quantifying current impacts from P and identifying the most effective means to mitigate P in water runoff. For example, colonial-era water mill construction affects current P loads to streams in the mid-Atlantic because of the vast deposits of P-laden legacy sediments now eroding from floodplains to downstream water bodies and estuaries including the Chesapeake Bay (Walter and Merritts 2008. In such cases, removal of sediments as a source of P may be an effective management and restoration practice (Hartranft et al., 2011; Merritts et al., 2011).

Further research is necessary to explain the considerable variability in the performance of BMP/LID practices (see above) and to model watershed-scale removal rates. Research designed to specifically fill gaps about effectiveness of various BMP/LID approaches will help to facilitate better decisions on which practices should be used and where. For example, we know of no studies that have examined the implementation of multiple BMPs or LIDs in tandem to determine if there may be positive synergistic effects of certain practices. Also, we know of no studies that have examined that possibility that, while continuing to be effective at retaining P, some BMPs may simultaneously become sources of other pollutants of concern such as heavy metals, e.g., bioretention ponds near roads accumulating copper residue from automobiles.

While P reduction is an objective for restoring many impaired waters, globally the supplies of P are limited and acute shortages are predicted for the future (Elser and Bennett 2011). It eventually may be necessary (and conceivably profitable) to implement certain BMPs/LIDs to capture and recycle P. Long term solutions to controlling excess P where it causes negative impacts while maintaining strategic reserves of this necessary nutrient will likely require a comprehensive approach including source control, improved distribution systems, land use management, appropriate BMP/LID practices, and functional policy.

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