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Utilizing Wetlands for Phosphorus Reduction in Great Lakes Watersheds: A Review of Available Literature Examining Soil Properties and Phosphorus Removal Efficiency

Steven J. Currie, Christine M. VanZomeren,
and Jacob F. Berkowitz

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Abstract

Excess nutrient loading continues to impact water quality within the Great Lakes. The Great Lakes Restoration Initiative (GLRI) seeks to improve water quality through the reduction of phosphorus inputs from surrounding watersheds. Both natural and constructed wetland ecosystems display the capacity to reduce phosphorus inputs in a variety of agricultural and urban settings. However, maximizing the efficiency and benefits of wetlands for phosphorus reduction requires an understanding of nutrient cycles, soil-nutrient interactions, legacy phosphorus, and other factors. The current report synthesizes existing literature related to wetland phosphorus retention, depicts opportunities for improving water quality outcomes, and identifies opportunities for further research.

Contents

Abstract ii

Figures and Tables v

Preface vi

Unit Conversion Factors vii

1 Introduction 1
- 1.1 Background 1
- 1.2 Purpose 2
- 1.3 Approach 2

2 Water Quality Challenges and the Use of Wetlands for Nutrient Reduction in the Great Lakes 4
- 2.1 Wetlands and P retention 4

3 Phosphorus Cycling in Wetlands 5
- 3.1 Common P forms in the environment 6
- 3.2 Phosphorus cycling in Great Lakes watersheds 7
- 3.3 Phosphorus transport in surface and subsurface water 8

4 Influence of Soil Properties on P Retention and Transport in Wetlands 11
- 4.1 Soil P sorption capacity 11
- 4.2 Iron, aluminum, and calcium 11

5 Wetland P Removal Efficiency 14

6 Legacy P 16

7 Determining Soil P Storage Capacity 19
- 7.1 Extrapolating the SPSC concept to a watershed level 20
- 7.2 Utilizing SPSC for siting construction activities 21

8 Research Within the Great Lakes Watershed 22
- 8.1 Measuring wetland inflow and outflow water 22
- 8.2 Phosphorus modeling 22
- 8.3 Review articles 23
- 8.4 Other studies 23

9 Knowledge Gaps and Opportunities for Further Research 26
- 9.1 Soil P retention capacity and legacy P in GLRI target watersheds 26
- 9.2 Incorporation of soil data to improve model outputs 27

10 Summary 28

References........29

Appendix A: Journals Researched........39

Appendix B: Citations Related To P In Agricultural Landscapes........41

Report Documentation Page

Figures and Tables

Figures

Figure 1. Excess P loading from surrounding watersheds results in poor water quality, including large algal blooms observed in Lake Erie (From Michalak et al. 2013). 1

Figure 2. Locations of priority watersheds and associated harmful algal blooms identified in the GLRI Action Plan II (From Great Lakes Restoration 2014). 2

Figure 3. Phosphorus cycling in wetlands (from Reddy and DeLaune 2008). POP, particulate organic P; PIP, particulate inorganic P; DIP, dissolved inorganic P; DOP, dissolved organic P; Al, aluminum; Fe, iron; Ca, calcium 5

Figure 4. Distribution of phosphate species as a function of pH (From Reddy and DeLaune 2008). 7

Figure 5. Solubility of calcium phosphates in comparison to aluminum and iron phosphates (From Reddy and DeLaune 2008). 12

Figure 6. Soil Phosphorus Storage Capacity (SPSC) concept for assessing the available soil capacity to retain P (From Nair et al. 2015). 20

Tables

Table 1. Great Lakes annual total P load estimates averaged from 1994–2008 data (MTA) (adapted from Dolan and Chapra 2012) 8

Table 2. Distribution of total P sources to Lake Erie 2003–2011 (adapted from Dolan and Chapra 2012) 8

Table 3. Wetland P removal efficiencies. 15

Table 4. Reported impact of legacy P on soil nutient concentrations and recovery timeframes across a range of soils. Adapted from Sharpley et al. (2013). 18

Table 5. Depicts P related research within the Great Lakes watershed and factors evaluated. TP, Total P; DP, Dissolved P/Dissolved Reactive P/Ortho P; SS, Suspended Solids; PP, Particulate P; I/O, Inflow/Outflow; GL, Multiple locations within the Great Lakes watershed; GL +. Areas within and outside of the Great Lakes watershed.*Modeling includes calculation of P budgets. 24

Preface

This study was conducted under the phosphorus optimized wetlands literature review - Great Lakes Restoration Initiative non-point source technical support project, project number 398004. This project was a joint effort by the U.S. Army Corps of Engineers (USACE) Buffalo District, the U.S. Army Research and Development Center, Environmental Laboratory (ERDC-EL), and the Great Lakes Research Initiative (GLRI). Mr. Tony Friona was the ERDC Great Lakes liaison during the study.

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The Commander of ERDC was COL Bryan S. Green and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
hectares	1.0 E+04	square meters

1 Introduction

1.1 Background

The Great Lakes Restoration Initiative (GLRI) was established in 2010 with the goal of restoring and protecting the largest system of fresh surface water in the world (Great Lakes Restoration 2014). Recent interest focused on excess nutrient loading within the region, which results in degraded water quality and the occurrence of harmful algal blooms (HABs) (Figure 1). Phosphorus (P) is required for both vegetation and microbial biomass production, limiting growth in most freshwater systems (Kadlec and Wallace 2009). As a result, increased P concentrations within the Great Lakes resulted in excess plant and algal growth leading to eutrophication and water quality impairments. In response, the GLRI Action Plan identified three watersheds (Lower Fox, Saginaw, and Maumee) as priority areas exhibiting high P export rates associated with agricultural and other land use practices (Figure 2). The GLRI Action Plan recommended reducing P export within these watersheds to address and mitigate water quality concerns.

Figure 1. Excess P loading from surrounding watersheds results in poor water quality, including large algal blooms observed in Lake Erie (From Michalak et al. 2013).

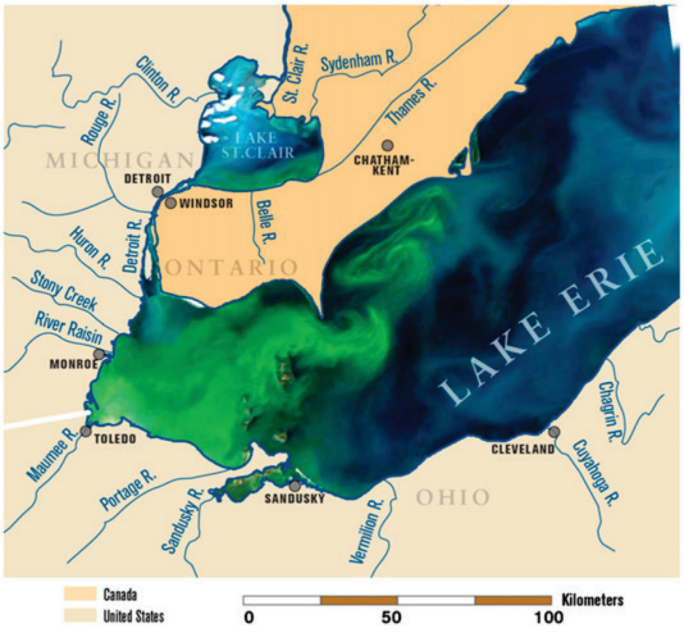
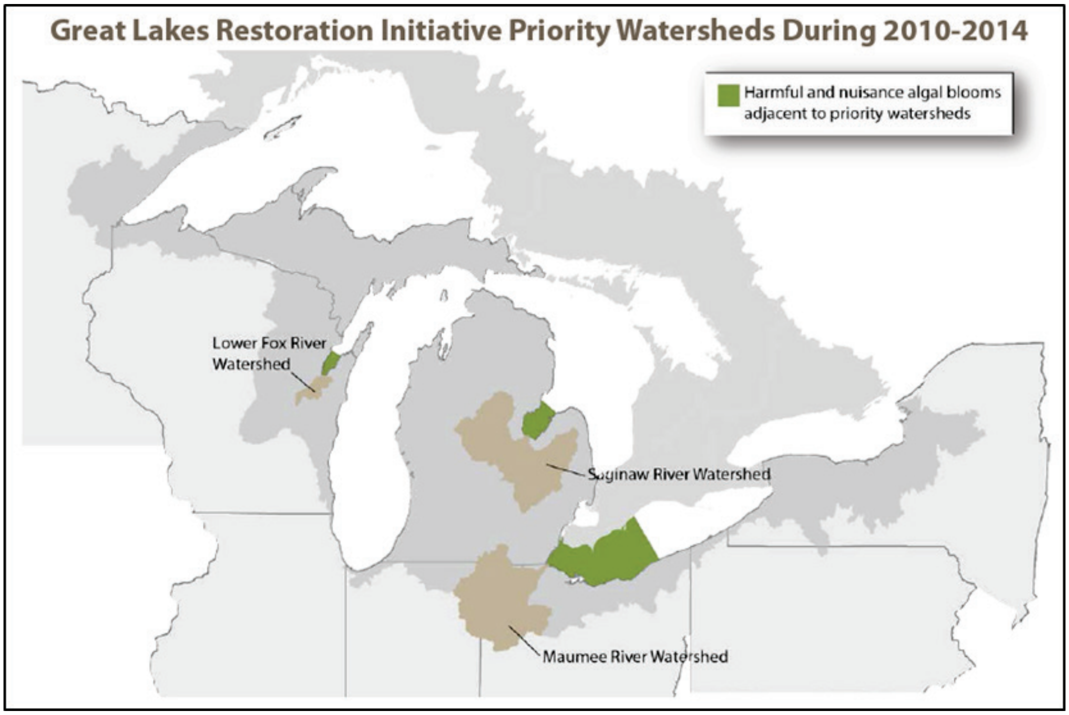


Figure 2. Locations of priority watersheds and associated harmful algal blooms identified in the GLRI Action Plan II (From Great Lakes Restoration 2014).



1.2 Purpose

The following report reviews available literature examining the potential for wetlands to contribute to water quality improvements within the Great Lakes region. The report highlights the challenges excess phosphorus (P) inputs pose to water quality, examines the current state-of-the-science regarding soil-water P interactions in wetlands, synthesizes data related to wetland P removal efficiencies, and identifies knowledge gaps and research opportunities for P reduction strategies utilizing natural and constructed wetland systems.

1.3 Approach

This report address topics related to the potential for wetland ecosystems to decrease P loading to the Great Lakes based upon a review of 116 peer-reviewed journal articles and published reports. Several other review articles provide an overview of P removal in agricultural and urban landscapes. However, as noted in the literature, data related to soil-nutrient interactions remains limited. Additionally, a number of published articles examine P removal efficiencies in wetlands, yet few reports synthesize data across multiple studies. As a result, the following review focuses on soil properties and processes related to P removal in wetlands

and P removal efficiencies. Specific focus areas addressed within the report include: (1) an introduction to water quality challenges facing the Great Lakes region, (2) a brief overview of the P cycle in wetlands, (3) soil and landscape factors influencing P dynamics, (4) phosphorus removal efficiency in natural and constructed wetlands, (5) determining wetland P removal capacity and, (6) identifying knowledge gaps and opportunities for additional research. A series of appendixes provide a list of resources examined along with abstracts for each publication cited.

2 Water Quality Challenges and the Use of Wetlands for Nutrient Reduction in the Great Lakes

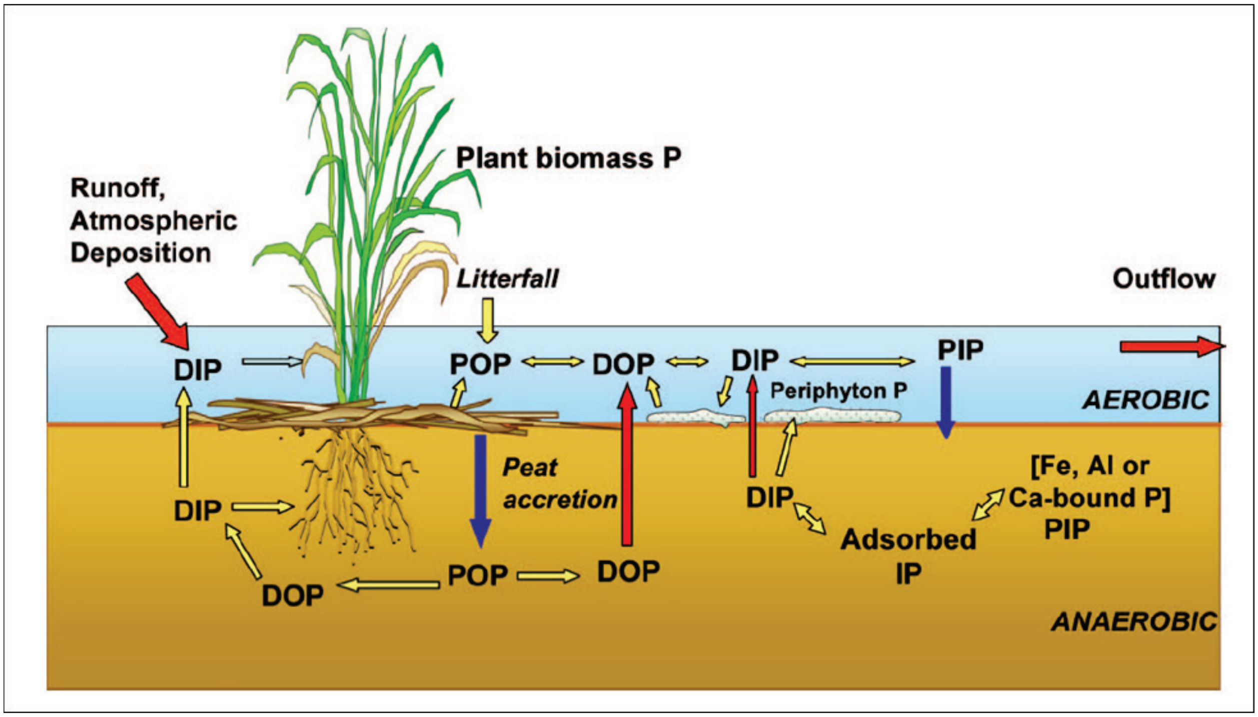
2.1 Wetlands and P retention

Wetlands display the capacity to intercept and retain P from surface and groundwater sources, limiting excessive P concentrations in open water lakes and reservoirs (Zedler 2003; Dunne et al. 2015). As a result, stakeholders within the Great Lakes region expressed interest in potential application of wetlands to reduce P loading (van Bochove et al. 2011; Wang and Mitsch 1998). However, P dynamics in freshwater systems remain complex (Reddy and DeLaune 2008). Optimizing the potential benefits of P reduction using wetland systems requires an understanding of landscape, soil, hydrologic, and other ecosystem factors related to P sources, forms, transport, and fate within the environment (Richardson 1985). Additionally, these factors influence management decisions related to prioritizing restoration, construction, and the timing, loading rates, and P removal capacity of wetlands (Beutel et al. 2014; Pant and Reddy 2003). Therefore, examining available literature related to P cycling, retention, release, and removal efficiency promotes development of optimal wetland systems for retention of P in the Great Lakes region.

3 Phosphorus Cycling in Wetlands

Phosphorus cycling in wetlands occurs through several ecosystem components or pools (i.e., soil, water, and vegetation) (Figure 3). Inorganic and organic P forms cycle through these components at different rates and time scales (Reddy and DeLaune 2008). Wetland P retention capacities depend on both biotic and abiotic processes (Nair et al. 2015). Biotic processes include incorporation of P into vegetation, plankton, and microorganisms. Abiotic retention processes include sedimentation and accretion, adsorption onto soil surfaces, precipitation, and P exchange between the soil and the water column.

Figure 3. Phosphorus cycling in wetlands (from Reddy and DeLaune 2008). POP, particulate organic P; PIP, particulate inorganic P; DIP, dissolved inorganic P; DOP, dissolved organic P; Al, aluminum; Fe, iron; Ca, calcium.



Short term retention and storage of P is facilitated by microbial and vegetation assimilation, which temporarily removes P from the available pool (Reddy et al. 1999). Active cycling of P in wetlands is regulated by microbial mediated mineralization of organic P. Mineralization transforms organic P to inorganic P, primarily as dissolved inorganic P. Dissolved inorganic P (DIP) is available for uptake by vegetation, assimilation into microbial biomass, or transport via concentration driven diffusion gradients. Microbial biomass typically accounts for <3% of the total P pool, but can reach values as high as 5–10% in P impacted wetlands (Groffman et al. 1996; Reddy et al. 2011).

Vegetation often plays a significant role in short term P retention (i.e., assimilation and storage). Retention rates depend on vegetation type and growth characteristics. For example, dissolved inorganic P is actively incorporated into above- and below- ground tissue through plant root uptake of P from the soil pore water. A substantial portion of incorporated P in above-ground tissues is translocated to below-ground tissue prior to senescence. The residual above-ground biomass is deposited on the soil surface and is incorporated into the soil as long term storage mainly in the form of organic P (i.e., dead plant materials).

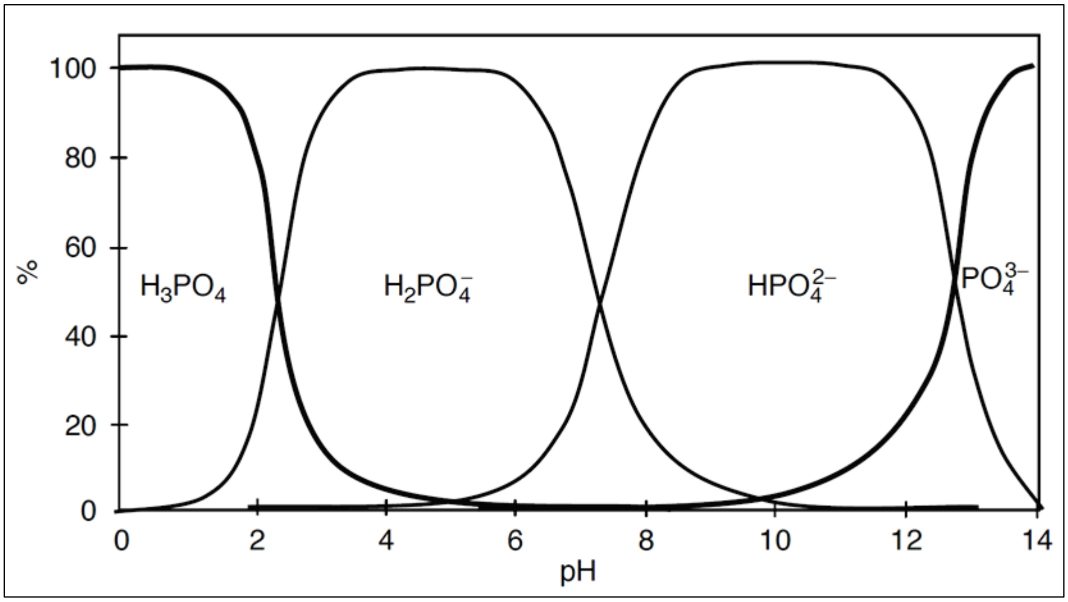
Long term retention is mediated by soil-P chemical interactions and accretion of organic matter (Figure 3) (Richardson and Marshall 1986). In mineral soils, inorganic P forms are retained by sorption onto clay particles, or iron and aluminum oxides and hydroxides (Mitsch and Gosselink 2015; Nair et al. 2015; Reddy et al. 1999). Phosphorus sorption is a two-step process wherein P is rapidly exchanged with the mineral surfaces of the soil (adsorption) followed by P slowly being incorporated into the soil phase (absorption; Kadlec and Wallace, 2009). This process continues until all available soil surfaces are saturated with P (Reddy et al., 1999). Notably, once all soil sorption sites become saturated with P, the wetland cannot retain additional P. As a result, P entering the system continues to move downgradient, increasing the potential for water quality impacts. If this scenario occurs, wetlands can be converted from a P sink to a non-point P source.

3.1 Common P forms in the environment

Phosphorus occurs in both dissolved (DP) and particulate (PP) forms in the environment. Dissolved P is categorized as inorganic or organic (DIP; DOP, respectively). Inorganic and organic particulate P (PIP; POP, respectively) are also common forms of P in wetlands. The PIP is P associated with clay particles and precipitates of Fe, Al, and Ca. The POP is P associated with biological material including decomposing bacteria, phytoplankton, and vegetation. Dissolved inorganic P is considered readily bioavailable (i.e. orthophosphate, soluble reactive P) whereas DOP, PIP, and POP require transformations to inorganic P before becoming biologically available (DeLaune and Reddy 2008). The settling of incoming suspended particulate P (PP) may be a significant P retention process, especially in areas with high erosion rates (Kadlac and Wallace 2009; Reddy et al. 1999) and warrants consideration when designing wetlands to intercept P from runoff.

Phosphorus speciation and availability is affected by both pH and soil oxidation-reduction potential. The form of orthophosphate (H_3PO_4, $H_2PO_4^-$, HPO_4^{2-}, or PO_4^{3-}) is pH dependent (Figure 4) (Reddy and DeLaune 2008). Orthophosphoric acid (H_3PO_4) is dominant at $pH < 2$ whereas PO_4^{3-} is dominant at $pH > 13$. The prevailing phosphate species under natural pH conditions are $H_2PO_4^-$ and HPO_4^{2-}. Under oxidized conditions, P is bound in Fe-P forms (i.e. strengite, $FePO_4$). Under reducing conditions, Fe is utilized as an alternative electron acceptor resulting in potential P release to the environment (Vepraskas et al. 2016).

Figure 4. Distribution of phosphate species as a function of pH (From Reddy and DeLaune 2008).



3.2 Phosphorus cycling in Great Lakes watersheds

Modeling efforts have been utilized to estimate annual P loading to the Great Lakes (Table 1). Results indicate that Lake Erie is experiencing the largest input of P among the lakes. This data, coupled with regular occurrences of HABs is likely the trigger for recent focus on Lake Erie. The Great Lakes Water Quality Agreement (GLWQA 2012) calls for particular emphasis on Lake Erie for minimizing P related water quality issues which has generated recent efforts to refine and update models for the Lake Erie basin.

Table 1. Great Lakes annual total P load estimates averaged from 1994–2008 data (MTA) (adapted from Dolan and Chapra 2012)

Lake	Total P Load
Superior	3144
Michigan	3485
Huron	3101
Erie	9388
Ontario	4798

Phosphorus entering the Great Lakes occurs through non-point (i.e., agricultural and urban runoff) and point (i.e., municipal wastewater discharge) sources with levels differing between watersheds and tributaries. Recent modeling efforts depict that non-point sources of P accounts for the majority of P entering Lake Erie (Table 2) (Maccoux et al. 2016). The DP and TP loads from tributaries within the Lake Erie basin are markedly variable as reported by Scavia et al. (2014). Differences have been attributed to land use. Crosbie and Chow-Fraser (1999) found that aquatic resources within agricultural dominated watersheds tended to be turbid and nutrient rich when compared with clear and nutrient poor surface waters draining forested landscapes. Soil-water contact time is a driving factor influencing the form of P ultimately discharged to downstream waters as interactions with the soil matrix along the flow gradient can result in P transformations (Christiansen et al. 2016).

Table 2. Distribution of total P sources to Lake Erie 2003–2011 (adapted from Dolan and Chapra 2012)

Source	Metric tons P per year
Non-point inputs	6183
Point inputs	1884
Atmospheric inputs	525
Upstream Lake Huron inputs	336
Total	8929

3.3 Phosphorus transport in surface and subsurface water

Surface erosion is largely influenced by the frequency and intensity of precipitation in addition to land cover (forested, cover crop, bare soil, etc.). A bare agricultural soil left fallow has a greater potential to be impacted by raindrops than a canopy covered forest (Brady and Weil 1996). Surface erosion increases on bare ground, leading to the development of rill or gully erosion and potential transport of P adsorbed to surface soils. Utilizing cover crops reduces the erosion potential by stabilizing the soil surface. Additionally, the use of a drainage network assists with surface runoff and erosion reduction. King et al. (2015) suggests that surface and sediment runoff is significantly reduced on tile drained fields.

Phosphorus associated with soil porewater has the potential for offsite transport via preferential flow paths and artificial drainage networks (King et al. 2015). Preferential flow through large soil cracks (i.e., soil macropores), animal burrows, and other features is a critical process in subsurface movement of P and should be considered when evaluating sites for P management (Stamm et al. 1998; Simard et al., 2000; Smith et al. 2015a). Subsurface transport of P can be significant in watersheds with high soil P and artificial drainage (e.g., tiles and ditches) (Sims et al. 1998). For example, Gachter et al. (1998) identified that soil macropores and artificial drainage systems as the most important pathways for the vertical and lateral transport of DP to surface waters. Agricultural land use practices may be an important factor regulating preferential flow path development. Periodically disrupting soil macropores through deep tillage reduces P concentrations in subsurface drainage (King et al. 2015). Geohring et al. (2001) noted significant reductions in total P concentrations after plowing.

There has been a dramatic increase in the extent of tile drainage since 2005 in the Lake Erie Basin (Sharpley et al. 2013). King et al. (2014) found that tile drainage contributed 51% of annual stream flow in a headwater watershed in Ohio. This is of great concern in tile drained landscapes due to the potential for tile drainage to contribute P to downstream waters. Smith et al. (2015b) found that 49% of soluble P and 48% of total P losses occurred via tile discharge from fields in Indiana. There are a variety of factors that need to be considered when making management decisions related to limiting P movement to subsurface drainage including landscape position, P concentration, climate, and management activities (King et al. 2015).

The P cycle dictates the movement of P through a wetland system, including transformations related to P retention and release. Additionally, the P cycle highlights the relationship between dissolved and particulate P forms, which impart a significant influence on P retention and potential transport. For example, sediment laden runoff or tile drainage water has been associated with high concentrations of particulate P capable of transport to surface and ground waters (King et al. 2015). Conversely, dissolved P moves slowly through the soil matrix, with transport dynamics largely dictated by concentration driven diffusion gradients (Havlin et al. 2014). Understanding the P cycle, and the extent of P pools within each cycle component remains critical when restoring, enhancing, or creating wetlands for optimal P retention.

4 Influence of Soil Properties on P Retention and Transport in Wetlands

While the P cycle describes how P is transported and transformed within wetland ecosystems, the rate, extent, and magnitude of P cycling is largely determined by soil-water interactions (Reddy and DeLaune 2008). As a result, the following sections examine the properties and processes controlling P movement within the soil, including P sorption and approaches to P testing. The impact of legacy P on nutrient reduction potentials is also discussed.

4.1 Soil P sorption capacity

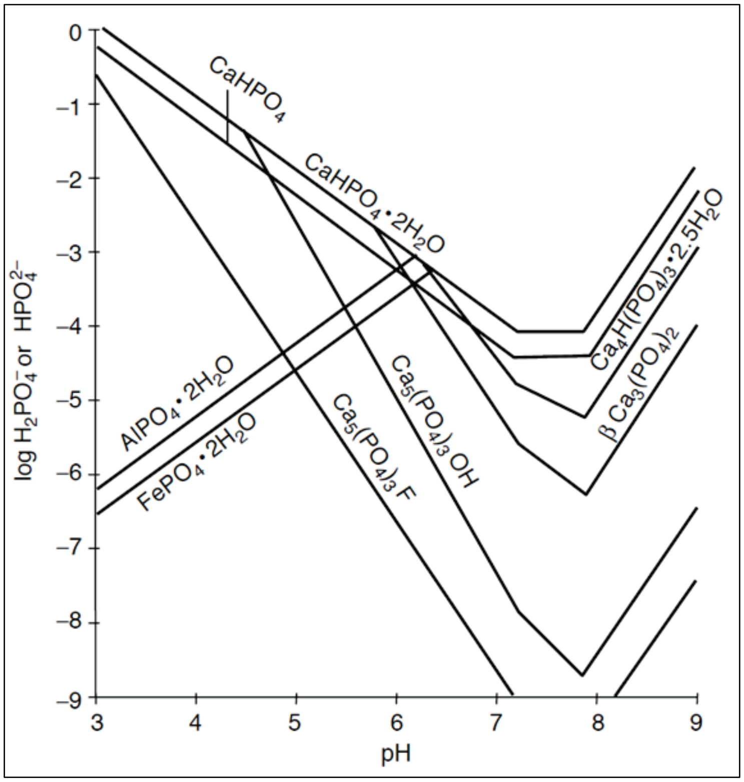
Once P has entered a soil system, soil sorption capacity largely determines the transport and fate of P compounds (Kleinman and Sharpley 2002). Soils have a finite P sorption capacity, which determines a soils ability to retain nutrients and improve water quality. Sorption capacity varies as a function of clay content, clay type, organic matter content, the concentration of Al, Fe, and Ca, and soil pH (Hanson et al. 2002). Phosphorus sorption capacity increases with soil particle surface areas (Stumm 1992). As a result, high clay content soils display increase P retention capacity, while sandy soils generally display a low P sorption capacity. Additionally, soils high in Al, Fe, or Ca exhibit increased P sorption capacity. Organic matter also adsorbs P under certain conditions, but the relationship between organic matter content and sorption remains complex (Hansen et al. 2002; Vepraskas et al., 2016). These soil chemical parameters are often measured and reported in soil series descriptions (Soil Survey Staff 1999); thus providing useful information for the potential risk of certain soil to P losses (Sekhon et al. 2014). The following paragraphs address the major factors influencing P sorption.

4.2 Iron, aluminum, and calcium

The concentration of amorphous (i.e., non-crystalline) Al and Fe oxides and hydroxides determines P adsorption capacity at $\text{pH} < 6.5$, while Ca species dictate P sorption dynamics at higher pH (Figure 5) (Richardson 1985; Reddy and D’Angelo 1994; Havlin et al. 2014). At $\text{pH} > 7.5$ P sorption is dominated by Ca species in calcareous soils or wetlands that receive Ca inputs (Reddy and DeLaune 2008). For example, P sorption to Ca is a particularly important mechanism for P retention in the Everglades

(Reddy et al. 2011). Since most soils in the United States exhibit pH values < 7.0, soil Al and Fe concentrations primarily drive P sorption and retention (Marton and Roberts 2014). Sekhon et al. (2014) reported that Al associated with crystalline clay minerals determined P retention and release in floodplain soils. Additionally, based on P sorption being linked to Al and Fe content in a wide range of Albanian soils. McDowell et al. (2001) indicate that soil parent material may be useful for predicting sorption capacity. This suggests that utilizing available sources of soils information such as the Natural Resource Conservation Service (NRCS) Web Soil Survey is essential for resource management at the watershed scale.

Figure 5. Solubility of calcium phosphates in comparison to aluminum and iron phosphates (From Reddy and DeLaune 2008).



Soil oxidation-reduction potentials influence the Fe controls on P sorption capacity, especially in wetlands (Vepraskas et al. 2016). Following soil saturation and chemical reduction, formation of amorphous ferrous hydroxides may increase surface area, the number of P sorption sites, and P sorption capacity (Holford and Patrick 1979). Conversely, P associated with ferric iron compounds (e.g., strengite [FePO4 · 2H2O]) and P occluded within oxidized iron soil coatings may be released under low soil oxidation-reduction potentials (Moore and Reddy 1994).

Because soils have a finite amount of Fe and Al oxides and hydroxides, soil P sorbing capacity remains limited. Once it is exceeded, no additional P retention occurs and P may be discharged to receiving water bodies. Understanding the Fe and Al complexes and transformations associated with wetland soils represents an important component for decreasing P in surface waters and undertaking steps to optimize P retention.

Soil texture and organic matter content also play an important role in regulating P sorption capacity (Sekhon et al. 2014). Phosphorus leaching remains strongly correlated to soil texture, with fine textured (e.g., clay) soils displaying increased P sorption and retention (McDowell et al. 2001). For example, Eastman et al. (2010) demonstrated that sandy loam soils adsorb less P than clay loam soils. Tile drainage DP in six mineral soils was found to be considerably less than that of three organic soils in Ontario, Canada (Miller 1979).

Soil organic matter content can retain P under certain conditions; however, the interaction of P and organic matter is complex (Hansen et al. 2002; Vepraskas et al. 2016). Phosphorus is retained as it is incorporated with newly formed organic soil as decaying vegetation material is buried over time (Reddy and DeLaune 2008). In some cases P may be retained indirectly by Fe and Al complexation with organic matter (Reddy et al. 1995). Significant P release by mineralization can occur with oxidation-reduction changes in wetlands related to hydrologic changes (Reddy et al. 1995). As a result, soil organic matter can both release and retain P depending on wetland conditions.

5 Wetland P Removal Efficiency

A number of studies examine the capacity of wetlands to remove P in dissolved and particulate forms (Beutel et al. 2014; Reddy et al. 1999). Many studies evaluate wetland P removal efficiencies by measuring P concentrations in inflow and outflow locations, allowing for the calculation of P removal efficiency (Table 3). Wetland P removal efficiencies differ based upon size, catchment area, soil characteristics, inflow P concentration and form, residence time, and other factors. Available literature demonstrates P removal occurs in a variety of wetland types (i.e., depressional and riparian wetlands) and within natural, restored, and constructed wetlands (Blankenberg et al. 2016; Hoffmann et al. 2012; Jordan et al. 2003). Additionally, wetlands remove P in both dissolved and particulate forms (Coveney et al. 2002). As a result, studies document wetland P removal efficiencies across a number of landscape settings, including agricultural areas. Examining wetland removal efficiency provides a number of benefits, including the capability for modeling water quality outcomes following wetland preservation, restoration, or construction (Dunne et al. 2006; 2012). Although determining wetland P removal efficiencies provide valuable data regarding the amount of P sequestered from downstream surface waters, removal efficiencies provide limited insight into the lifespan of wetlands P removal capacity and additional data is required to predict future P sorption capacity.

Table 3. Wetland P removal efficiencies.

Location	Dissolved P reduction (%)	Total P reduction (%)	Citation
Illinois	22	2	Kovacic et al. 2000
Illinois	45		Kirkham et al. 2015
	77		
Wisconsin		18	Robertson et al. 2000
Washington	22	37	Beutal et al. 2004
	33	43	
California	63	60	Maynard et al. 2009
	61	56	
Norway		41	Braskerud 2002
		32	
		21	
		37	
		44	
Sweden	9	36	Kynkäänniemi 2014
New York		24	Albright 2013
Florida		26	Dunne et al. 2015

6 Legacy P

The long term application of P as organic and inorganic fertilizers has resulted in non-point source P pollution by runoff (Daniel et al. 1998). Best management practices (BMPs) have been implemented in agricultural lands and other areas to address non-point source P pollution by promoting soil, water, and nutrient retention prior to off-site transport to receiving waters (Sharpley et al. 2014). In general BMPs reduce P inputs; however, their implementation often fails to meet P reduction targets required to improve water quality of nearby water bodies (Dunne et al. 2006; Sharpley et al. 2014). Reddy et al. (2011) and others investigated the concept of legacy P to account for the observed disconnect between the implementation of BMPs and limited water quality improvements (Dunne et al. 2011; Sharpley et al. 2014).

Legacy P is defined as the accumulation of soil P over time from historical land use, primarily from agricultural practices (Sharpley et al. 2014; Nair et al. 2015). The P accumulation largely occurs through P sorption onto mineral soils, accounting for the majority of long term P retention in wetlands (Richardson and Marshall 1986; Dunne et al. 2006). As described above, soils have a finite capacity to retain P (Kadlec and Wallace 2009). Once the P retention capacity is exceeded, stored legacy P becomes a potential source of P (Nair et al. 2015). The remobilization of legacy P occurs in two phases. Initially, labile P may be released upon flooding, resulting in an initial flush of excess P from the wetland. The second phase consists of destabilization of legacy P resulting in a steady release of soil P over time (Pant and Reddy 2003).

Dissolved P that is desorbed from soils and sediments and discharged to downstream waters may also be considered legacy P, as it derives from historical applications of P to soil. Even when external P loads are minimized or eliminated, the continuous release of legacy P can negatively affect water quality. This makes it difficult to distinguish the effects of current conservation measures from historical land management (Sharpley et al. 2011). Several studies suggest that conservation strategies have not adequately accounted for legacy P (Kleinman et al. 2011a; Sharpley et al. 2011). In many cases, legacy P has resulted in increased pressure on watershed organizations to address apparent failures of water quality initiatives that involved significant economic investment (Sharpley et al. 2013). Today, the role of legacy P in delaying the response of watersheds to remediation initiatives remains poorly understood (Kleinman et al. 2011a). A soil containing a surplus of soil P in excess of plant requirements may require substantial time to reach concentrations below environmentally acceptable levels. For example, Johnston and Poulton (1976) reported that a formerly fertilized field required 73 years to deplete excess P concentrations via crop removal. Sharpley et al. (2013) summarized soil recovery time lags associated with legacy P, which ranged from years to decades in a variety of soils types (Table 5).

Table 4. Reported impact of legacy P on soil nutient concentrations and recovery timeframes across a range of soils. Adapted from Sharpley et al. (2013).

Soil Type	Crop	Location	P Analysis	P (mg kg^{-1} yr^{-1})	Time Lag (yrs)	P (mg kg^{-1} yr^{-1})	Reference
Thurlow loam	grains	Montana	Olsen P	60–6	9	6.0	Campbell (1965)
Portsmouth fine sandy loam	grains	North Carolina	Mehlich-1 P	54–26	9	3.1	Cox et al. (1981)
Haverhill clay	wheat	North Carolina	Olsen P	74–33	14	2.9	Cox et al. (1981)
Haverhill clay	wheat	North Carolina	Olsen P	135–70	14	4.6	Cox et al. (1981)
Portsmouth fine sandy loam	corn	North Carolina	Mehlich-3 P	100–20	16–18	4.7	McCollum (1991)
Ruston fine sandy loam	hay	Oklahoma	Mehlich-3 P	258–192	6	11.0	Sharpley et al. (2007)
Othello silt loam	corn	Maryland	Mehlich-3 P	488–465	5	4.6	Sharpley et al. (2009)
Range of soils	arable and pasture	Ireland	Morgan’s P	>8 to 5–8§	7–15	0.4	Schulte et al. (2010)
Carroll clay loam	wheat	Manitoba	Olsen P	71–10	8	7.6	Spratt et al. (1980)
Carroll clay loam	wheat	Manitoba	Olsen P	135–23	8	14.0	Spratt et al. (1980)
Carroll clay loam	wheat	Manitoba	Olsen P	222–50	8	21.5	Spratt et al. (1980)
Waskada loam	wheat	Manitoba	Olsen P	88–23	8	8.1	Spratt et al. (1980)
Waskada loam	wheat	Manitoba	Olsen P	200–50	8	18.9	Spratt et al. (1980)
Waskada clay loam	wheat	Manitoba	Bray-1 P	140–50	8	11.3	Wagar et al. (1986)
Waskada clay loam	wheat	Manitoba	Bray-1 P	320–80	8	30.0	Wagar et al. (1986)
Ste. Rosalie clay	corn	Montreal	Mehlich-3 P	125–109	4	4.0	Zhang et al. (2004)
Nicollet–Webster loam	corn-soybean	Iowa	Bray-1 P	60–5	27	2.0	Dodd and Mallarino (2005)
Nicollet–Webster loam	corn-soybean	Iowa	Bray-1 P	95–8	27	3.2	Dodd and Mallarino (2005)
Webster–Canisteo loam	corn-soybean	Iowa	Bray-1 P	42–8	27	1.3	Dodd and Mallarino (2005)
Webster–Canisteo loam	corn-soybean	Iowa	Bray-1 P	85–9	27	2.8	Dodd and Mallarino (2005)

7 Determining Soil P Storage Capacity

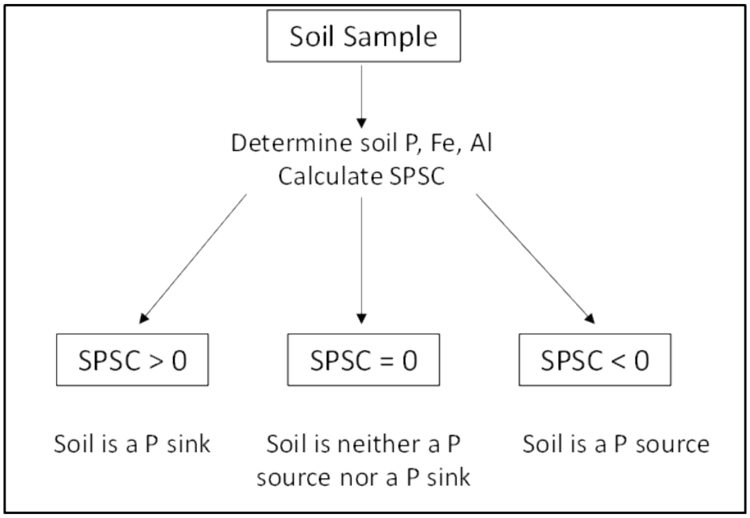
Several analytical techniques evaluate P concentrations in soils, sediment, surface water and pore water and the evaluation technique must be selected based upon the objective of the measurement (Sparks 1996). For example, measurements of total P do not reflect plant and microbial P availability; providing limited utility to investigate potential water quality impacts (Havlin et al 2014). Conversely, soluble reactive P determinations fail to account for sorbed P that may become available over time. As a result, a number of soil extractions have been developed to estimate the labile and readily releasable P pool (Kuo 1996). However, evaluating water quality risks using traditional approaches (e.g., soil extractable P) often fails to measure the forms of P responsible for eutrophication and does not account for soil properties that control P transport to water, including aspects associated with legacy P (Hansen et al. 2002).

Many field and laboratory treatment wetland studies assess short term P storage dynamics but fail to adequately assess long term soil P storage capacities (Reddy et al. 1999). Long term P assimilation in wetlands remain a function of soil accretion rates, soil P sorption capacity, water volume and P loading, water retention time, and landuse history. While researchers commonly account for water volume, P loading, and water retention time, the soil properties governing P retention and storage capacity are rarely measured (Reddy et al. 1999).

Reliable techniques for evaluating legacy P and the potential risk for P release from agricultural soils have been applied in wetland soils (Nair et al. 2015). In particular, evaluating legacy P and the environmental risk for P loss is required for establishing suitable treatment wetland locations (Nair and Harris 2014). The Soil Phosphorus Storage Capacity Index (SPSC) (Figure 6) evaluates the capacity for soils to retain P and the potential environmental risk of P release. The SPSC provides an index that describes the remaining P retention capacity of a soil, or the point at which mineral soil P sorption sites are no longer available to sorb P (Nair and Harris 2004; Nair et al. 2015). Soil P levels become a potential source of P if the threshold P concentration is exceeded (Dunne et al. 2006). The SPSC captures two different soil scenarios with equal P loss risk potential: 1) soils with inherent properties that limit P retention; and 2) soils with legacy P that occupy all sorption sites, limiting the retention of additional P entering the system (Nair et al. 2015). The SPSC describes the remaining soil P storage capacity without requiring specific historical land use data (Nair and Harris 2014).

The SPSC approach provides a mechanism for assessing the environmental limits of natural and constructed wetlands. The SPSC concept may prove useful for siting suitable locations for treatment wetland construction or restoration to maximize P retention. In other words, if the SPSC of a potential site is negative, then the site lacks excess P retention capacity and will not be suitable for project implementation. The SPSC also provides a tool for estimating the time required for a wetland to exhaust available P retention capacity prior to the soil converting to a source of P (Nair et al. 2015).

Figure 6. Soil Phosphorus Storage Capacity (SPSC) concept for assessing the available soil capacity to retain P (From Nair et al. 2015).



7.1 Extrapolating the SPSC concept to a watershed level

Nair et al. (2015) depicted the potential of SPSC to be used on a site-specific basis, as well as to predict P storage and release across a watershed, irrespective of the land use. Since this tool has been extended to wetlands, ditches, and streams, SPSC will likely be useful for predicting P releases from soils within a watershed in addition to identifying locations of legacy P accumulation and address the issue via application of appropriate BMPs.

7.2 Utilizing SPSC for siting construction activities

Determining P storage capacity is essential when applying landscape scale nutrient BMPs (Dunne et al. 2006; Nair and Harris, 2014; Sekhon et al., 2014; Sims et al. 1998). Identifying and maintaining a soils' ability to retain P (i.e., soil P storage capacity) over time remains a critical component to the design, construction, and management of agricultural BMP wetlands. Additionally, quantifying the potential soil legacy P release or flux is essential for optimizing P retention at local and watershed scales (Nair and Harris 2014; Nair et al. 2015; Pant and Reddy 2003). Reddy et al. (1995) suggested that the following questions should be addressed prior to constructing treatment wetlands for P management:

- Will potential soil locations display the capacity to retain additional P?
- What is the long term P storage capacity of the soil?
- What is the stability of stored P and under what conditions can stored P be released?

The SPSC provides a tool for evaluating stormwater retention ponds and treatment wetland locations. The higher the SPSC at a given location, the greater the potential for the constructed feature to filter and retain P (Nair et al. 2015). Negative SPSC values suggest that the soil already functions as a P source and therefore, remains unsuitable for establishing wetlands or other features for P retention.

8 Research Within the Great Lakes Watershed

A large number of studies investigate agricultural P pollution within the Great Lakes region over the past several decades. The majority of the publications focus on measuring inflow/outflow water from agricultural BMP wetlands; utilize models to estimate P loading in receiving waters; and review available literature regarding P transport, management, and policy (Table 5).

8.1 Measuring wetland inflow and outflow water

One of the primary methods employed for evaluating the potential for wetlands to retain P in the Great Lakes region has been to measure inflow and outflow water from tile drains or weirs. Section 6.0 provides a meta-analysis based upon a number of these studies. For example, Kovacic et al. (2000) found that 22% of DP was removed after testing inflow and outflow water from three constructed wetlands intercepting agricultural tile drainage. Expansion of a 6 ha wetland into a 38 ha wetland in Wisconsin resulted in retention of 18% of TP as reported by Robertson et al. (2000). The Franklin Research and Demonstration Farm in McLean County, Illinois created three experimental wetland complexes designed to intercept tile drainage water from three different sized agricultural catchments. Estimates of cumulative nine-year loading reductions of DP range from 31–93% amongst the wetland cells (Kirkham et al. 2015). Data displays that wetlands are effective at removing P from agricultural drainage. Variable results suggest wetland soil properties may be driving removal rates.

8.2 Phosphorus modeling

Models are an important component for environmental risk assessment at a large scale. It is not usually feasible to collect site specific data in mass quantities in a region as large as the Great Lakes region. As a result, models allow for projection based on a smaller set of data. In response to the Great Lakes Water Quality Agreement (GLWQA 2012), new P objectives and target loads were required to be evaluated for Lake Erie. Scavia et al. (2016) utilized nine different water quality models to generate recommendations for this effort. Additionally, Dalogl u et al. (2012) found that higher intensity storms resulted in elevated DP loads from the

Sandusky River watershed in Ohio using a modeling approach. Models are used to inform environmental management and policy decisions, collection and analysis of emerging scientific data provides opportunities to improve model outcomes.

8.3 Review articles

Natural resource management requires informed policy making. Knowing the "state of the science" is an important driver guiding successful programs. Numerous articles have been written that evaluate the role of P in a landscape context. For example, Scavia et al. (2014) assessed the re-eutrophication of Lake Erie, Simard et al. (2000) explored potential for preferential pathways of phosphorus transport, and Christiansen et al. (2016) assessed and synthesized fifty years of published drainage P data. Further, Ziegler (2016) reviewed information relating to using treatment wetlands as a nutrient management strategy in Wisconsin, Kleinman et al. (2011b) researched management barriers and opportunities of soil controls over P in runoff, McDowell et al. (2001) reported on processes controlling soil P release to runoff and implications for agricultural management, and King et al. (2015) performed a review of P transport in agricultural subsurface drainage. The majority of the literature reviews in the Great Lakes region directly inform the GLRI Interagency Task Force and Regional Working Groups.

8.4 Other studies

A number of other studies provide data and analysis evaluating tributary water quality, BMPs, land use impacts, preferential flow paths, soil type, and climate. However these studies remain limited. As a result, these studies are included as "other" in Table 5. Despite the large amount of high quality research completed, a paucity of data exists regarding soil sorption properties and P retention capacity of soils in the region. Additional work will also be required to determine the quantity of legacy P within priority watersheds identified in the GLRI Action Plan. Understanding the level of P impact on soils within the region is an essential component to any adaptive management plan focusing on utilizing wetlands for P retention and water quality improvements.

Table 5. Depicts P related research within the Great Lakes watershed and factors evaluated. TP, Total P; DP, Dissolved P/Dissolved Reactive P/Ortho P; SS, Suspended Solids; PP, Particulate P; I/O, Inflow/Outflow; GL, Multiple locations within the Great Lakes watershed; GL +. Areas within and outside of the Great Lakes watershed.*Modeling includes calculation of P budgets.

Location	P Tested	I/O Water	*Modeling	Review Paper	Other	Citation
Illinois	DP	X			X	Algoazany et al. (2007)
Canada			X		X	Allaire et al. (2011)
Ohio			X			Baker and Richards (2002)
GL			X		X	Bosch et al. (2013)
GL +				X		Christianson et al. (2016)
Canada	TP/DP				X	Crosbie and Chow-Fraser (1999)
Ohio			X			Daloglu et al. (2012)
GL			X		X	Danz et al. (2007)
Canada	TP/PP/DP	X			X	Eastman et al.(2010)
Canada	DP	X			X	Gaynor and Findlay (1995)
Wisconsin	TP/DP/SS		X		X	Graczyk et al. (2011)
GL			X			Han et al. (2011)
GL	TP/DP					Hill et al. (2006)
GL				X		Joosse and Baker (2011)
GL +				X		King et al. (2015)
Illinois	DP	X				Kirkham et al. (2015)
GL +				X		Kleinman et al. (2011b)
GL+				X	X	Kleinman et al. (2015)
Illinois	TP/DP	X				Kovacic et al. (2000)
GL			X		X	LaBeau et al. (2014)
Illinois	TP/DP/SS				X	Lemke et al. (2011)
Lake Erie	TP/DP		X		X	Maccoux et al. (2016)
GL +				X		McDowell et al. (2001)
Lake Erie	DP				X	Michalak et al. (2013)
Ohio			X			Mitsch and Reeder (1990)
GL			X			Mitsch and Wang (2000)
GL	TP/SS					Morrice et al. (2007)
Ohio						Reeder (1994)
GL			X			Robertson and Saad (2011)
Wisconsin	TP/SS	X			X	Robertson et al. (2000)
GL				X		Robinson (2015)
Lake Erie	TP/DP			X		Scavia et al. (2014)
Lake Erie			X	X		Scavia et al. (2016)

Location	P Tested	I/O Water	*Modeling	Review Paper	Other	Citation
GL +				X		Schindler et al. (2016)
GL +				X		Sharpley et al. (1994)
GL +				X		Sharpley et al. (2013)
GL +				X	X	Simard et al. (2000)
Indiana	TP/DP	X			X	Smith et al. (2015a)
Indiana	TP/DP	X			X	Smith et al. (2015b)
Canada			X			van Bochove et al. (2011)
Lake Erie			X			Verhamme et al. (2016)
Michigan			X			Wang and Mitsch (1998)
Ohio	TP/DP	X			X	Williams et al. (2016a)
Ohio	TP/DP/SS				X	Williams et al. (2016b)
GL +				X		Woltemade (2000)
GL +				X		Zedler (2003)
GL +				X		Ziegler (2016)

9 Knowledge Gaps and Opportunities for Further Research

The National Science and Technology Council (2016) identified expansion of cropland into vulnerable areas such as wetlands, excessive application or poor management of nutrients, poor water management, and agricultural practices that excessively disturb the soil as key threats to U.S. soil and water resources. In order to improve water quality with the Great Lakes, efforts must focus on areas with high P concentrations, low soil P sorption capacities, and enhanced P transport (e.g., artificial drainage systems) (Sims et al. 1998). Particularly, the priority watersheds identified in the GLRI Action Plan represent ideal areas for initiatives focused on optimizing P retention in wetlands. For example, Scavia et al. (2016) recommended that reducing total P loading from the Maumee River to decrease harmful algal blooms in Lake Erie. Mitsch and Wang (2000) estimated the potential P removal associated with large scale wetland restoration projects in the region. Their analysis suggested that 48 km^2 of restored wetlands could remove up to 63 metric tons of P per year.

Van der Valk and Jolly (1992) recommended three efforts needed to improve the economic and environmental efficiency of restored wetlands.

1. Conduct whole watershed demonstration studies in several regions to establish the feasibility and utility of using restored wetlands as sinks for contaminants.
2. Develop landscape simulation models of contaminant sources and transport processes to determine the extent of wetlands needed and where they should be located to reduce contaminants to acceptable levels.
3. Establish site selection and design criteria for created and restored wetlands.

9.1 Soil P retention capacity and legacy P in GLRI target watersheds

As noted in the sections above, soil characteristics dictate the capacity of wetlands to remove and retain P. Ziegler (2016) suggests the phosphorus adsorption capacity of wetland soils has generally not been considered prior to design and construction of many treatment wetlands. As a result, evaluating the P storage capacity of Great Lakes soils remains an essential component to successfully reducing P loads that impair water quality.

Investigating wetland soils within priority watersheds using the SPSC would guide future efforts to reduce P transport in the region. This will allow identification of suitable soil types for the optimization of P removal by wetlands and address potential limitations associated with legacy P.

9.2 Incorporation of soil data to improve model outputs

According to the *Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team* (2015), any complete and sustainable adaptive management program for a large lake such as Lake Erie must contain modeling which allows insight and ability to make projections, research that provides understanding and parameterization for models, and monitoring for input and credibility. Models can then be revised and recalibrated based on collected data. For example, recent work by Daloglu (2012) utilized the Soil and Water Assessment Tool (SWAT) (Radcliffe et al. 2009) to quantify P transport and fate in the entire Sandusky watershed from 1970–2010. Data regarding sorption capacity of soils in relation to legacy P provides opportunities to refine these models. Detailed site specific soil information should be recorded and applied to existing SWAT and Geographic Information System (GIS) models to assist with nutrient management plans and application of wetlands as agricultural BMPs. Johannesson et al. (2015) demonstrated the difficulties in using available geographical data alone to identify the best location for wetlands intended to retain P. Expanded research and data collection should contribute to the development, assessment, and validation of models and practices Federal agencies use to measure, predict and manage soil ecosystem services, especially in the case of agricultural conservation practices (National Science and Technology Council 2016).

10 Summary

The current report contributes to the state-of-the-science regarding opportunities to utilize wetlands for P reduction in the Great Lakes region. A literature review summarizes the numerous studies highlighting the benefits of wetlands for P reduction in both particulate and dissolved forms via interception, adsorption, and assimilation. Despite the number of high quality studies conducted, additional research is recommended to evaluate legacy P and determine the soil P sorption capacity of soils in the region. Further research into soil-nutrient interactions will aid in management decisions supporting the citing, construction, and restoration of wetlands for optimal P removal.

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Appendix A: Journals Researched

Advances in Agriculture

Agricultural Water Management

Agronomy Journal

Ambio

Biogeochemistry

Canadian Journal of Fisheries and Aquatic Sciences

Canadian Journal of Soil Science

Communications in Soil Science and Plant Analysis

Critical Reviews in Environmental Science and Technology

Ecological Engineering

Ecological Modelling

Ecological Monographs

Environmental Earth Science

Environmental Management

Environmental Science & Technology

Environmental Science Policy

Freshwater Biology

Frontiers in Ecology and the Environment

Journal of American Water Resources Association

Journal of Environment Quality

Journal of Freshwater Ecology

Journal of Geophysical Research: Biogeosciences

Journal of Great Lakes Research

Journal of Hydrology

Journal of Soil and Water Conservation

Lake and Reservoir Management

New Zealand Journal of Agricultural Research

Nutrient Cycling in Agroecosystems

Plant Soil

Proceedings of the National Academy of Sciences

Science

Soil Science

Soil Science Society of America Journal

Soil Tillage Research

Water Research

Water Resources Research

Water Science and Technology

Wetlands

Wetlands Ecology and Management

Appendix B: Citations Related To P In Agricultural Landscapes

Albright, M. F. 2013. Monitoring the effectiveness of the Cooperstown wastewater treatment wetland, 2013. *In* 46th Annual Report. SUNY Oneonta Biological Field Station, SUNY Oneonta.

Wetlands have been used as water treatment cells for a number of years, but, until recently, only on a very limited basis. Since the mid 1990s, however, the number of constructed wetlands, having a broad range of system configurations and treatment applications, has increased markedly (Kadlec and Wallace 2009). When associated with municipal sewage outfalls, the parameters that are most often targeted for reduction are phosphorus, various nitrogenous compounds (ammonia, nitrate, total nitrogen), suspended solids and biological oxygen demand. The demonstrated effectiveness of the removal of these constituents has been promising, though quite variable, as design and site characteristics are, in practically every case, unique. Because of this, every time a treatment wetland is utilized, the opportunity exists to collect meaningful data which can aid in the design of future systems. More directly, data collection at some level is necessary to evaluate whether or not the goals of the treatment wetland, and the regulated limits of the parameters, are met.

Algoazany, A., P. Kalita, G. Czapar, and J. Mitchell. 2007. Phosphorus transport through subsurface drainage and surface runoff from a flat watershed in east central Illinois, USA. *Journal of Environmental Quality* 36:681–693. doi:10.2134/ jeq2006.0161.

A long-term water quality monitoring program was established to evaluate the effects of agricultural management practices on water quality in the Little Vermilion River (LVR) watershed, IL. This watershed has intensive random and irregular subsurface drainage systems.

The objective of this study was to assess the fate and transport of soluble phosphorus (soluble P) through subsurface drainage and surface runoff. Four sites (sites A, B, C, and E) that had subsurface and surface monitoring programs were selected for this study. Three of the four study sites had corn (Zea mays L.) and soybeans (Glycine max L.) planted in rotations and the other site had seed corn and soybeans. Subsurface drainage and surface runoff across all sites removed an average of 16.1 and 2.6% of rainfall, respectively. Annual flow-weighted soluble P concentrations fluctuated with the precipitation, while concentrations tended to increase with high precipitation coupled with high application rates. The long-term average flow-weighted soluble P concentrations in subsurface flow were 102, 99, 194, and 86 mg L21 for sites A, B, C, and E, respectively. In contrast, the long-term average flow-weighted soluble P concentrations in surface runoff were 270, 253, 534, and 572 mg L21 for sites As, Bs, Cs, and Es, respectively. These values were substantially greater than the critical values that promote eutrophication. Statistical analysis indicated that the effects of crop, discharge, and the interactions between site and discharge and crop and discharge on soluble P concentrations in subsurface flow were significant (a 5 0.05). Soluble P mass loads in surface runoff responded to discharge more consistently than in the subsurface flow. Subsurface flow had substantially greater annual average soluble P mass loads than surface runoff due to greater flow volume.

Allaire, S. E., van Bochove, E., Denault, J. T., Dadfar, H., The´riault, G., Charles, A. and De Jong, R. 2011. Preferential pathways of phosphorus movement from agricultural land to water bodies in the Canadian Great Lakes basin: A predictive tool. *Canadian Journal of Soil Sciences* 91: 361–374.

Preferential flow processes, such as crack flow (CF), burrow flow (BF), finger flow (FF) and lateral flow (LF) are known as factors enhancing phosphorus (P) transport from agricultural soils to water bodies. The objective of this study was to develop a methodology for predicting the likelihood of preferential flow processes in agricultural soils at the landscape scale and their potential occurrence around the Canadian Great Lakes. The methodology considered climate, soil and crop parameters and a water budget that calculated surface runoff and drainage. Crack flow largely depended upon soil clay content, BF on soil texture and climate, FF on layering in sandy soils and LF on the presence of trees, slope and soil restricting layers. Crack flow had a high likelihood to occur southern Lake Ontario and all around Lake Erie. A high likelihood of FF could be found in the area where CF was low (i.e., in the sandy soils north of Lake Huron and Lake Ontario). Burrow flow had a medium likelihood to occur on Manitoulin Island and close to the shoreline north of Lake Ontario. Medium to high likelihood of lateral flow might occur in the area south of

Lake Ontario, west of Toronto in a narrow band towards Lake Huron, and to a lesser extend in a large area northeast of Lake Huron. Lateral flow may transport soluble P in areas where P was previously carried downward by FF from inland

(in soils) to surface water bodies. In several areas, tile drainage may transport all forms of P carried downward from the soil surface to the subsurface by CF and BF to lake tributaries. Preferential flow distribution maps could be used as tools for supporting the identification of agricultural lands where management might enhance subsurface processes of P transport toward groundwater or surface water bodies.

Baker, D. B., and Richards, R. P. 2002. Phosphorus Budgets and Riverine Phosphorus Export in Northwestern Ohio Watersheds. *Journal of Environmental Quality* 31:96–108.

Phosphorus (P) budgets for large watersheds are often used to predict trends in riverine P export. To test such predictions, we calculated annual P budgets for 1975–1995 for soils of the Maumee and Sandusky watersheds of northwestern Ohio and compared them with riverine P export from these watersheds. Phosphorus inputs to the soils include fertilizers, manure, rainfall, and sludge while outputs include crop removal and nonpoint-source export via rivers. Annual P inputs decreased due to reductions in fertilizer and manure inputs. Annual outputs increased due to increasing crop yields. Net P accumulation decreased from peak values of 13.4 and 9.5 kg P ha^{-1} yr^{-1} to 3.7 and 2.6 kg P ha^{-1} yr^{-1} for the Maumee and Sandusky watersheds, respectively. Thus, P budget analysis suggests that riverine P export should have increased throughout the study period, with smaller increases during more recent years. However, detailed water quality studies show that riverine export of total phosphorus (TP) has decreased by 25 to 40% and soluble reactive phosphorus (SRP) by 60 to 89%, both due primarily to decreases from nonpoint sources. We suggest that these decreases are associated with farmers' adoption of practices that minimize transport of recently applied P fertilizer and of sediments via surface runoff, coupled with changes in winter weather conditions. In comparison with most Midwestern watersheds, rivers draining these watersheds have high unit area yields of TP, low unit area yields of SRP, and high ratios of nonpoint source to point source derived P.

Beutel, M. W., Morgan, M. R., Erlenmeyer, J. J., and Brouillard, E. S. 2014. Phosphorus removal in a surface-flow constructed wetland treating agricultural runoff. *Journal of Environmental Quality* 43(3):1071–1080.

Agricultural runoff is a leading source of phosphorus (P) pollution to lakes and streams. The objective of this study was to evaluate P removal dynamics in a constructed treatment wetland (CTW) treating agricultural irrigation return flows. The CTW included a sedimentation basin (SB) followed by two surface-flow wetlands in parallel. Typical retention times and total P (TP) loading were 1.4 d and 50 to 110 g m^{-2} yr^{-1} P, respectively, for the SB and 5 to 6 d and 4 to 10 g m^{-2} yr^{-1} P, respectively, for wetlands. On the basis of this multiyear study, concentration removal efficiency in the SB averaged 21% for TP and 32% for reactive phosphorus (RP). Concentration removal efficiency in wetlands averaged 37 and 43% for TP and 22 and 33% for RP. Areal first-order removal rates for TP averaged 22 and 31 m yr^{-1} in wetlands. Total P removal in wetlands exhibited a strong seasonal pattern, with minimum removal in the summer when high temperatures likely enhanced P release from decaying plant biomass. The performance of the CTW was stochastic, with removal unpredictably poorer in some years in part as a result of muskrat bioturbation and plant harvesting. In years before muskrat impacts, concentration removal efficiencies in wetlands were 50% for TP and 65% for RP.

Blankenberg, A. G. B., A. M. Paruch, L. Paruch, J. Deelstra, and K. Haarstad. 2016. Nutrients tracking and removal in constructed wetlands treating catchment runoff in Norway. J. Vymazal (Ed.). *Natural and Constructed Wetlands* 23–40). Springer International Publishing.

Water quality problems in Norway are caused mainly by high phosphorus (P) inputs from catchment areas. Multiple pollution sources contributes to P inputs into watercourses, and the two main sources in rural areas are agricultural runoff and discharge from on-site wastewater treatment systems (OWTSs). To reduce these inputs, Constructed wetlands (CWs) treating catchment runoff have been implemented in Norway since early 1990s. These CWs have been proven effective as supplements to agricultural best management practices for water quality improvements and therefore there are more than 1000 CWs established in Norway at present. This study aims to present some overall data on the present status of CWs treating catchment runoff in Norway, and in particular recent results of source tracking and retention of sediments and total phosphorus

(TP) in a model, full-scale, long-term operated CW, which in practice treats runoff from a typical rural catchment with pollution from both point and diffuse sources. Nutrient contributions from agricultural runoff and OWTSs have been quantified in eight catchments, while the source tracking and retention of sediments and P has been studied in the model CW. P runoff in the catchments was largely affected by precipitation and runoff situation, and varied both throughout the year (every single year) and from one year to another. Annual TP contribution that origins from OWTSs was in general limited, and only 1 % in the catchment of the model CW. Monthly contribution, however, was higher than 30 % during warm/dry season, and cold months with frost season. For the purpose of source tracking study, faecal indicator bacteria (reported in terms of *Escherichia coli* - *E. coli*) and host-specific 16S rRNA gene markers *Bacteroidales* have been applied. High *E.coli* concentrations were well associated with high TP inputs into waterbodies during dry or/and cold season with little or no agriculture runoff, and further microbial source tracking (MST) tests proved human contribution. There are considerable variations in retention of sediments and TP in the CW between the years, and the annual yearly retention was about 38 % and 16 %, respectively. During the study period, the average monthly retention of sediments and TP was 54 % and 32 %, respectively. *E. coli* concentrations were also reduced in water passing the CW. The study confirmed that runoff from agricultural areas is the main P source in watercourses, however, discharges from OWTS can also be of great importance for the water quality, especially during warm/dry- and cold/frosty periods. Small CWs treating catchment runoff contribute substantially to the reduction of sediments, TP and faecal indicator bacteria transport into water recipients.

Bosch, N. S., Allan, J. D., Selegean, J. P., and Scavia, D. 2013. Scenario-testing of agricultural best management practices in Lake Erie watersheds. *Journal of Great Lakes Research* 39:429–436.

Current research has shown that reductions in nonpoint nutrient loading are needed to reduce the incidence of harmful algal blooms and hypoxia in the western and central basins of Lake Erie. We used the Soil and Water Assessment Tool (SWAT) to test various sediment and nutrient load reduction strategies, including agricultural best management practice (BMP) implementation and source reduction in various combinations for six watersheds. These watersheds, in order of decreasing phosphorus loads, include the Maumee, Sandusky, Cuyahoga, Raisin, Grand, and

Huron, and together comprise 53% of the binational Lake Erie Basin area. Hypothetical pristine nutrient yields, after eliminating all anthropogenic influences, were estimated to be an order of magnitude lower than current yields, underscoring the need for stronger management actions. However, cover crops, filter strips, and no-till BMPs, when implemented at levels considered feasible, were minimally effective, reducing sediment and nutrient yields by only 0–11% relative to current values. Sediment yield reduction was greater than nutrient yield reduction, and the greatest reduction was found when all three BMPs were implemented simultaneously. When BMPs were targeted at specific locations rather than at random, greater reduction in nutrient yields was achieved with BMPs placed in high source locations, whereas reduction in sediment yields was greatest whenBMPswere located near the river outlet. Modest nutrient source reduction also was minimally effective in reducing yields. Our model results indicate that an “all-of-above” strategy is needed to substantially reduce nutrient yields and that BMPs should be much more widely implemented.

Brady, N. C. and R. R. Weil. 1996. *The nature and properties of soils*. 14ed. Pearson Education Inc, Upper Saddle River, NJ.

Developed for Introduction to Soils or Soil Science courses, *The Nature and Properties of Soils, 14e* can be used in courses such as Soil Fertility, Land Resources, Earth Science and Soil Geography. Now in its 14th edition, this text is designed to help make students study of soils a fascinating and intellectually satisfying experience. Written for both majors and non-majors, this text highlights the many interactions between the soil and other components of forest, range, agricultural, wetland and constructed ecosystems.

Braskerud, B. C. 2002. Factors affecting phosphorus retention in small constructed wetlands treating agricultural non-point source pollution. *Ecological Engineering* 19:41-61.

Four surface flow constructed wetlands (CWs) have been intensively investigated for phosphorus retention, from 3 to 7 years in the cold temperate climate of Norway. The aim of this study was to identify factors that affect phosphorus retention from non-point sources. The wetlands were located in first order streams, with surface areas of 0.06–0.4% of the watershed (CW-area 350–900 m^2). Volume proportional composite samples were taken from inlet and outlet, and sedimentation plates were used in selected areas. The average retention of total phosphorus for the individual CWs was 21–44% of input, despite the high hydraulic load (mean load was 0.7–1.8 m per day). This equals a retention of 26–71 g phosphorus m^{-2} surface area per year. A first-order model was fitted to the data giving an average removal constant, *k*, of 214 m per year. However, the constant increased with increasing hydraulic load due to the simultaneous increase particle settling velocity. Hence, retention increased in spite of increasing hydraulic loads. Moreover, linear multiple regression models showed that retention was influenced by several external variables, e.g. input of phosphorus, season, phosphorus content on suspended solids and phosphorus settling velocity. The results suggest that the first-order model is less suitable to estimate phosphorus retention in similar gravity fed wetlands. The best of the proposed statistical prediction models, reproduced observed data from two independent test-CWs with a deviation of 0.1%. The investigation shows that small wetlands are a useful supplement to best management practice on arable fields. However, the present study focuses on the necessity to investigate how pollutants enter wetlands. Such knowledge can then be used to suggest improvements of wetland layout.

Campbell, R.E. 1965. Phosphorus fertilizer residual effects on irrigated crops in rotation. *Soil Science Society of America Proc* 29:67–70.

Residual effects for 8 years of O, *26,* 52, 105, and 210 Ib of P per acre applied for barley were measured in a 6-year rotation of barley, alfalfa (3 years), corn, and sugar beets grown on Thurlow clay loam. Amounts of P removed by crops in 9 years totaled 96, 109, 124, 136, and 179 Ib, respectively. Corresponding recoveries of applied P were 49, 54, 38, and 40%. Most of the 26 pounds of P was used in 4 years. Residual response over the entire period increased with higher rates. Residual P soluble in NaHCOs decreased with continued crop removal of applied P. The results of this experiment which was located in Montana agreed well with similar experiments run concurrently in New Mexico, Oregon, and South Dakota. The differences among them can be reconciled on the basis of soil textural differences as they affect P adsorption and availability.

Christiansen, L. E., R. D. Harmel, D. Smith, M. R. Williams, and K. King. 2016. Assessment and synthesis of 50 Years of published drainage phosphorus losses. *Journal of Environmental Quality* 45:1467-1477.

The prevalence of anthropogenic drainage systems in intensively cropped areas across North America combined with the degradation of important freshwater resources in these regions has created a critical intersection where understanding phosphorus (P) transport in drainage waters is vital. In this study, drainage-associated nutrient load data were retrieved and quantitatively analyzed to develop a more comprehensive understanding of the P loading and crop yield impacts of agronomic management practices within drained landscapes. Using the Drain Load table in the MANAGE (Measured Annual Nutrient loads from AGricultural Environments) database, the effect of factors such as soil characteristics, tillage, and nutrient management on P loading were analyzed. Across site years, generally less than 2% of applied P was lost in drainage water, which corroborates the order of magnitude difference between agronomic P application rates and P loadings that can cause deleterious water quality impacts. The practice of no-till significantly increased drainage dissolved P loads compared with conventional tillage (0.12 vs. 0.04 kg P ha^{-1}). The timing and method of P application are both known to be important for P losses, but these conclusions could not be verified due to low site-year counts. Findings indicate there is a substantial need for additional field-scale studies documenting not only P losses in drainage water but also important cropping management, nutrient application, soil property, and drainage design impacts on such losses.

Coveney, M. F., D. L. Stites, E. F. Lowe, L. E. Battoe, and R. Conrow. 2002. Nutrient removal from eutrophic lake water by wetland filtration. *Ecological Engineering* 19:141–159. doi:10.1016/S0925-8574(02)00037-X.

Lake Apopka is a large (125 km2), shallow (mean depth 1.6 m) lake in Florida, USA. The lake was made hypereutrophic by phosphorus loading from floodplain farms and has high levels of nutrients, phytoplankton (Chl a 80 $\mu g\ l^{-1}$), and suspended matter. The restoration plan developed by the St. Johns River Water Management District encompasses the biomanipulation concept in which the critical step for large shallow lakes is increasing the transparency of the water to allow the re-establishment of submerged macrophytes. Restoration includes operation of a treatment wetland, reduction in external P loading, harvest of fish, fluctuation of lake levels, and littoral planting. The District constructed a 2-km^2 pilot-scale treatment wetland to test nutrient-removal and hydraulic performance. Lake water was recirculated for 29 months, and the removal of suspended solids and particle-bound nutrients was assessed. Hydraulic loading rate varied from 6.5 to 65 m year^{-1} with a mean hydraulic residence time of about 7 days. The inflow contained 40–180 mg l^{-1} TSS, 80–380 µg l^{-1} TP (mostly particulate organic), and 3–9 mg l^{-1} TN (mostly dissolved and particulate organic). Overall, particulate matter was removed (> 90%) by the wetland, and soluble organic compounds were unaffected. Soluble inorganic compounds such as nitrate, ammonia, and soluble reactive phosphate (SRP) were low in the lake water but increased during passage through the wetland. Particulate matter at the outlet was enriched in both N (2-fold) and P (5-fold) compared to particles in the inflow. Mass removal efficiencies were 89–99 (TSS), 30–67 (TP), and 30–52% (TN), but efficiency fell when hydraulic short-circuiting occurred. First-order removal coefficients were 107 (TSS), 63 m year^{-1} (TP) and 98 m year^{-1} (particulate N). Areal particulate removal rates were 5.4 g dry matter m^{-2} day^{-1}, 0.18 g PON m^{-2} day^{-1}, and 0.006 g POP m^{-2} day^{-1}. The ratio of N:P removal was 28:1. Total sedimentation rate was 0.4 mm day–l of very light matter (4.4 g dw l^{-1}). About 40% of the dry matter and nitrogen removed and about 80% of the phosphorus was found in the new sediments. Relative to the inflow of lake water, evapotranspiration (4.3%), seepage (2.6%), and rainfall (2.8%) were low. Major problems were initial leaching of SRP, but not ammonia, from native organic soils and vegetation when this former farmland was flooded; hydraulic short-circuiting via former drainage ditches; and low inflows under drought conditions. After 6 months SRP release declined, and initial SRP leaching could be prevented with soil treatment. Hydraulic short-circuiting occurred only after modifications were made. Low gravity flows were augmented with pumped inflows. With these improvements P-removal should increase from the measured 0.48 to at least 3 g P m^{-2} year^{-1}. Based on the pilot project results, the first phase of an improved 14-km^{2} wetland filter has been constructed. This project should accelerate improvements in the water quality of Lake Apopka and, ultimately, create a new, large wildlife-rich marsh.

Cox, F. R., E. J. Kamprath, and R. E. McCollum. 1981. A descriptive model of soil test nutrient levels following fertilization. *Soil Science Society of America Journal* 45:529–532. doi:10.2136/sssaj1981.03615995004500030018x.

For efficient utilization of fertilizer, a practical means of expressing the residual effect of certain plant nutrients is needed. A descriptive model was developed to show the change in extractable nutrient levels with time assuming a rapid increase after fertilization followed by a slower exponential decrease. The information needed or parameters for the model include (i) the equilibrium soil test level, (ii) the magnitude of the initial sorption reaction, and (iii) a loss constant. These were determined for seven long-term fertilizer studies with phosphorus (P). There was a large difference in P-sorption capacity of the soils; all parameters reflected this difference. The initial sorption reaction was linearly related to rate of fertilization in some soils and quadratically in others. The model was applied to conditions in which fertilizer was applied at various time intervals. Good agreement between observed and predicted values was obtained. The main value of this model is to be able to calculate the amount of fertilizer needed to establish and maintain a given soil test level.

Crosbie, B. and Chow-Fraser, P. 1999. Percentage land use in the watershed determines the water and sediment quality of 22 marshes in the Great Lakes Basin. *Canadian Journal of Fisheries Aquatic Science* 56: 1781–1791.

Data from 22 Ontario marshes were used to test the hypothesis that distribution of forested, agricultural, and urban land in the watershed determines the water and sediment quality of Great Lakes wetlands. The first three components of the principal components analysis explained 82% of the overall variation. PC1 ordinated wetlands along a trophic gradient; species richness of submergent vegetation decreased with PC1 scores. PC2 reflected the content of inorganic solids and phosphorus in sediment and the ionic strength of the water. Both PC1 and PC2 scores were positively correlated with percent agricultural land, whereas PC1 scores were negatively correlated with forested land. Correlation between PC1 and agricultural land improved when best-management practices were considered. Accounting for common carp (*Cyprinus carpio*) disturbance did not confound the relationship between land use and water quality. PC3, driven by soluble reactive phosphorus and nitrate nitrogen concentration in the water, was not correlated with land use. Concentrations of polycyclic aromatic hydrocarbons and Metolachlor were correlated with urban and agricultural land, respectively, and may be useful as land use surrogates. Watershed management favoring the retention of forested land, or creation of buffer strips to trap agricultural runoff in the drainage basin, should help maintain aquatic plant diversity in coastal wetlands.

Daloglu, I., K. H. Cho, D. Scavia. 2012. Evaluating causes of trends in long-term dissolved reactive phosphorus loads to Lake Erie. *Environmental Science and Technology* 46:10660–10666.

Renewed harmful algal blooms and hypoxia in Lake Erie have drawn significant attention to phosphorus loads, particularly increased dissolved reactive phosphorus (DRP) from highly agricultural watersheds. We use the Soil and Water Assessment Tool (SWAT) to model DRP in the agriculture-dominated Sandusky watershed for 1970–2010 to explore potential reasons for the recent increased DRP load from Lake Erie watersheds. We demonstrate that recent increased storm events, interacting with changes in fertilizer application timing and rate, as well as management practices that increase soil stratification and phosphorus accumulation at the soil surface, appear to drive the increasing DRP trend after the mid-1990s. This study is the first long-term, detailed analysis of DRP load estimation using SWAT.

Daniel, T. C., A. N. Sharpley, and J. L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. *Journal of Environmental Quality* 27(2): 251–257.

Phosphorus in runoff from agricultural land is an important component of nonpoint-source pollution and can accelerate eutrophication of lakes and streams. Long-term land application of P as fertilizer and animal wastes has resulted in elevated levels of soil P in many locations in the USA. Problems with soils high in P are often aggravated by the proximity of many of these areas to P-sensitive water bodies, such as the Great Lakes, Chesapeake and Delaware Bays,

Lake Okeechobee, and the Everglades. This paper provides a brief overview of the issues and options related to management of agricultural P that were discussed at a special symposium titled, "Agricultural Phosphorus and Eutrophication," held at the November 1996 American

Society of Agronomy annual meetings. Topics discussed at the symposium and reviewed here included the role of P in eutrophication identification of P-sensitive water bodies; P transport mechanisms; chemical forms and fate of P; identification of P source areas; modeling of P transport; water quality criteria; and management of soil and manure P, off-farm P inputs, and P transport processes.

Danz, N. P., Niemi, G. J., Regal, R. R., Hollenhorst, T. Johnson, L. B., Hanowski, J. M., Axler, R. P., Ciborowski, J. J. H., Hrabik, T., Brady, V. J., Kelly, J. R., Morrice, J. A., Brazner, J. C., Howe, R. W., Johnston, C. A., Host, G. E. 2007. Integrated measures of anthropogenic stress in the U.S. Great Lakes Basin. *Environmental Management* 39:631–647.

Integrated, quantitative expressions of anthropogenic stress over large geographic regions can be valuable tools in environmental research and management. Despite the fundamental appeal of a regional approach, development of regional stress measures remains one of the most important current challenges in environmental science. Using publicly available, pre-existing spatial datasets, we developed a geographic information system database of 86 variables related to five classes of anthropogenic stress in the U.S. Great Lakes basin: agriculture, atmospheric deposition, human population, land cover, and point source pollution. The original variables were quantified by a variety of data types over a broad range of spatial and classification resolutions. We summarized the original data for 762 watershed-based units that comprise the U.S. portion of the basin and then used principal components analysis to develop overall stress measures within each stress category. We developed a cumulative stress index by combining the first principal component from each of the five stress categories. Maps of the stress measures illustrate strong spatial patterns across the basin, with the greatest amount of stress occurring on the western shore of Lake Michigan, southwest Lake Erie, and southeastern Lake Ontario. We found strong relationships between the stress measures and characteristics of bird communities, fish communities, and water chemistry measurements from the coastal region. The stress measures are taken to represent the major threats to coastal ecosystems in the U.S. Great Lakes. Such regional-scale efforts are critical for understanding relationships between human disturbance and ecosystem response, and can be used to guide environmental decision-making at both regional and local scales.

DeLaune, R. D. and K. R. Reddy. 2008. Biogeochemistry of wetlands: Science and Applications. CRC Press. Boca Raton, FL.

Wetland ecosystems maintain a fragile balance of soil, water, plant, and atmospheric components in order to regulate water flow, flooding, and water quality. Marginally covered in traditional texts on biogeochemistry or on wetland soils, Biogeochemistry of Wetlands is the first to focus entirely on the biological, geological, physical, and chemical processes that affect these critical habitats.

This book offers an in-depth look at the chemical and biological cycling of nutrients, trace elements, and toxic organic compounds in wetland soil and water column as related to water quality, carbon sequestration, and greenhouse gases. It details the electrochemistry, biochemical processes, and transformation mechanisms for the elemental cycling of carbon, oxygen, nitrogen, phosphorus, and sulfur. Additional chapters examine the fate and chemistry of heavy metals and toxic organic compounds in wetland environments. The authors emphasize the role of redox-pH conditions, organic matter, microbial-mediated processes that drive transformation in wetlands, plant responses and adaptation to wetland soil conditions. They also analyze how excess water, sediment water, and atmospheric change relate to elemental biogeochemical cycling.

Dodd, J. R., and A. P. Mallarino. 2005. Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn–soybean rotations. *Soil Science Society of America Journal* 69:1118–1128. doi:10.2136/sssaj2004.0279.

Farmers and nutrient management regulatory agencies are requesting better knowledge of P fertilization impacts on soil-test P (STP) and crop yield. This study evaluated STP and grain yield of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] as affected by long-term P fertilization in three trials evaluated from the 1970s until 2002 near Boone, Kanawha, and Nashua in central, northern, and northeast Iowa. Soils were Aquic Hapludolls and Typic Endoaquolls at Boone, Typic Endoaquolls at Kanawha, and Typic Hapludolls at Nashua. At Boone and Kanawha, treatments were the combinations of three initial STP levels (17–96 mg P kg^{-1}, Bray-P_1) and four annual rates (0–33 kg P ha^{-1}). At Nashua, initial STP was 28 mg P kg^{-1} and treatments were 0, 22, and 44 kg P ha^{-1} Ten to twenty years of cropping were needed on soils testing 43 to 96 mg P kg^{-1} to observe yield response to P. Annual P rates that maintained near optimum STP (16–20 mg P kg^{-1}) were 17, 14, and 13 kg P ha^{-1} yr^{-1} at Boone, Kanawha, and Nashua, respectively. Phosphorus required to increase STP 1 mg P kg^{-1} yr^{-1} were 23, 28, and 17 kg P ha^{-1} yr^{-1} at Boone, Kanawha, and Nashua, respectively. Critical STP concentrations (CC) identified across sites and years were 15 to 21 mg P kg^{-1} for corn and 12 to 18 mg P kg^{-1} for soybean. Observed grain yield and STP responses are useful to develop effective P management plans for corn–soybean rotations under approximately similar conditions to those in this study.

Dolan D. M., and S. C. Chapra. 2012. Great Lakes total phosphorus revisited: Loading analysis and update (1994–2008). *Great Lakes Restoration* 38:730–740.

Phosphorus load estimates have been updated for all of the Great Lakes with an emphasis on lakes Superior, Michigan, Huron and Ontario for 1994–2008. Lake Erie phosphorus loads have been kept current with previous work and for completeness are reported here. A combination of modeling and data analysis is employed to evaluate whether target loads established by the Great Lakes Water Quality Agreement (GLWQA, 1978, Annex 3) have been and are currently being met. Data from federal, state, and provincial agencies were assembled and processed to yield annual estimates for all lakes and sources. A mass-balance model was used to check the consistency of loads and to estimate interlake transport. The analysis suggests that the GLWQA target loads have been consistently met for the main bodies of lakes Superior, Michigan and

Huron. However, exceedances still persist for Saginaw Bay. For lakes Erie and Ontario, loadings are currently estimated to be at or just under the target (with some notable exceptions). Because interannual variability is high, the target loads have not been met consistently for the lower Great Lakes. The analysis also indicates that, because of decreasing TP concentrations in the lakes, interlake transport of TP has declined significantly since the mid-1970s. Thus, it is important that these changes be included in future assessments of compliance with TP load targets. Finally, detailed tables of the yearly (1994–2008) estimates are provided, as well as annual summaries by lake tributary basin (in Supplementary Information).

Dunne, E. J., R. Reddy, and M. W. Clark. 2006. Biogeochemical indices of phosphorus retention and release by wetland soils and adjacent stream sediments. *Wetlands* 26:1026–1041.

Eutrophication is still a water quality problem within many watersheds. The Lake Okeechobee Basin, Florida, USA, like many watersheds is impacted by eutrophication caused by excess phosphorus (P). To meet water quality criteria to reduce this impairment, several levels of information on P dynamics within the Basin are required. The use of biogeochemical indices to help determine P retention/release of different landscape units such as wetlands and streams provides useful information on P dynamics. The objective of our study was to determine P retention/release indices for a range of wetland soils and their adjacent stream sediments. We sampled several wetlands and adjacent streams within Okeechobee's Basin, which represented a range of P impacted systems. Regression analyses suggest that a single incubation of sediment/soil equilibrated at 1000 mg P kg21 was sufficient (› 96% of the time) to estimate maximum P sorption capacity (Smax). Using this single incubation, sampled wetlands had nearly twice the P sorption capacity (238 6 21 mg P kg21) of stream sediments (146 614 mg P kg21). Stream sediments also had a greater P saturation ratio (PSR) than wetland soils, indicating that sediment had a greater potential to release P. Phosphorus sorption under ambient P conditions (soil equilibrated with ambient site water) covaried best with P concentrations in site surface water and, as concentrations increased, P sorption also increased. Finally, we used soil P storage capacity (SPSC) to help estimate the ability of soils and sediments to retain additional P loadings and found that wetland soils had a greater ability to retain P. Phosphorus sorption was predicted equally well (› 73%) using either ammonium oxalate or 1 M HCl extractable Fe and Al. The use of indices to quantify P dynamics of different landscape units can inform watershed management and policies aimed at reducing P loads to receiving water bodies.

Dunne, E. J., M. W. Clark, R. Corstanje, K. R. Reddy. 2011. Legacy phosphorus in subtropical wetland soils: Influence of dairy, improved, and unimproved pasture land use. *Ecological Engineering* 37:1481–1491.

Wetlands provide various ecosystem services. One of these services includes nutrient storage in soils. Soils retain and release nutrients such as phosphorus (P). This dynamic can be controlled by soil characteristics, overlying water quality, environmental conditions and historical nutrient loading. Historical nutrient loading contributes to a legacy of P stored in soils and this may influence present day P dynamics between soil and water. We quantified P characteristics of wetland soils and determined the availability and capacity of soils to retain additional P loadings. We sampled surface (0–10) and subsurface (10–30) wetland soils within dairy, improved and unimproved pastures. Surface soils had much greater concentrations of organic and inorganic P. Wetland soils in dairy had greatest concentrations of Ca and Mg, probably due to inputs of inorganic fertilizer. They also had much greater total P, inorganic P, and P sorption capacity; however, these soils were P saturated and had little capacity to retain additional P loading. Improved and unimproved pasture wetland soils had greatest amounts of organic P (>84%) and a capacity to store additional P loadings. Using multivariate statistics, we determined that rather than being different based on land use, wetland soils in improved and unimproved pasture were dissimilar based upon organic matter, organic P fractions, residual P, and soil metal (Fe and Al) content. The legacy of stored P in soils, particularly wetland soils from dairies, combined with best management practices (BMPs) to reduce nutrient loading to these systems, could contribute to a short-term release of soil-stored P to overlying wetland water.

Dunne, E. J., M. R. Coveney, V. R. Hoge, R. Conrow, R. Naleway, E. F. Lowe, L. E. Battoe, Y. Wang. 2015. Phosphorus removal performance of a large-scale constructed treatment wetland receiving eutropic lake water. *Ecological Engineering* 79:132–142.

Eutrophication continues to impact watersheds and their receiving water bodies. One approach to mitigate this problem is to use constructed treatment wetlands. Our objectives were to determine long-term phosphorus (P) removal by a large-scale constructed treatment wetland (the marsh flow-way at Lake Apopka, Florida, USA) that treats lake water and to quantify the monetary costs for performance. The marsh flow-way treated substantial amounts of lake water (30 m yr^{-1}, which is about 30% of the lake's volume on an annual basis). Associated with this, P was removed at an average rate of 0.85 g m^{-2} yr^{-1} (2.6 metric tons yr^{-1}). The marsh flow-way removed mostly particulate P, while it released dissolved P fractions (mostly during the first few years of operation; thereafter, release was negligible). The long-term first-order removal rate constant (k) for P averaged 27 m yr_1. Phosphorus removal performance varied seasonally, with greater removal during cool periods (September–May) and poor removal during warm periods (June–August). Incurred annual operation and maintenance (O&M) costs averaged $455,000 (2012$), which was equivalent to $1,648 ha yr_1 or $177 per kilogram of P removed. We also calculated costs for a 25-year project life cycle, and compared the incurred and the 25-year costs to other systems that illustrated the marsh flow-way was cost competitive. Both P removal and costs were useful metrics in helping us determine operational and management changes. This resulted in a seasonal management strategy that contributed to increased P removal and a reduction in O&M, thereby increasing cost effectiveness. In addition to costs, treatment wetlands provide benefits that include a range of ecosystem services. We challenge ourselves and other treatment wetland managers to adopt both a cost and benefit approach to assessing system performance.

Dunne, E. J., M. F. Coveney, E. R. Marzolf, V. R. Hoge, R. Conrow, R. Naleway, E. F. Lowe, L. E. Battoe. (2012). Efficacy of a large-scale constructed wetland to remove phosphorus and suspended solids from Lake Apopka, Florida. *Ecological Engineering* 42, 90–100.

Constructed wetlands treat various types of waters. We examined the efficacy of a large-scale constructed wetland (the marsh flow-way), which was designed to treat lake water by maximizing the removal rate of total phosphorus (TP), and total suspended solids (TSS) from Lake Apopka. The flow-way was constructed on former agricultural land and has four independently operated wetland cells (treatment area is ~276 ha). During the operating period (November 2003–March 2007), hydraulic loading rate (HLR) was high, with annual median values between 32 and 49 m yr^{-1}. On average, 87% of the treated water returned to the lake, and the remainder flowed downstream. The wetland released soluble P (mostly soluble reactive P [SRP]), which was probably caused by P release from soils and/or senescing vegetation. This release was high initially and high during summers, but declined overall with time. Despite SRP release, the system removed TP over annual periods, with maximum net TP removal in 2007 (1.8 g m^{-2} yr^{-1}). Most of the incoming and retained P was particulate. Median percent mass removal was 58% for particulate P (PP) and about 30% for TP. Total suspended solids were always removed (median removal rate = 1.4 kg m^{-2} yr^{-1}) and the percent mass removal was high (93%). Median first-order rate constants (P-k-C* model) were 43 m yr^{-1} for TP and 228 m yr^{-1} for TSS. Removal rates of TP and PP appeared to increase linearly up to the highest loading (5–6 g m^{-2} yr^{-1}), whereas removal rate of TSS may have approached an asymptote at loading >3 kg m^{-2} yr^{-1}. We found that C* declined from 0.070 in the previous pilot project to 0.045 mg L^{-1} in the current flow-way system. Continued reduction in C* as TP declines in inflow lake water would assist P removal. Otherwise, selective wetland operation during periods of high lakewater TP concentrations may be required in the future to maintain net P removal.

Eastman, M., A. Gollamudi, N. Stampfli, C. Madramootoo, and A. Sarangi. 2010. Comparative evaluation of phosphorus losses from subsurface and naturally drained agricultural fields in the Pike River watershed of Quebec, Canada. *Agricultural Water Management* 97:596–604. doi:10.1016/j.agwat.2009.11.010

Phosphorus (P) is the limiting nutrient responsible for the development of algal blooms in freshwater bodies, adversely impacting the water quality of downstream lakes and rivers. Since agriculture is a major non-point source of P in southern Quebec, this study was carried out to investigate P transport under subsurface and naturally drained agricultural fields with two common soil types (clay loam and sandy loam). Monitoring stations were installed at four sites (A, B, C and D) in the Pike River watershed of southern Quebec. Sites A–B had subsurface drainage whereas sites C–D were naturally drained. In addition, sites A–C had clay loam soils whereas sites B–D had sandy loam soils. Analysis of data acquired over two hydrologic years (2004–2006) revealed that site A discharged 1.8 times more water than site B, 4 times more than site C and 3 times more than site D. The presence of subsurface drainage in sandy loam soils had a significant beneficial effect in minimizing surface runoff and total phosphorus (TP) losses from the field, but the contrary was observed in clay loam soils. This was attributed to the finding that P speciation as particulate phosphorus (PP) and dissolved phosphorus (DP) remained relatively independent of the hydrologic transport pathway, and was a strong function of soil texture. While 80% of TP occurred as PP at both clay loam sites, only 20% occurred as PP at both sandy loam sites. Moreover, P transport pathways in artificially drained soils were greatly influenced by the prevailing preferential and macropore flow conditions.

Gachter, R., J. M. Ngatiah, and C. Stamm. 1998. Transport of phosphate from soil to surface waters by preferential flow. *Environmental Science Technology* 32:1865–1869. doi:10.1021/es9707825.

Enrichment of lakes with soluble reactive phosphorus (SRP) leads to their deterioration as ecosystems, recreation areas, and drinking water reservoirs. In many cases, fertilized soils are their most important P source. Most studies dealing with P losses from soils to surface waters concentrate on erosion and surface runoff. Leaching is mostly considered to be of minor importance. On the basis of an in-situ sprinkling experiment with dye and bromide as tracers and of observations of the dynamics of SRP concentration and water discharge at the watershed scale, we identify soil macropores and artificial drainage systems as the most important pathways for the vertical and lateral transport of SRP from P-enriched soil surfaces to surface waters. A conceptional model explains why in drainage systems flow rate and SRP concentration are positively related. We estimate that more than half of the yearly SRP load is leached from the soil, and thus conclude that counter to the conventional wisdom, in the investigated watershed, leaching and not surface runoff is the most important mechanism for P transfer from soils to surface waters. It should be tested to see whether this conclusion can be generalized and also hold true for other watersheds with artificially drained, P-enriched soils with a low matrix permeability.

Gaynor, J. D. and W. I. Findlay. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. *Journal of Environmental Quality* 24:734–741.

Conservation tillage is encouraged in southwestern Ontario by concern for soil erosion and compaction. The contribution of agriculture to eutrophication of the Great Lakes by P is also at issue. Soil loss and ortho-P transport were measured from a conventional and two conservation tillage treatments (zero and ridge tillage) from January 1988 to 30 Sept. 1990 to evaluate their impact on meeting Great Lakes water quality objectives for P. Sediment concentration from the poorly drained, Brookston clay loam (clayey, mixed, mesic Typic Haplaquolls), cropped to corn *(Zea mays* L.) was 2.1 times larger in surface runoff than tile discharge (0.20 g -1) but tiled is charge contributed 44 to 65% of the soil loss probably from preferential flow. Conservation tillage reduced average soil loss 49% from conventional tillage (899 kg ha^{-1}). Conservation tillage increased ortho-P concentrations in runoff 2.2 times from conventional tillage (0.25 mg L-1). Orthophosphate transport decreased in the order zero>ridge>conventional tillage. Average ortho-P loss was 1.7 to 2.7 times greater from conservation than conventional tillage (559 g ha^{-1} yr^{-1}). Subsurface drainage accounted for 55 to 68% of the ortho-P transported. Transport of total soluble P and total P (sum of sediment-attached P and soluble P, only measured in 1990) increased 2.2 and 2.0 times, respectively, with conservation than conventional tillage. Dissolved P accounted for 84 to 93% of the P transported from the three tillage treatments. Sediment-attached P constituted 7 to 16% of total P loss. Conservation tillage effectively reduced soil erosion but increased P loss.

Geohring, L. D., McHugh, O. V., Walter, M. T., Steenhuis, T .S., Akhtar, M. S., and Walter, M. F. 2001. Phosphorous transport into subsurface drains by macropores after manure applications: Implications for best manure management practices. *Soil Science* 166(12).

Land application of liquid manure can result in nutrient enrichment of subsurface drainage efiluent when conditions promote leaching or macropore flow. This contamination is most likely to occur when precipitation follows manure application closely and may cause environmental impacts to receiving waters. Field and column studies were initiated in New York to investigate the impact of manure applications on phosphorus (P) transport through the soil into subsurface drains. Field studies evaluated tile efiluent contamination from liquid manure under wet and dry antecedent soil moisture conditions (year 1) and under disk and plow tillage practices (year 2). In year 1, liquid dairy manure was broadcast on the surface and the field was then irrigated. Though the tile drains in the wet plots flowed much earlier and in greater volume than the drains in the dry plots, both wet and dry plots produced similar average peak total phosphorus (TP) concentrations. Irrigation 6 days later produced similar tile discharges, but the peak TP concentrations were about one-third of the earlier values. Cumulative TP loss was significantly higher from wet than dry plots. In year 2, manure was tilled into the soil via one-pass disking or plowing before irrigation commenced. The disking did not incorporate the manure into the soil as effectively as did plowing and exhibited one order of magnitude higher effluent TP concentrations and cumulative TP loss. The timing of P transport in tile effluent relative to the tile flow is consistent with macropore transport as the primary mechanism moving TP through the soil. Column studies utilizing packed soil and artificial macropores were used to examine further the role of macropore size on P sorption to pore walls. Dissolved P was added directly to the macropore, and the efiluent from the macropore showed that soluble P may be transported through macropores 1 mm or greater with negligible P sorption to pore walls. In the absence of macropores, no measurable P was transported through the soil columns. Consequently, high P concentrations observed in the tile drain effluent soon after manure application during the field studies can be attributed to macropore transport processes. Even small continuous macropores are potential pathways. Plowing-in manure apparently disturbs these macropores and promotes matrix flow, resulting in greatly reduced P concentrations in the drainage efiluent.

Graczyk, D. J., D. M. Robertson, P. D. Baumgart, and K. J. Fermanich 2011. *Hydrology, phosphorus, and suspended solids in five agricultural streams in the lower Fox River and Green Bay Watersheds, Wisconsin, Water Years 2004–06*. United States Geological Survey (USGS) Scientific Investigations Report, 5111.

A 3-year study was conducted by the U.S. Geological Survey and the University of Wisconsin-Green Bay to characterize water quality in agricultural streams in the Fox/Wolf watershed in northeastern Wisconsin and provide information to assist in the calibration of a watershed model for the area. Streamflow, phosphorus, and suspended solids data were collected between October 1, 2003 and September 30, 2006 in five streams, including Apple Creek, Ashwaubenon Creek, Baird Creek, Duck Creek, and the East River. During this study, total annual precipitation was close to the 30-year normal of 29.12 inches. The 3-year mean streamflow was highest in the East River (113 ft3/s), followed by Duck Creek (58.2 ft3/s), Apple Creek (26.9 ft3/s), Baird Creek (12.8 ft3/s), and Ashwaubenon Creek (9.11 ft3/s). On a yield basis, during these three years, the East River had the highest flow (0.78 ft3/s/mi2), followed by Baird Creek (0.61 ft3/s/mi2), Apple Creek (0.59 ft3/s/mi2), Duck Creek (0.54 ft3/s/mi2), and Ashwaubenon Creek (0.46 ft3/s/mi2).

The overall median total suspended solids (TSS) concentration was highest in Baird Creek (73.5 mg/L), followed by Apple and Ashwaubenon Creeks (65 mg/L), East River (40 mg/L), and Duck Creek (30 mg/L). The median total phosphorus (TP) concentration was highest in Ashwaubenon Creek (0.60 mg/L), followed by Baird Creek (0.47 mg/L), Apple Creek (0.37 mg/L), East River (0.26 mg/L), and Duck Creek (0.22 mg/L).

The average annual TSS yields ranged from 111 tons/mi2 in Apple Creek to 45 tons/mi2 in Duck Creek. All five watersheds yielded more TSS than the median value (32.4 tons/mi2) from previous studies in the Southeastern Wisconsin Till Plains (SWTP) ecoregion. The average annual TP yields ranged from 663 lbs/mi2 in Baird Creek to 382 lbs/mi2 in Duck Creek. All five watersheds yielded more TP than the median value from previous studies in the SWTP ecoregion, and the Baird Creek watershed yielded more TP than the statewide median of 650 lbs/mi2 from previous studies.

Overall, Duck Creek had the lowest median and volumetric weighted concentrations and mean yield of TSS and TP. The same pattern was true for dissolved phosphorus (DP), except the volumetrically weighted concentration was lowest in the East River. In contrast, Ashwaubenon, Baird, and Apple Creeks had greater median and volumetrically weighted concentrations and mean yields of TSS, TP, DP than Duck Creek and the East River. Water quality in Duck Creek and East River were distinctly different from Ashwaubenon, Baird, and Apple Creeks.

Loads from individual runoff events for all of these streams were important to the total annual mass transport of the constituents. On average, about 20 percent of the annual TSS loads and about 17 percent of the TP loads were transported in 1-day events in each stream.

Great Lakes Restoration. *Great Lakes Restoration Initiative Action Plan II*. 2014.

The Great Lakes Restoration Initiative was launched in 2010 to accelerate efforts to protect and restore the largest system of fresh surface water in the world — to provide additional resources to make progress toward the most critical long-term goals for this important ecosystem.

The Great Lakes Restoration Initiative has been a catalyst for unprecedented federal agency coordination — through the Interagency Task Force and the Regional Working Group, which are led by EPA. This coordination has produced unprecedented results. Great Lakes Restoration Initiative resources have supplemented agency base budgets to fund the cleanup actions required to delist five Great Lakes Areas of Concern and to formally delist the Presque Isle Bay

Area of Concern — a major change from the 25 years before the Initiative, during which only one Area of Concern was cleaned up and delisted. Great Lakes Restoration Initiative resources have also been used to double the acreage enrolled in agricultural conservation programs in watersheds where phosphorus runoff contributes to harmful algal blooms in western Lake Erie, Saginaw Bay and Green Bay. So far, Great Lakes Restoration Initiative resources have been used to fund over 2,000 projects to improve water quality, to protect and restore native habitat and species, to prevent and control invasive species and to address other Great Lakes environmental problems.

During the next five years, federal agencies plan to continue to use Great Lakes Restoration Initiative resources to strategically target the biggest threats to the Great Lakes ecosystem and to accelerate progress toward long term goals — by combining Great Lakes Restoration Initiative resources with agency base budgets and by using these resources to work with nonfederal partners to implement protection and restoration projects. To guide this work, federal agencies have drafted GLRI Action Plan II, which summarizes the actions that federal agencies plan to implement during FY15-19 using Great Lakes Restoration Initiative funding. GLRI Action Plan II outlines the next phase of work on Great Lakes environmental problems and associated human health issues — many of which will take decades to resolve. GLRI Action Plan II lays out the necessary next steps to get us closer to the day when we will be able to achieve our long-term goals for the Great Lakes and our commitments under the U.S.-Canada Great Lakes Water Quality Agreement.

Great Lakes Water Quality Agreement (GLWQA). 2012. *The 2012 Great Lakes Water Quality Agreement — Annex 4.*

The purpose of this Annex is to contribute to the achievement of the General and Specific Objectives of this Agreement by coordinating binational actions to manage phosphorus concentrations and loadings, and other nutrients if warranted, in the Waters of the Great Lakes.

Great Lakes Water Quality Agreement Annex 4 Objectives and Targets Task Team. 2015. Recommendations for monitoring, modeling, research and reporting to support adaptive management.

Following submission of the Objectives and Targets Task Team's final report on 11 May 2015, the Task Team was asked by the Annex 4 Subcommittee to develop recommendations for monitoring, modeling and research to support adaptive management and evaluate progress toward achieving the targets in the Team's report and Lake Ecosystem objectives. The Team was asked to focus on harmful algal blooms (HABs) in the Western Basin of Lake Erie, hypoxia in the Central Basin, nuisance growths of *Cladophora* in the Eastern Basin, priority tributaries, tributary mouths, and nearshore and open lake waters. The Task Team met at the University of Windsor on 26 August and at NOAA's Great Lakes Environmental Research Laboratory on 16 October to prepare the recommendations.

Groffman, P. M., G. C. Hanson, E. Kiviat, and G. Stevens. 1996. Variation in microbial biomass and activity in four different wetland types. *Soil Science Society of America Journal* 60:622–629.

Functional evaluation of wetlands in nutrient cycling, water quality maintenance, and wetland construction and restoration contexts requires knowledge of differences in microbial processes between different wetland types and understanding of the nature and extent of variation in these processes within a given wetland type. In this study, we measured a suite of microbial variables (microbial biomass C and N content, denitrification enzyme activity, potential net N mineralization and nitrification, and soil respiration) that are indices of wetland nutrient cycling and water quality maintenance functions in four different wetland types (calcareous fens, red maple swamps, woodland pools, and wet clay meadows) in eastern New York state. Total soil C and N content, water content, pH, water-table levels, and groundwater NH^{+}_{4}, NO^{-}_{3}, and electrical conductivity were also measured. The clay meadow wetlands were drier and had lower levels of organic matter and most microbial variables than the other wetland types. Site-to-site variation within the fens was very high and was not strongly controlled by water-table levels. Organic matter content and N status appear to be strong regulators of microbial biomass and activity in fens. Red maple swamps and woodland pools had similar levels of most microbial variables. Variation within these wetland types was controlled by hydrology and organic matter quality. The suite of microbial variables that we measured identified potential functional differences between wetland types and should be useful for comparisons of the water quality maintenance value of different wetlands and for functional evaluation of altered or restored sites.

Han, H., N. Bosch, and J. D. Allan. 2011. Spatial and temporal variation in phosphorus budgets for 24 watersheds in the Lake Erie and Lake Michigan basins. *Biogeochemistry* 102:45–58.

We estimated net anthropogenic phosphorus inputs (NAPI) to 18 Lake Michigan (LM) and 6Lake Erie (LE) watersheds for 1974, 1978, 1982, 1987, and 1992. NAPI quantifies all anthropogenic inputs of P (fertilizer use, atmospheric deposition, and detergents) as well as trade of P in food and feed, which can be a net input or output. Fertilizer was the dominant input overall, varying by three orders of magnitude among the 24 watersheds, but detergent was the largest input in the most urbanized watershed. NAPI increased in relation to area of disturbed land (R2 = 0.90) and decreased with forested and wetland area (R2 = 0.90). Export of P by rivers varied with NAPI, especially for the 18 watersheds of LM (R2 = 0.93), whereas the relationship was more variable among the six LE watersheds (R2 = 0.59). On average, rivers of the LE watersheds exported about 10% of NAPI, whereas LM watersheds exported 5% of estimated NAPI. A comparison of our results with others as well as nitrogen (N) budgets suggests that fractional export of P may vary regionally, as has been reported for N, and the proportion of P inputs exported by rivers appears lower than comparable findings with N.

Hansen, N. C., T. Daniel, A. Sharpley, and J. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. *Journal of Soil Water Conservation* 57:408–417.

Phosphorus (P) is an important input for economic crop and livestock production systems. Excessive losses of P from agricultural systems to surface waters can accelerate eutrophication and degrade water quality. This paper reviews the behavior of P in agricultural soils and discusses the transport of P from land to water. The forms, measurement, and sorption processes of Pin both soil and water are discussed. Soil test P, the most common soil P analysis, is described relative to other forms of soil P and its use for agricultural and environmental purposes is explained. Loss of soil P to water can occur in particulate forms with eroded surface soil and in soluble forms in runoff, soil interflow, and deep leaching. This paper discusses the relative importance of each transport pathway as affected by soil type and management. Soil P dynamics and water quality risks associated with fertilizer and manure application are illustrated with several examples. Finally, the paper reviews management practices that can effectively reduce the loss of agricultural P to surface waters.

Havlin, J. L., S. L. Tisdale, W. L. Nelson, J. D. Beaton. 2014. *Soil Fertility and Fertilizers: An introduction to nutrient management*. 8th Edition. Pearson Education, Inc. New Jersey, USA.

Soil Fertility and Fertilizers: An Introduction to Nutrient Management, Eighth Edition, provides a thorough understanding of the biological, chemical, and physical properties affecting soil fertility and plant nutrition. Covering all aspects of nutrient management for profitable crop production, the text pays particular attention to minimizing the environmental impact of soil and fertilizer management. The eighth edition of this proven text has been substantially revised to reflect rapidly advancing knowledge and technologies in both plant nutrition and nutrient management.

Hill, B. H., C. M. Elonen, T. M. Jicha, A. M. Cotter, A. S. Trebitz, and N. P. Danz. 2006. Sediment microbial enzyme activity as an indicator of nutrient limitation in Great Lakes coastal wetlands. *Freshwater Biology* 51:1670–1683.

1. We compared the extracellular enzyme activity (EEA) of sediment microbial assemblages with sediment and water chemistry, gradients in agricultural nutrient loading (derived from principal component analyses), atmospheric deposition and hydrological turnover time in coastal wetlands of the Laurentian Great Lakes.

2. There were distinct increases in nutrient concentrations in the water and in atmospheric

N deposition along the gradient from Lake Superior to Lake Ontario, but few differences between lakes in sediment carbon (C), nitrogen (N) or phosphorus (P). Wetland water and sediment chemistry were correlated with the agricultural stress gradient, hydrological turnover time and atmospheric deposition.

3. The N:P ratio of wetland waters and sediments indicated that these coastal wetlands were N-limited. Nutrient stoichiometry was correlated with the agricultural stress gradient, hydrological turnover time and atmospheric deposition.

4. Extracellular enzyme activity was correlated with wetland sediment and water chemistry and stoichiometry, atmospheric N deposition, the agricultural stress gradient and the hydrological turnover time. The ratios of glycosidases to peptidases and phosphatases yielded estimates of nutrient limitation that agreed with those based solely on nutrient chemistry.

5. This study, the first to link microbial enzyme activities to regional-scale anthropogenic stressors, suggests that quantities and ratios of microbial enzymes are directly related to the concentrations and ratios of limiting

nutrients, and may be sensitive indicators of nutrient dynamics in wetland ecosystems, but further work is needed to elucidate these relationships.

Hoffmann, C. C., L. Heiberg, J. Audet, B. Schønfeldt, A. Fuglsang, B. Kronvang, N. B. Ovesen, C. Kjaergaard, H. C. B. Hansen, and H. S. Jensen. 2012. Low phosphorus release but high nitrogen removal in two restored riparian wetlands inundated with agricultural drainage water. *Ecological Engineering* 46:75–87. doi:10.1016/j.ecoleng.2012.04.039.

Re-established riparian wetlands used to mitigate nitrogen (N) loss from agricultural soils to surface water may lose phosphorus (P) from the top soils that often have received fertilizers. This could lead to eutrophication of lakes and estuaries. For a 2-year period we established mass balances of N and P in two restored riparian wetlands of ~0.6 ha situated on mineral soil. Monitoring began 5 years after restoration. Both wetlands received drainage water from upland agricultural fields rich in nitrate (1.5–12.3 mg N L^{-1}) and low in total P (TP) (0.016–0.04 mg P L^{-1}). Water balances were reasonably accounted for (15% imbalance at most). Water passed the wetlands as sheet flow without exchange with groundwater because of clay horizons in sub-soils, and sheet pilings along the stream banks allowed continuous measurements of inflow and outflow. The Egeskov riparian wetland (wetland:upland ratio 0.13) removed 121 and 28 kg N ha^{-1} yr^{-1} (43 and 75% of the load) and retained 0.08 kg P ha^{-1} (6% of the load) in year one and had a net release of 0.15 kg P ha^{-1} (25% of the load) in year two. The Stor Å riparian wetland (wetland:upland ratio 0.02) removed 229 and 158 kg N ha^{-1} yr^{-1} (32 and 26%). Net releases of P were 0.33 and 0.90 kg P ha^{-1} yr^{-1} (22 and 127%). Nitrogen removal rates are on par with published rates for similar wetlands, while the P release rates appear surprisingly low. Phosphate outlet concentrations resembled the equilibrium concentrations (EPC_0) where no phosphate exchange occurred between top soils and drainage water, suggesting that P release or retention was controlled by phosphate adsorption. This value was 0.015 mg P L^{-1} for Egeskov and 0.047 mg P L^{-1} for Stor Å. The high phosphate affinity was probably governed by high ratios between oxidized iron and iron-bound P. The top soils (10 cm) contained 87 and 201 kg P ha^{-1} as iron-bound P and herbaceous vegetation accumulated 10.7 and 16.5 kg P ha^{-1} yr^{-1}. These figures are 55–136 and 8–11 times higher than the annual P-load to the wetlands, and we suggest that annual harvest of vegetation could maintain or even improve the P retention capacity of these wetlands.

Holford, I. C. R., and W. H. Patrick, Jr. 1979. Effects of reduction and pH changes on phosphate sorption and mobility in an acid soil. *Soil Science Society of America Journal* 43:292–297.

Suspensions of a silt loam in 0.01M CaCl, (1:6) were incubated at redox potentials of 500, 280, 65, and —150 mV for 26+ *2* days in factorial combination with pH treatments of 5.0, 6.5, and 8.0. Samples were then removed and equilibrated with graded concentrations of KH2PO, under O2-free conditions. Isotopically-exchangeable P was measured on the zero treatment and P sorption on the other treatments after 24 hours equilibration. Sorption properties of the soil were determined by application of the Langmuir equation. The largest changes occurred in the most reduced treatment (—150 mV) and at pH 8.0. At pH 5.0, an unnaturally low pH for an anaerobic soil, reduction to —150 mV decreased P sorption at solution P concentrations below 20 ppm because of the reduction and dissolution of ferric hydrous oxides. At higher concentrations sorption was increased by ferrous phosphate precipitation due to the very high concentrations of soluble Fe. At pH 6.5, reduction caused a very large increase in P sorption apparently because of increased adsorption on freshly precipitated amorphous ferrous hydroxides. At pH 8.0, P sorption was deceased at P concentrations below 2 ppm, probably because of increased surface negative charge, but increased at higher P concentrations due to precipitation of Ca phosphates. At all pH values, reduction increased the concentration of native P in solution. At pH 6.5 this was caused by an increase in labile P due to the release of P occluded and precipitated in ferric compounds. At pH 5.0 and 8.0 it was caused by a decrease in P bonding energy. Reduction to —150 mV caused the largest increase in soluble P and the smallest increase in P sorption capacity at pH 5.

Johannesson, K. M., P. Kynkaanniemi, B. Ulen, S. E. B. Weisner, and K. S. Tonderski. 2015. Phosphorus and particle retention in constructed wetlands - A catchment comparison. *Ecological Engineering* 80:20–31.

Seven constructed wetlands (0.05–0.69 ha), situated in agricultural catchments (22–267 ha) in the south of Sweden, were studied for two years with two aims: to (i) quantify their function as sinks for particles and phosphorus (P) lost from the catchments, and (ii) investigate to what degree catchment and wetland characteristics and modeled loads (using hydrochemical catchment models) could be used to explain differences in retention between the wetlands. The wetland areas ranged from 0.04 to 0.8% of the respective catchment area, and they were situated in areas dominated by fine-textured soils with relatively high P losses and the main proportion of P transported in particulate form. Net P and particle retention were estimated during two years from annual accumulation of particles on sedimentation plates (40×40 cm) on the bottom of the wetlands.

There was an annual net retention of particles and P, but with a large variation (for particles 13–108 t ha^{-1} yr^{-1} and for P 11–175 kg ha^{-1} yr^{-1}), both between wetlands and between years. The difference between the two years was larger than the difference in mean P retention between the seven wetlands. There was a positive relationship between P and particle retention and three catchment factors, i.e. P status (P-AL) of agricultural soils, average slope in the catchments and the livestock density, and a negative relationship with the agricultural soil clay content. In addition, there was a positive relationship with the wetland length:width ratio. Contrary to expectations, neither the modeled hydraulic load nor P load was significantly correlated with the measured particle and P retention. There was also a positive relationship between P concentration in the sediment and soil P status in the catchment. The results imply that considerable errors are introduced when down-scaling modeled regional nutrient losses to estimate the P loads to small wetlands in agriculturally dominated catchments. A more qualitative approach, using catchment characteristics for identification of hot-spot fields, may be equally good to identify suitable locations for constructed wetlands to reduce diffuse P loads.

Johnston A. E. and P. R. Poulton. 1976. *Yields on the exhaustion land and changes in the NPK content of the soils due to cropping and manuring, 1852–1975*. Rothamsted Exp Stat. Rep 1976, Part 2, 53–101.

The Exhaustion Land experiment now compares yields of barley grown on soil without P or K since 1852 with soils containing residues from PK manuring given during 1856-1901. Few visitors to Rothansted Farm fail to appreciate the significance of the results which show that these residues, accumulated from dressings of either fertilizers or farmyard manure (FYM), have doubled yields of barley during 1949-74 when adequate N was given. Soils enriched with residues gave yields at least equal to the average of all barley crops grown in Great Britain. The experiment, which occupies 1.01 ha on the north side of Hoosfield, derived its name in the early part of this century. At that time unmanured cereal cropping, which started in 1902, measured the residual effects of manures applied in previous experiments. Warren and Johnston (1960) gave reasons for starting the three experiments made between 1852-1901 and discussed the results. They also gave yields for the period 1902-1953. This paper summaries the early experiments and gives some previously unpublished data. Yields and NPK uptakes during 1949-74 are given in detail. We also discuss analysis of the soils including % N, and relate changes in total, soluble and isotopically exchangeable P and exchangeable K to the amounts of these nutrients removed in the crops.

Joosse, P. J. and D. B. Baker. 2011. Context for re-evaluating agricultural source phosphorus loadings to the Great Lakes. *Canadian Journal of Soil Science* 91:317–327.

Over the past decade, scientists have been discussing the re-emergence of harmful algal blooms and excessive growth of Cladophora in some areas of the Great Lakes. An observation that has emerged from these discussions is that management of non-point or diffuse sources of phosphorus will be more important in the future in order to address symptoms of eutrophication in the nearshore. This paper provides context for this renewed focus on managing non-point source tributary loads and is based primarily on materials and discussions from the Great Lakes P Forum. There are changes that have occurred in the lakes and tributaries in the past 15 yr that indicate a greater need to focus on non-point sources, whether urban or rural. Changes have also occurred in land management to reduce non-point P losses from agriculture. While these changes have reduced sediment and particulate P loading in some Ohio tributaries, the more bioavailable, dissolved P forms have increased. As there is incomplete knowledge about the mechanisms that are influencing algal growth, it could be a challenge to demonstrate, in the near term, improvements in water quality with further P reductions from agriculture alone. Regardless, there appears to be a desire for improved accountability and transparency for agricultural non-point source P management.

Jordan, T. E., D. F. Whigham, K. H. Hofmockel, and M. A. Pittek. 2003. Nutrient and sediment removal by a restored wetland receiving agricultural runoff. *Journal of Environmental Quality* 4:1534–1547.

Few studies have measured removal of pollutants by restored wetlands that receive highly variable inflows. We used automated flow-proportional sampling to monitor the removal of nutrients and suspended solids by a 1.3-ha restored wetland receiving unregulated inflows from a 14-ha agricultural watershed in Maryland, USA. Water entered the wetland mainly in brief pulses of runoff, which sometimes exceeded the 2500-m3 water holding capacity of the wetland. Half of the total water inflow occurred in only 24 days scattered throughout the two-year study. Measured annual water gains were within 5% of balancing water losses. Annual removal of nutrients differed greatly between the two years of the study. The most removal occurred in the first year, which included a three-month period of decreasing water level in the wetland. In that year, the wetland removed 59% of the total P, 38% of the total N, and 41% of the total organic C it received. However, in the second year, which lacked a drying period, there was no significant ($p > 0.05$) net removal of total N or P, although 30% of the total organic C input was removed. For the entire two-year period, the wetland removed 25% of the ammonium, 52% of the nitrate, and 34% of the organic C it received, but there was no significant net removal of total suspended solids (TSS) or other forms of N and P. Although the variability of inflow may have decreased the capacity of the wetland to remove materials, the wetland still reduced nonpoint-source pollution.

Kadlec, R. H. and S. D. Wallace. 2009. *Treatment wetlands*. CRC Press. Boca Raton, FL.

This book provides a complete reference that includes: detailed information on wetland ecology, design for consistent performance, construction guidance and operational control through effective monitoring. Case histories of operational wetland treatment systems illustrate the variety of design approaches presented allowing you to tailor them to the needs of your wetlands treatment projects. The sheer amount of information found in Treatment Wetlands, Second Edition makes it the resource you will turn to again and again.

King, K. W., Fausey, N. R., and Williams, M. R. 2014. Effect of subsurface drainage on streamflow in an agricultural headwater watershed. *Journal of Hydrology*. 519:438–445.

Artificial drainage, also known as subsurface or tile drainage is paramount to sustaining crop production agriculture in the poorly-drained, humid regions of the world. Hydrologic assessments of individual plots and fields with tile drainage are becoming common; however, a major void exists in our understanding of the contribution of systematic tile drainage to watershed hydrology. A headwater watershed (4 km2) in central Ohio, USA and all functioning tile were monitored from 2005 to 2010 in order to characterize the magnitude and frequency of flows, quantify the role and seasonal contributions of tile drainage to watershed hydrology, and relate tile drainage to precipitation and antecedent conditions. Results indicated that tile drainage contributions to watershed hydrology were significant. Specifically, 21% of precipitation (206 mm) was recovered through tile drainage annually. Tile drainage also accounted for 47% of watershed discharge and was seasonally variable. Median monthly tile discharges in winter (23.4 mm), spring (10.2 mm), and fall (15.6 mm) were significantly greater ($P < 0.05$) than the median monthly summer discharge (0.9 mm). Results from this study will help enhance hydrology and water quality prediction technologies as well as the design and implementation of best management practices that address water quality concerns.

King, K. W., M. R. Williams, M. L. Macrae, N. R. Fausey, J. Frankenberger. D. R. Smith, P. J. A. Kleinman, and L. C. Brown. 2015. Phosphorus transport in agricultural subsurface drainage: A review *Journal of Environmental Quality* 44:467–485.

Phosphorus (P) loss from agricultural fields and watersheds has been an important water quality issue for decades because of the critical role P plays in eutrophication. Historically, most research has focused on P losses by surface runoff and erosion because subsurface P losses were often deemed to be negligible. Perceptions of subsurface P transport, however, have evolved, and considerable work has been conducted to better understand the magnitude and importance of subsurface P transport and to identify practices and treatments that decrease subsurface P loads to surface waters. The objectives of this paper were (i) to critically review research on P transport in subsurface drainage, (ii) to determine factors that control P losses, and (iii) to identify gaps in the current scientific understanding of the role of subsurface drainage in P transport. Factors that affect subsurface P transport are discussed within the framework of intensively drained agricultural settings. These factors include soil characteristics (e.g., preferential flow, P sorption capacity, and redox conditions), drainage design (e.g., tile spacing, tile depth, and the installation of surface inlets), prevailing conditions and management (e.g., soil-test P levels, tillage, cropping system, and the source, rate, placement, and timing of P application), and hydrologic and climatic variables (e.g., baseflow, event flow, and seasonal differences). Structural, treatment, and management approaches to mitigate subsurface P transport— such as practices that disconnect flow pathways between surface soils and tile drains, drainage water management, in-stream or end-of-tile treatments, and ditch design and management—are also discussed. The review concludes by identifying gaps in the current understanding of P transport in subsurface drains and suggesting areas where future research is needed.

Kirkham, K., A. Maybanks, D. Kovacic, M. Wallace, and M. Lemke. 2015. *Franklin research and demonstration farm report*. The Nature Conservancy of Illinois.

The Franklin Research and Demonstration Farm, located in Lexington, IL is a collaborative effort between The Nature Conservancy, University of Illinois Champaign-Urbana (UIUC), Illinois State University (ISU), McLean County Soil and Water Conservation District (SWCD), McLean County Natural Resources Conservation Service (NRCS) and the Franklin family. The goals of the Research and Demonstration Farm project are to (1) study methods designed to reduce nutrient export from tile drained agricultural systems into adjacent waterways of Illinois, (2) demonstrate a wide variety of on-the-ground conservation practices in the context of a modern farm to local landowners, agency personnel, policy makers and the general public, and (3) restore woodland, savanna, prairie and wetland habitats to increase the biodiversity of plants and animals coexisting within an agricultural landscape.

Kleinman, P. J. A. and Sharpley, A.N. 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data', Communications. *Soil Science and Plant Analysis* 33:1825–1839.

Soil phosphorus sorption saturation (Psat) measures the degree to which soil phosphorus (P) sorption sites have been filled and has been found to be a good indicator of P availability to runoff and leachate. At present, analytical methods required to estimate Psat are generally not offered by soil testing laboratories. This study evaluated the use of Mehlich-3 data in estimating Psat in a wide range of soils. In acidic soils (pH = 4:1–5:9), Psat estimated from Mehlich-3 P, iron (Fe), and aluminum (Al) was highly correlated with Psat estimated from ammonium oxalate data (r = 94) as well as with a reference Psat estimated from bicarbonate P and the Langmuir sorption maximum (r = 0:89): In alkaline soils (pH = 7:3–8:4); Psat estimated with Mehlich-3 P and calcium (Ca) was highly correlated with the reference Psat (r = 0.84), and the strength of that correlation improved only slightly by factoring in soil clay content (r = 0.86). Results indicate that Psat may be effectively estimated from Mehlich-3 data across a wide range of soils. This study confirms that Psat may be readily estimated by soil testing laboratories that routinely measure Mehlich-3 P, Al, Fe, and Ca.

Kleinman, P. J. A., A. N. Sharpley, A. R. Buda, R. W. McDowell, and A. L. Allen. 2011a. Soil controls of phosphorus in runoff: Management barriers and opportunities. *Canadian Journal of Soil Science* 91:329–338. doi:10.4141/cjss09106.

The persistent problem of eutrophication, the biological enrichment of surface waters, has produced a vast literature on soil phosphorus (P) effects on runoff water quality. This paper considers the mechanisms controlling soil P transfers from agricultural soils to runoff waters, and the management of these transfers. Historical emphases on soil conservation and control of sediment delivery to surface waters have demonstrated that comprehensive strategies to mitigate sediment-bound P transfer can produce long-term water quality improvements at a watershed scale. Less responsive are dissolved P releases from soils that have historically received P applications in excess of crop requirements. While halting further P applications to such soils may prevent dissolved P losses from growing, the desorption of P from soils that is derived from historical inputs, termed here as “legacy P”, can persist for long periods of time. Articulating the role of legacy P in delaying the response of watersheds to remedial programs requires more work, delivering the difficult message that yesterday’s sinks of P may be today’s sources. Even legacy sources of P that occur in low concentration relative to agronomic requirement can support significant loads of P in runoff under the right hydrologic conditions. Strategies that take advantage of the capacity of soils to buffer dissolved P losses, such as periodic tillage to diminish severe vertical stratification of P in no-till soils, offer short-term solutions to mitigating P losses. In some cases, more aggressive strategies are required to mitigate both short-term and legacy P losses.

Kleinman, P. J. A., A.N. Sharpley, R. W. McDowell, D. N. Flaten, A. R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. 2011b. Managing agricultural phosphorus for water quality protection: Principles for progress. *Plant Soil* 349:169–182. doi:10.1007/s11104-011-0832-9.

Background The eutrophication of aquatic systems due to diffuse pollution of agricultural phosphorus (P) is a local, even regional, water quality problem that can be found world-wide.

Scope Sustainable management of P requires prudent tempering of agronomic practices, recognizing that additional steps are often required to reduce the downstream impacts of most production systems.

Conclusions Strategies to mitigate diffuse losses of P must consider chronic (edaphic) and acute, temporary (fertilizer, manure, vegetation) sources. Even then, hydrology can readily convert modest sources into significant loads, including via subsurface pathways. Systemic drivers, particularly P surpluses that result in long-term over-application of P to soils, are the most recalcitrant causes of diffuse P loss. Even in systems where P application is in balance with withdrawal, diffuse pollution can be exacerbated by management systems that promote accumulation of P within the effective layer of effective interaction between soils and runoff water. Indeed, conventional conservation practices aimed at controlling soil erosion must be evaluated in light of their ability to exacerbate dissolved P pollution. Understanding the opportunities and limitations of P management strategies is essential to ensure that water quality expectations are realistic and that our beneficial management practices are both efficient and effective.

Kleinman, P. J., A. N. Sharpley, P. J. A. Withers, L. Bergstrom, L. T. Johnson, D. G. Doody. 2015. Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio* 2015, 44:S297–S310.

Experience with implementing agricultural phosphorus (P) strategies highlights successes and uncertainty over outcomes. We examine case studies from the USA, UK, and Sweden under a gradient of voluntary, litigated, and regulatory settings. In the USA, voluntary strategies are complicated by competing objectives between soil conservation and dissolved P mitigation. In litigated watersheds, mandated manure export has not wrought dire consequences on poultry farms, but has adversely affected beef producers who fertilize pastures with manure. In the UK, regulatory and voluntary approaches are improving farmer awareness, but require a comprehensive consideration of P management options to achieve downstream reductions. In Sweden, widespread subsidies sometime hinder serious assessment of program effectiveness. In all cases, absence of local data can undermine recommendations from models and outside experts. Effective action requires iterative application of existing knowledge of P fate and transport, coupled with unabashed description and demonstration of tradeoffs to local stakeholders.

Kovacic, D. A., M. B. David, L. E. Gentry, K. M. Starks, and R. A. Cooke. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *Journal of Environmental Quality* 29:1262–1274.

Much of the nonpoint N and P entering surface waters of the Midwest is from agriculture. We determined if constructed wetlands could be used to reduce nonpoint N and P exports from agricultural tile drainage systems to surface waters. Three treatment wetlands (0.3 to 0.8 ha in surface area, 1200 to 5400 m3 in volume) that intercepted subsurface tile drainage water were constructed in 1994 on Colo soils (fine-silty, mixed, superactive, mesic Cumulic Endoaquoll) between upland maize *(Zea mays* L.) and soybean *[Glycine max* (L.) Merr.] cropland and the adjacent Embarras River. Water (tile flow, precipitation, evapotranspiration, outlet flow, and seepage) and nutrient (N and P) budgets were determined from 1 Oct. 1994 through 30 Sept. 1997 for each wetland. Wetlands received 4639 kg total N during the 3-yr period (96% as NO3-N) and removed 1697 kg N, or 37% of inputs. Wetlands decreased NO3-N concentrations in inlet water (annual outlet volume weighted average concentrations of 4.6 to 14.5 mg N L-~) by 28% compared with the outlets. When the wetlands were coupled with the 15.3-m buffer strip between the wetlands and the river, an additional 9% of the tile NO~-N was apparently removed, increasing the N removal efficiency to 46%. Overall, total P removal was only 2% during the 3-yr period, with highly variable results in each wetland and year. Treatment wetlands can be an effective tool in reducing agricultural N loading to surface water and for attaining drinking water standards in the Midwest.

Kuo S. 1996. Phosphorus. *In:* Sparks, D.L. (ed) Methods of Soil Analysis. Part 3: Chemical Methods, 3rd ed. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin.

The total P concentration in soils is generally in the range from 200 to 5000 mg P kg^{-1} with an average of 600 mg kg^{-1} (Lindsay, 1979). Physicochemical and biological reactions in soils and sediments act in concert to regulate P solubility which in turn affects both agronomic production as well as eutrophication of surface water.

LaBeau, M.B., D. M. Robertson, A. S. Mayer, B. C. Pijanowsi, D. A. Saad. 2014. Effects of future urban and biofuel crop expansions on the riverine export of phosphorus to the Laurentian Great Lakes. *Ecological Modelling* 277:27–37.

Increased phosphorus (P) loadings threaten the health of the world’s largest freshwater resource, the Laurentian Great Lakes (GL). To understand the linkages between land use and P delivery, we coupled two spatially explicit models, the landscape-scale SPARROW P fate and transport watershed model and the Land Transformation Model (LTM) land use change model, to predict future P export from nonpoint and point sources caused by changes in land use. According to LTM predictions over the period 2010–2040, the GL region of the U.S. may experience a doubling of urbanized areas and agricultural areas may increase by10%, due to biofuel feedstock cultivation. These land use changes are predicted to increase P loadings from the U.S. side of the GL basin by 3.5–9.5%, depending on the Lake watershed and development scenario. The exception is Lake Ontario, where loading is predicted to decrease by 1.8% for one scenario, due to population losses in the drainage area. Overall, urban expansion is estimated to increase P loadings by 3.4%. Agricultural expansion associated with predicted biofuel feedstock cultivation is predicted to increase P loadings by an additional 2.4%. Watersheds that export P most efficiently and thus are the most vulnerable to increases in P sources tend to be found along southern Lake Ontario, southeastern Lake Erie, western Lake Michigan, and southwestern Lake Superior where watershed areas are concentrated along the coastline with shorter flow paths. In contrast, watersheds with high soil permeabilities, fractions of land underlain by tile drains, and long distances to the GL are less vulnerable.

Lemke, A. M., K. G. Kirkham, T. T. Lindenbaum, M. E. Herbert, T. H. Tear, W. L. Perry, and J. R. Herkert. 2011. Evaluating agricultural best management practices in tile-drained subwatersheds of the Mackinaw River, Illinois, USA. *Journal of Environmental Quality* 40:1215–1228.

Best management practices (BMPs) are widely promoted in agricultural watersheds as a means of improving water quality and ameliorating altered hydrology. We used a paired watershed approach to evaluate whether focused outreach could increase BMP implementation rates and whether BMPs could induce watershed-scale (4000 ha) changes in nutrients, suspended sediment concentrations, or hydrology in an agricultural watershed in central Illinois. Land use was >90% row crop agriculture with extensive subsurface tile drainage. Outreach successfully increased BMP implementation rates for grassed waterways, stream buffers, and strip-tillage within the treatment watershed, which are designed to reduce surface runoff and soil erosion. No significant changes in nitrate-nitrogen (NO3–N), total phosphorus (TP), dissolved reactive phosphorus, total suspended sediment (TSS), or hydrology were observed after implementation of these BMPs over 7 yr of monitoring. Annual NO3–N export (39–299 Mg) in the two watersheds was equally exported during baseflow and stormflow. Mean annual TP export was similar between the watersheds (3.8 Mg) and was greater for TSS in the treatment (1626 ± 497 Mg) than in the reference (940 ± 327 Mg) watershed. Export of TP and TSS was primarily due to stormflow (>85%). Results suggest that the BMPs established during this study were not adequate to override nutrient export from subsurface drainage tiles. Conservation planning in tile-drained agricultural watersheds will require a combination of surface-water BMPs and conservation practices that intercept and retain subsurface agricultural runoff. Our study emphasizes the need to measure conservation outcomes and not just implementation rates of conservation practices.

Maccoux, M. J., A. Dove, S. M. Backus, D. M. Dolan. 2016. Total and soluble reactive phosphorus loadings to Lake Erie. *Journal of Great Lakes Research*.

Information about the loads of total and soluble reactive phosphorus entering Lake Erie is required in order to support commitments made under Annex 4 of the Great Lakes Water Quality Agreement. For these purposes, annual (water year) total phosphorus loads to Lake Erie are updated (2003–2013) and soluble reactive loads are reported on a lake wide basis for the first time (2009–2013). Complete documentation including input data and error estimates are provided. The results confirm previously documented long-term declining TP loads and show how these are driven by early and recent improvements in point source discharges, but are confounded by recent increases in nonpoint source loads that may in turn be due to increasing trends in precipitation and river discharge. The record since 2009 for SRP indicates high inter annual variability and no discernible change in loadings over time. Recent TP loads are dominated by nonpoint sources (71%), with lower contributions from point sources (19%) and the balance comprising atmospheric deposition and loads from the upstream Great Lakes. Approximately one-half (49%) of the load of SRP is contributed from nonpoint sources, approximately 39% comprises point sources, and atmospheric deposition and upstream loads comprise 6% each. Loads are highest to the western basin for TP and highest to the Huron–Erie corridor for SRP. U.S. sources account for a majority (N80%) of the phosphorus loads entering the lake. Recommendations for improvements to the study approach are made including the identification of monitoring gaps and the testing of assumptions that require independent verification.

Marton, J. M. and B. J. Roberts. 2014. Spatial variability of phosphorus sorption dynamics in Louisiana salt marshes. *Journal of Geophysical Research: Biogeosciences* 119:451–465.

Phosphorus (P) biogeochemistry has been studied in multiple wetland ecosystems, though few data exist on P sorption in U.S. Gulf Coast marshes. There also is a limited understanding of how oil spills in coastal zones can influence P dynamics in wetland soils. In this study, we measured P sorption potential, using the P sorption index (PSI), soil properties, and P saturation at increasing distances from the marsh edge in oiled and unoiled marshes in three regions along the southeastern Louisiana coast (Terrebonne Bay, western, and eastern Barataria Bay). Individual PSI values were highly variable, ranging from 19.5 to 175.6mg P 100 g^{-1} and varying by at least a factor of five within each of the three regions, and did not significantly differ between regions or between oiled and unoiled marshes. Soil pH, organic matter, total N, N:P ratio, moisture content, cation exchange capacity, and P saturation differed between regions, and all soil parameters showed great variability between and within individual marshes. Extractable iron was the strongest predictor of

PSI across all regions, explaining between 51 and 95% of the variability in individual regions. PSI increased with distance from marsh edge in Terrebonne Bay where other soil properties exhibited similar trends. Results suggest mineral composition of marsh soils, influenced by elevation-inundation gradients, are critical in dictating P loading to estuaries and open waters, and overall marsh functioning. Further, within 2 years of the Deepwater Horizon oil spill, oiled marshes are able to sorb phosphorus at comparable levels as unoiled marshes.

Maynard, J. J., A. T. O'Geen, and R. A. Dahlgren. 2009. Bioavailability and fate of phosphorus in constructed wetlands receiving agricultural runoff in the San Joaquin Valley, California. *Journal of Environmental Quality* 38:360–372.

Elevated nutrient concentrations in agricultural runoff contribute to seasonal eutrophication and hypoxia in the lower portion of the San Joaquin River, California. Interception and filtration of agricultural runoff by constructed wetlands may improve water quality of return flows ultimately destined for major water bodies. This study evaluated the efficacy of two small flow-through wetlands (2.3 and 7.3 ha; hydraulic residence time = 11 and 31 h) for attenuating various forms of P from irrigation tailwaters during the 2005 irrigation season (May to September). Our goal was to examine transformations and removal efficiencies for bioavailable

P in constructed wetlands. Inflow and outflow water volumes were monitored continuously and weekly water samples were collected to measure total P (TP), dissolved-reactive P (DRP), and bioavailable P (BAP). Suspended sediment was characterized and fractionated into five operationally-defined P fractions (i.e., NH4Cl, bicarbonate-dithionite, NaOH, HCl, residual) to evaluate particulate P (PP) transformations. DRP was the major source of BAP with the particulate fraction contributing from 11 to 26%. On a seasonal basis, wetlands removed 55 to 65% of PP, 61 to 63% of DRP, 57 to 62% of BAP, and 88 to 91% of TSS. Sequential fractionation indicated that the bioavailable fraction of PP was largely associated with clay-sized particles that remain in suspension, while less labile P forms preferentially settle with coarser sediment. Thus, removal of potentially bioavailable PP is dependent on factors that promote particle settling and allow for the removal of colloids. This study suggests that treatment of tailwaters in small, flow-through wetlands can effectively remove BAP. Wetland design and management strategies that enhance sedimentation of colloids can improve BAP retention efficiency.

McCollum, R. E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umprabuult. Agron. Journal 83:77–85. doi:10.2134/agronj1991.00021962008300010019x.

Phosphorus reserves in Ultisols are inherently low; but many Ultisols along the Atlantic seaboard are now high in P, both extractable and total, because P additions have exceeded P removal for many years. How long a high-P soil will maintain plant-available P above yield-limiting levels is of agroeconomic relevance. A field experiment initiated 35 yr ago on Portsmouth soil (fine sandy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquult) and monitored for crop yields and soil-test P (Mehlich-1 extractant) during 8 yr of active P buildup and 26 yr of residual decline has provided quantitative data on this issue. Yields of corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] were maximal with soil-test P ≥ 22 g m^{-3}, and extractable P was maintained in this range (20-24 g nr3) when P removed in harvested products (16 kg ha $^{-1}$ yr^{-1}) was replaced annually as band-applied fertilizer. High soil-test levels (≥50 g m^{-3}) could not be maintained by annual replacement of crop-removed P because P reversion to unextractable forms was a larger factor than crop removal in depleting the extractable-P pool. Regardless of initial level, P disappearance into these unextractable forms was best described via equations having the form of a first-order chemical reaction; but the magnitude of the rate constant varied with size of the extractable-P pool, i.e., high-P soils have large rate constants; low-P soils have small rate constants. A Portsmouth soil testing 50 to 60 g P m^{-3} today will test above 22 g m^{-3}, the approximate critical level for corn, for the next 8 to 10 yr without further P additions. Doubling the initial soil test will not double the time to reach yieldlimiting P levels, however; the same soil with 100 to 120 g P m^{-3} initially will drop to 22 g m^{-3} in about 14 yr.

McDowell, R., A. Sharpley, L. Condron, P. Haygarth, and P. Brookes. 2001. Processes controlling soil phosphorus release to runoff and implications for agricultural management. *Nutrient Cycling in Agroecosystems*. 59:269–284. doi:10.1023/A:1014419206761.

Phosphorus (P) loss from agricultural land to surface waters is well known as an environmental issue because of the role of P in freshwater eutrophication. Much research has been conducted on the erosion and loss of P in sediments and surface runoff. Recently, P loss in sub-surface runoff via agricultural drainage has been identified as environmentally significant. High soil P levels are considered as a potential source of P loss. However, without favourable hydrological conditions P will not move. In this paper, we review the basis of soil P release into solution and transport in surface and sub-surface runoff. Our objectives are to outline the role of soil P and hydrology in P movement and management practices that can minimize P loss to surface waters. Remedial strategies to reduce the risk of P loss in the short-term are discussed, although it is acknowledged that long-term solutions must focus on achieving a balance between P inputs in fertilizers and feed and P outputs in production systems.

Michalak, A. M., E. J. Anderson, D. Beletsky, S. Boland, N. S. Bosch, T. B. Bridgeman, J. D. Chaffin, K. Cho, R. Confesor, I. Daloglu, J. V. DePinto, M. A. Evans, G. L. Fahnenstiel, L. He, J. C. Ho, L. Jenkins, T. H. Johengen, K. C. Kuo, E. LaPorte, X. Liu, M. R. McWilliams, M. R. Moore, D. L. Posselt, R. P. Richards, D. Scavia, A. L. Steiner, E. Verhamme, D. M. Wright, M. A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. In *Proceedings of the National Academy of Sciences of the United States* 110(16):6448–6452. doi: 10.1073/pnas.1216006110.

In 2011, Lake Erie experienced the largest harmful algal bloom in its recorded history, with a peak intensity over three times greater than any previously observed bloom. Here we show that long-term trends in agricultural practices are consistent with increasing phosphorus loading to the western basin of the lake, and that these trends, coupled with meteorological conditions in spring 2011, produced record-breaking nutrient loads. An extended period of weak lake circulation then led to abnormally long residence times that incubated the bloom, and warm and quiescent conditions after bloom onset allowed algae to remain near the top of the water column and prevented flushing of nutrients from the system. We further find that all of these factors are consistent with expected future conditions. If a scientifically guided management plan to mitigate these impacts is not implemented, we can therefore expect this bloom to be a harbinger of future blooms in Lake Erie.

Miller, M. H. 1979. Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario. *Journal of Environmental Quality*. 8:42–48.

Nutrient content of tile drainage water was measured continuously from six mineral soil sites during 1972 and 1973 and from three organic soil sites during 1972 to 1975. The sites ranged in size from 5 to 113 ha and varied in cropping and fertilization practices. Average weekly concentrations of NO_3-N in drainage water from mineral soils which were fertilized at or below recommended rates seldom exceeded 10 mg/liter, whereas those from sites fertilized at rates greater than recommended were seldom below 10 mg/liter. Annual NO_3-N contribution ranged from 4 to 64 kg/ha with the larger amounts associated with those sites fertilized at rates greater than recommended. Average annual concentrations of NO_3-N in drainage water from organic soils ranged from 14.8 to 42.7 mg/liter and the average annual contribution ranged from 37 to 245 kg/ha. The PO_4-P concentrations in drainage water from the organic sites increased markedly during the course of the study and averaged 18.2 mg/liter on one site for the 1974/1975 drainage period. Laboratory leaching studies indicated that the high PO_4-P concentrations could be attributed to fertilizer use. Laboratory studies also indicated that the P-adsorption capacity of organic soils in southern Ontario varied widely depending on the total Fe and Al contents of the samples. It is suggested that the P-adsorption capacity should be considered before organic soil areas are developed for crop production.

Mitsch, W. J. and B. C. Reeder. 1991. Modelling nutrient retention of a freshwater coastal wetland: estimating the roles of primary productivity, sedimentation, resuspension and hydrology. *Ecological Modelling* 54:151–187.

A simulation model is developed for a coastal wetland of Lake Erie, one of the North American Laurentian Great Lakes, to determine the fate and retention of phosphorus in the wetland as water flows from an agricultural watershed through the wetland and into Lake Erie. Phosphorus retention in the wetland is a desirable to prevent eutrophication of Lake Erie. The model is developed with sub-models for hydrology, productivity, and phosphorus and a simulated barrier beach that can be opened or closed to Lake Erie. A simulation based on 1988 data is calibrated in step-wise fashion. Resuspension is a necessary inclusion in the model to predict phosphorus concentrations in the wetland's water column. Subsequent simulations are made for various combinations of increased flow from the watershed and changing Lake Erie water levels. Phosphorus retention varies from 17 to 52% with highest retention when high inflows are coupled with high lake levels. A nutrient budget constructed from the model for 1988 conditions showed marked differences with budgets developed from empirical models or field data. The model results suggest a near balance between inorganic sedimentation and resuspension but an active plankton sedimentation that results in a net phosphorus retention rate of 2.9 mg P m^{-2} day^{-1}.

Mitsch, W. J. and N. Wang. 2000. Large-scale coastal wetland restoration on the LaurentianGreat Lakes: Determining the potential for water quality improvement. *Ecological Engineering* 15:267–282.

Coastal wetlands around the Laurentian Great Lakes, estimated to cover 1290 km2 in the USA after extensive losses in the past 200 years, are rarely restored for water quality enhancement of the Great Lakes, despite the need for minimizing phosphorus and other pollutant inputs to the lakes. A simulation model, developed and validated for a series of created experimental marshes in northeastern Illinois, was aggregated and simplified to estimate the nutrient retention capacity of hypothetical large-scale coastal wetland restoration in Michigan and Ohio. Restoration of 31.2 km2 of wetlands on agricultural land along Saginaw Bay, Michigan, would retain 25 metric tons-P $year^{-1}$ (53% of the phosphorus flow from the upstream watershed). Hydrologic restoration of 17.3 km^2 of mostly diked wetlands in Sandusky Bay, Ohio, would retain 38 metric tons $year^{-1}$ (12% of the phosphorus flow from the upstream watershed). A wetland distribution model developed for the Saginaw Bay site illustrated a technique for identifying sites that have high potential for being transition zones between open water and upland and thus logical locations for wetland restoration.

Mitsch, W. J. and J. G. Gosselink. 2015. *Wetlands*. John Wiley & Sons, Inc. Hoboken, NJ.

- As nature's kidneys, wetland ecosystems help the environment process toxins and excess fertilizers and maintain the relative health of our aquatic ecosystems. As the understanding of their importance grows, their management and ecology have gained increased attention and have become an area of professional specialization over the past two decades. This book gives readers a solid understanding of wetlands, how they work, what they do, and why the Earth can't live without them.

- Understand wetlands' role in the ecosystem, from local to global scales
- Appreciate the fact that wetlands may be the most logical and economical way to sequester carbon from the atmosphere
- Discover the unique characteristics that make wetlands critically important for improving water quality, reducing storm and flood damage, and providing habitat to support biodiversity
- Learn how wetlands are being managed or destroyed around the globe but also how we can create and restore them
- Examine the ways in which climate change is affecting wetland ecosystems and wetland ecosystems affect climate change
- Wetlands are crucial to the health of the planet, and we've only begun to realize the magnitude of the damage that has already been done as we scramble to save them. A generation of ecologists, ecological engineers, land use planners, and water resource managers worldwide owe their knowledge of the wetlands to this book – for the next generation to follow in their footsteps, *Wetlands* 5th edition is the quintessential guide to these critical systems.

Moore, P. A. and K. R. Reddy. 1994. Role of Eh and pH on phosphorus geochemistry in sediments of Lake Okeechobee, Florida. *Journal of Environmental Quality* 23: 955–964.

Increases in total P levels in Lake Okeechobee, Florida, have given rise to concern over eutrophication. The objective of this study was to evaluate the effects of redox potential and pH on the solubility of P in lake sediments. Bulk sediment samples were obtained from the mud zone of Lake Okeecbobee and were equilibrated under controlled conditions at fixed Eh and pH levels. The pH levels evaluated were 5.5, 6.5, 7.5, and 8.5; the Eh levels studied were 500, 250, 0, and −250 mV. Redox reactions were very important in the regulation of P in Lake Okeechobee sediments. Under oxidized conditions, soluble reactive P (SRP) concentrations were low ($\approx$ 0.1 mg P L^{-1}), whereas under reducing conditions SRP increased to over 1 mg P L^{-1}. Soluble reactive P was extremely high (18 mg P L^{-1}) under acidic (pH 5.5), reducing (Eh < 0 mV) conditions. Water soluble Fe was highly correlated to water soluble P, implicating it as a possible agent governing P behavior. Sodium hydroxide-extractable P (Fe and Al bound) increased with increases in Eh, which indicated Fe phosphate precipitation or adsorption of P by Fe oxides or hydroxides. This was supported by mineral equilibria calculations, which showed porewaters were supersaturated with respect to strengite under oxidized conditions. Calcium-bound P was higher under reducing conditions. The results suggest that Fe phosphate precipitation controls the behavior of P in Lake Okeechobee sediments under oxidizing conditions, whereas Ca phosphate mineral precipitation governs P solubility under reducing conditions. These results also suggest that large fluxes of P from the sediment could occur if the lake water column were to experience low dissolved O_2 levels, due to the reduction and subsequent solubilization of ferric phosphate minerals in surficial sediments. Measurements of P fluxes from intact sediment cores and porewater SRP profiles taken in situ supported this hypothesis.

Morrice, J. A., Danz, N. P., Regal, R. R., Kelly, J. R., Niemi, G. J., Reavie, E. D., Hollenhorst, T., Axler, R. P., Trebitz, A. S., Cotter, A. M., and Peterson, G.S. 2007. Human influences on water quality in Great Lakes coastal wetlands. *Environmental Management* 41: 347–357.

A better understanding of relationships between human activities and water chemistry is needed to identify and manage sources of anthropogenic stress in Great Lakes coastal wetlands. The objective of the study described in this article was to characterize relationships between water chemistry and multiple classes of human activity (agriculture, population and development, point source pollution, and atmospheric deposition). We also evaluated the influence of geomorphology and biogeographic factors on stressor-water quality relationships. We collected water chemistry data from 98 coastal wetlands distributed along the United States shoreline of the Laurentian Great Lakes and GIS-based stressor data from the associated drainage basin to examine stressor-water quality relationships. The sampling captured broad ranges (1.5–2 orders of magnitude) in total phosphorus (TP), total nitrogen (TN), dissolved inorganic nitrogen (DIN), total suspended solids (TSS), chlorophyll a (Chl a), and chloride; concentrations were strongly correlated with stressor metrics. Hierarchical partitioning and all-subsets regression analyses were used to evaluate the independent influence of different stressor classes on water quality and to identify best predictive models. Results showed that all categories of stress influenced water quality and that the relative influence of different classes of disturbance varied among water quality parameters. Chloride exhibited the strongest relationships with stressors followed in order by TN, Chl a, TP, TSS, and DIN. In general, coarse scale classification of wetlands by morphology (three wetland classes: riverine, protected, open coastal) and biogeography (two ecoprovinces: Eastern Broadleaf Forest [EBF] and Laurentian

Mixed Forest [LMF]) did not improve predictive models. This study provides strong evidence of the link between water chemistry and human stress in Great Lakes coastal wetlands and can be used to inform management efforts to improve water quality in Great Lakes coastal ecosystems.

Nair, V. D., M. W. Clark, and K.R. Reddy. 2015. Evaluation of legacy phosphorus storage and release from wetland soils. *Journal of Environmental Quality* 44: 1956–1964.

To better manage legacy phosphorus (P) in watersheds, reliable techniques to predict P storage and release from uplands, ditches, streams, and wetlands must be developed. Techniques such as the P saturation ratio (PSR) and the soil P storage capacity (SPSC), originally developed for upland soils, are hypothesized to be applicable to wetland soils as well. Surface soils were collected from eight beef ranches within the Lake Okeechobee Watershed, FL, to obtain a threshold PSR value and to evaluate the use of PSR and SPSC for identifying legacy P storage and release from wetland soils. Water-soluble P (WSP) was determined for all soils; the equilibrium P concentration (EPC_0) was determined for selected soils through the generation of Langmuir isotherms. The threshold PSR for wetland soils, calculated from P, Fe, and Al in a Mehlich 1 solution, was determined to be 0.1; SPSC, calculated using the threshold PSR, was found to be related to WSP. When SPSC was positive, WSP and EPC_0 were minimal. However, both WSP and EPC_0 increased once SPSC became negative. Organic matter (OM) varied from 0.4 to 90 g kg^{-1} for both positive and negative SPSC, suggesting that OM in wetland soils does not have any effect on P retention and release below the threshold PSR. Moreover, when a wetland or drainage ditch is heavily P impacted, it could be a P source; wetland vegetation may no longer be able to assimilate additional P, resulting in P loss from the soil. This study suggests that the PSR–SPSC concept could be a valuable tool for evaluating legacy P release from wetlands.

Nair, V. D. and W. G. Harris. 2014. Soil phosphorus storage capacity for environmental risk assessment. *Advances in Agriculture* http://dx.doi.org/10.1155/2014/723064.

Reliable techniques must be developed to predict phosphorus (P) storage and release from soils of uplands, ditches, streams, and wetlands in order to better understand the natural, anthropogenic, and legacy sources of P and their impact on water quality at a field/plot as well as larger scales. A concept called the "safe" soil phosphorus storage capacity (SPSC) that is based on a threshold phosphorus saturation ratio (PSR) has been developed; the PSR is the molar ratio of P to Fe and Al, and SPSC is a PSR-based calculation of the remaining soil P storage capacity that captures risks arising from previous loading as well as inherently low P sorption capacity of a soil. Zero SPSC amounts to a threshold value below which P runoff or leaching risk increases precipitously. In addition to the use of the PSR/SPSC concept for P risk assessment and management, and its ability to predict isotherm parameters such as the Langmuir strength of bonding, K_L, and the equilibrium P concentration, EPC0, this simple, cost-effective, and quantitative approach has the potential to be used as an agronomic tool for more precise application of P for plant uptake.

Nair, V. D. and W. G. Harris. 2004. A capacity factor as an alternative to soil test phosphorus in phosphorus risk assessment. *New Zealand Journal of Agricultural Research* 47:491–497.

Soil test phosphorus (P) concentrations (STP) are often used as measures of environmental P risk. However, a low STP is not valid justification for further P application because P sorption capacity may be low and P added could be lost to surface waters. The degree of P saturation (DPS) normalises extractable P using extractable Al and Fe as a surrogate for P sorption capacity, but like STP, fails to convey a magnitude of capacity. We propose the use of a DPS-based prediction of the remaining soil P storage capacity (SPSC) that would capture risks arising from previous loading as well as inherently low P sorption capacity. The SPSC is a direct estimate of the amount of P a soil can sorb before exceeding a threshold soil equilibrium concentration. In this paper, we demonstrate the applicability of the SPSC for a variety of sandy soils impacted by dairy and poultry manure additions. The SPSC provides a means to assess the capacity of a soil to retain additional P and hence is a more useful indicator of P-related environmental risk than STP or DPS measures alone.

National Science and Technology Council. 2016. *The State and Future of U.S. Soils, Framework for a Federal Strategic Plan for Soil Science.* Subcommittee on Ecological Systems, committee on Environment, Natural Resources, and Sustainability.

The Soil Science Interagency Working Group (SSIWG) was established under the National Science and Technology Council to develop a Framework for a Federal Strategic Plan for Soil Science. This Framework aims to establish Federal soil research priorities, ensure availability of tools and information for improved soil management and stewardship, deliver key information to land managers to help them implement soil conserving systems, and inform related policy development and coordination. The Framework identifies current gaps, needs, and opportunities in soil science, and proposes Federal research priorities for the future. The Framework will inform a more comprehensive Federal Strategic Plan that will provide recommendations for improving the coordination of soil science research, as well as the development, implementation, and evaluation of soil conservation and management practices among Federal agencies and between Federal agencies and non-Federal organizations, both domestic and international. This notice solicits public comments on the Framework.

The Framework can be accessed at the following link: https://www.whitehouse.gov/sites/default/files/microsites/ostp/SSIWG_Framework_December_2016.pdf.

Pant, H. K. and K. R. Reddy, 2003. Potential internal loading of phosphorus in a wetland constructed in agricultural land. *Water Research* 37:965–972.

Wetland construction on agricultural or dairy lands could result in solubilization of phosphorus (P) stored in soils and release to the water column. To study the extent of P flux during the start-up period of a constructed wetland, intact soil-cores from areas used for dairy operations, in Okeechobee, Florida, USA were obtained and flooded with adjacent creek water. In the first 28-day hydraulic-retention period, P concentration in the water column increased several fold due to rapid P flux from impacted soils. A continuous decrease in P flux to the water column until the third hydraulic retention cycle (initial influent P concentration 0.2 mg L^{-1}), and constant thereafter suggest that the effect of initial influent P upon long-term P flux from soils could be limited. The initial release maybe due to high concentration of labile P in impacted soils; however, slow dissolution of relatively stable P pools could maintain a steady flux, well above of that observed from non-impacted soils. Water soluble P along with double acid-extractable magnesium explained 76% of the variability in cumulative P flux to the water column. Apparently, co-occurrence of active adsorption–desorption phenomena due to independent maintenance of equilibrium by individual P compounds regulates P dynamics of the water column. The results indicated that equilibrium P concentration of the water column of the wetland would be above 1.3 mg L^{-1}, which is well above the targeted P level in the water column of the Lake Okeechobee, one of the main water bodies in the area (0.04 mg P L^{-1}). This suggests construction of wetlands in agricultural lands could result to substantial internal P loading. However, preventative measures including chemical amendments, establishment of vegetative communities or flushing the initially released P may potentially stabilize the system, and maintain P removal efficiency.

Radcliffe, D. E., Z. Lin, L. Risse, J. J. Romeis, and C. R. Jackson. 2009. Modeling phosphorus in the Lake Allatoona watershed using SWAT: I. Developing phosphorus parameter values. *Journal of Environmental Quality* 38:111–120.

Lake Allatoona is a large reservoir north of Atlanta, GA, that drains an area of about 2870 km^2 scheduled for a phosphorus (P) total maximum daily load (TMDL). The Soil and Water Assessment Tool (SWAT) model has been widely used for watershed-scale modeling of P, but there is little guidance on how to estimate P-related parameters, especially those related to in-stream P processes. In this paper, methods are demonstrated to *individually* estimate SWAT soil-related P parameters and to *collectively* estimate P parameters related to stream processes. Stream related parameters were obtained using the nutrient uptake length concept. In a manner similar to experiments conducted by stream ecologists, a small point source is simulated in a headwater sub-basin of the SWAT models, then the instream parameter values are adjusted *collectively* to get an uptake length of P similar to the values measured in the streams in the region. After adjusting the in-stream parameters, the P uptake length estimated in the simulations ranged from 53 to 149 km compared to uptake lengths measured by ecologists in the region of 11 to 85 km. Once the a priori P-related parameter set was developed, the SWAT models of main tributaries to Lake Allatoona were calibrated for daily transport. Models using SWAT P parameters derived from the methods in this paper outperformed models using default parameter values when predicting total P (TP) concentrations in streams during storm events and TP annual loads to Lake Allatoona.

Reddy, K. R. and R. D. DeLaune. 2008. *Biogeochemistry of wetlands: Science and applications*. CRC Press. Boca Raton, FL.

Wetland ecosystems maintain a fragile balance of soil, water, plant, and atmospheric components in order to regulate water flow, flooding, and water quality. Marginally covered in traditional texts on biogeochemistry or on wetland soils, Biogeochemistry of Wetlands is the first to focus entirely on the biological, geological, physical, and chemical processes that affect these critical habitats. This book offers an in-depth look at the chemical and biological cycling of nutrients, trace elements, and toxic organic compounds in wetland soil and water column as related to water quality, carbon sequestration, and greenhouse gases. It details the electrochemistry, biochemical processes, and transformation mechanisms for the elemental cycling of carbon, oxygen, nitrogen, phosphorus, and sulfur. Additional chapters examine the fate and chemistry of heavy metals and toxic organic compounds in wetland environments. The authors emphasize the role of redox-pH conditions, organic matter, microbial-mediated processes that drive transformation in wetlands, plant responses and adaptation to wetland soil conditions. They also analyze how excess water, sediment water, and atmospheric change relate to elemental biogeochemical cycling.

Reddy, K. R., R. H. Kadlec, E. Flaig, and P. M. Gale. 1999. Phosphorus retention in streams and wetlands: A review. *Critical Reviews in Environmental Science and Technology* 29:83-146.

Wetlands and streams buffer the interactions among uplands and adjacent aquatic systems. Phosphorus (P) is often the key nutrient found to be limiting in both estuarine and freshwater ecosystems. As such, the ability of wetlands and streams to retain P is key to determining downstream water quality. This article reviews the processes and factors regulating P retention in streams and wetlands and evaluates selected methodologies used to estimate P retention in these systems. Phosphorus retention mechanisms reviewed include uptake and release by vegetation, periphyton and microorganisms; sorption and exchange reactions with soils and sediments; chemical precipitation in the water column; and sedimentation and entrainment. These mechanisms exemplify the combined biological, physical, and chemical nature of P retention in wetlands and streams. Methodologies used to estimate P retention include empirical input-output analysis and mass balances, and process kinetics applied at various scales, including micro- and mesocosms to full-scale systems. Although complex numerical models are available to estimate P retention and transport, a simple understanding of P retention at the process level is important, but the overall picture provided by mass balance and kinetic evaluations are often more useful in estimating long-term P retention.

Reddy, K. R., S. Newman, T. Z. Osborne, J. R. White, and H. C. Fitz. 2011. Phosphorus cycling in the greater Everglades ecosystem: Legacy phosphorus implications for management and restoration. *Critical Reviews in Environmental Science and Technology* 41: 149–186.

Phosphorus (P) retention in wetlands is an important function of watershed nutrient cycling, particularly in drainage basins with significant nonpoint nutrient contributions from agriculture and urban sources. Phosphorus storage involves complex interrelated physical, chemical, and biological processes that ultimately retain P in organic and inorganic forms. Both short-term storage of P mediated by assimilation into vegetation, translocation within above- and below-ground plant tissues, microorganisms, periphyton, and detritus, and long-term storage (retention by inorganic and organic soil particles and net accretion of organic matter) need to be considered. Here, we review and synthesize recent studies on P cycling and storage in soils and sediments throughout the Greater Everglades Ecosystem and the influence of biotic and abiotic regulation of P reactivity and mobility as related to restoration activities in south Florida. Total P storage in the floc/detrital layer and surface soils (0–10 cm) is estimated to be 400,000 metric tons (mt) within the entire Greater Everglades Ecosystem, of which 40% is present in the Lake Okeechobee Basin (LOB), 11% in sediments of Upper Chain of Lakes, Lake Istokpoga, and Lake Okeechobee, 30% in the Everglades Agricultural Area (EAA), and 19% in the Stormwater Treatment Areas (STAs) and the Everglades. Approximately, 35% of the P stored is in chemically nonreactive (not extractable after sequential extraction with acid or alkali) pool and is assumed to be stable. Phosphorus leakage rates from LOB and

EAA are approximately 500 and 170 mt P per year, respectively, based on long-term P discharges into adjacent ecosystems. The estimated reactive P in the LOB soils is 65% of the total P, of which only 10 –25% is assumed to leak out of the system. Under this scenario, legacy P in LOB would maintain P loads of 500 mt per year to the lake for the next 20– 50 years. Similarly, surface soils of the EAA are estimated to release approximately 170 mt P per year for the next 50–120 years. The role of the STAs in reducing loads to downstream regions is critical and requires effective management of P forms to ensure the P is stabilized in these systems by the addition of chemical amendments or by dredging of accumulated soils. Also, additional efforts to minimize leakage of the legacy P from the northern regions should also be evaluated to reduce external P loading loads to the STAs.

Reddy, K. R., O. A. Diaz, L. J. Scinto, M. Agami. 1995. Phosphorus dynamics in selected wetlands and streams in the Lake Okeechobee Basin. *Ecological Engineering* 5:183–207.

Lake Okeechobee is becoming increasingly eutrophic, presumably due to P loading from numerous dairy operations in the Lake's northern drainage basin. Phosphorus released from this basin is transported through canals, streams, and wetlands before its discharge into the lake. This paper summarizes the results of several studies on P dynamics in wetlands and stream sediments in the Lake Okeechobee Basin with primary focus on P interaction with soil/sediment-water column and vegetation. Stream sediments and wetland soils in the basin were characterized for labile and non-labile pools of P. The labile inorganic P (P_i) pool (KCl-extractable) accounted for 0.1 to 2.3% and 0.1 to 0.7% of the total P in sediments and wetland soils, respectively. The NaOH extractable P_i, representing the P associated with Fe and Al oxyhydroxides, was the dominant P_i in both stream sediments and wetland soils (accounting for up to 71 and 43% total P, respectively). The NaOH-*Po* (humic and fulvic acid associated organic P) is considered resistant to biological breakdown and accounted for 6 to 56% of total P. Stream sediments showed higher buffer intensity for P sorption than wetlands. Phosphate sorption capacity (S_{max}) and buffer intensity (Kd-adsorption coefficient) were highly correlated with oxalate extractable [Fe + Al] and total organic carbon (TOC) suggesting P sorption is associated with amorphous and weakly crystalline forms of Fe and Al, and/or complexed with organic matter. Phosphorus assimilation in vegetation was found to be short-term and dependent upon plant species, P loading, and wetland hydrology. Decomposition of detrital tissue resulted in rapid release of P into the water column. Phosphorus release was rapid during decomposition of floating macrophytes, as compared to herbaceous vegetation. Phosphorus retention coefficients were positively correlated with oxalate extractable Fe and Al content of soils and sediments. The average EPC_w (threshold P concentration in the water column where P retention = P release) for stream sediments was 0.10 mg p l^{-1} and 0.42 mg P l^{-1} for wetland soils. The stability of the P retained was regulated by the physico-chemical properties of the soils and sediments.

Reddy, K. R. and E. M. D'Angelo. 1994. *Soil processes regulating water quality in wetlands. Global Wetlands: Old World and New.* Ed. W.J. Mitsch. Elsevier, New York.

Wetlands play a critical role in functioning as sink for nutrients, thus reducing overall load to adjacent waterbodies. Dominant internal biogeochemical processes in the soil and the water column influence nutrient cycling and water quality of wetlands. Since wetlands are usually characterized by an accumulation of organic matter of planktonic and macrophytic origin, enzymatic hydrolysis of this material is an important first step in nutrient regeneration (i.e. conversion of organic nutrients to bioavailable forms). Factors which influence the rate of decomposition include the availability of electron acceptors, chemical makeup of organic substrate (e.g., lignin, protein, cellulose, C:N, and C:P ratio), and environmental factors such as temperature, pH, and nutrient availability. The fate of released nutrients depends on the physico-chemcial factors in the soil and water column. Thus, oxidation of organic matter (electron donor) and reduction of electron acceptors (oxygen, NO_3^-, Mn_4^+, Fe_3^+, SO_4^{2-}, and CO_2) can result in release of soluble NH_4^+ into the water column, thus impacting water quality.

Inorganic nitrogen transformations are largely mediated by microorganisms. These reactions mainly consist of coupled oxidation-reduction reactions in the water column and in the soil. In aerobic zones (such as in the water column and at the soil-water interface), oxidation of NH_4^+ to NO_3^- may occur. Nitrate formed readily diffuses into anaerobic zones where it is subsequently utilized as electron acceptor and lost from the system. Similarly, nitrification-denitrification reactions also occur in the root zone of wetland plants. Denitrification of nitrate to gaseous end-products is probably the most significant process involved in the removal of large quantities of nitrogen from the system. Although phosphorus transformations in wetlands are also biologically mediated, abiotic factors such as chemical precipitation-complexation and adsorption of inorganic phosphorus with iron and aluminum oxyhydroxides or $CaCO_3$ play an important role in the fate of phosphorus in the soil-water column, The main factors which influence these chemical reactions are pH and oxidation-reduction potential. These factors may largely be controlled by biological activity (e.g. photosynthesis, respiration, and decomposition of organic matter).

Reeder, B. C. 1994. Estimating the role of autotrophs in nonpoint source phosphorus retention in a Laurentian Great Lakes coastal wetland. *Ecological Engineering* 3:161-169.

Primary productivity of a *plankton/Nelumbo lutea* freshwater marsh (56 ha) with intermittent hydrologic links to Lake Erie (Ohio, USA) was determined in order to estimate the role of autotrophs in phosphorus uptake. Water column gross primary productivity, as measured by the diurnal oxygen technique, averaged 6.5 g O2 m^{-2} day^{-1} for 80 measurements during the growing season. This productivity could account for the uptake of 8600 kg P/year (15 g P m^{-2} year^{-l}). Chlorophyll a concentrations (which averaged 157 mg m -3 throughout the study period) suggest a phosphorus retention of 5500 kg P/year (10 g P m^{-2} year^{-l}). *Nelumbo lutea,* which covered about 23% of the wetland and averaged 125 g m –z above-ground dry weight at peak biomass, was estimated to be responsible for transforming approximately only 61 kg P/year (0.1 g P m^{-2} year^{-l}) of phosphorus. A barrier beach system, which generally restricts the wetland's connection to Lake Erie during the periods of highest nonpoint source phosphorus loading, combined with the high planktonic productivity, suggest an excellent ecological engineering design for constructed or restored coastal wetlands to protect the Laurentian Great Lakes from nonpoint phosphorus runoff.

Richardson, C. J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. *Science* 228:1424–1426.

Freshwater wetland ecosystems do not effectively conserve phosphorus in the way that terrestrial ecosystems do. The phosphorus retention capacity varies greatly among bogs, fens, and swamps and is concomitant with the amorphous acid oxalate-extractable aluminum and iron content in the soil.

However, the phosphorus adsorption potential in wetland ecosystems may be predicted solely from the extractable aluminum content of the soil. Wetlands tested as wastewater filtration systems became phosphorus-saturated in a few years, with the export of excessive quantities of phosphate.

Richardson, C. J. and P. E. Marshall. 1986. Processes controlling movement, storage, and export of phosphorus in a fen peatland. *Ecological Monographs* 56:279–302.

Field and laboratory studies were conducted to determine the mechanisms controlling P movement, storage, and export from a minerotrophic peatland (fen) in central Michigan that had demonstrated high P removal from nutrient additions. An annual P budget completed for the fen ecosystem revealed that plant uptake requirements were 7—9 $kg \cdot ha^{-1} \cdot yr^{-1}$, but 35% of aboveground P uptake by plants was returned to the peatland surface via litterfall. Permanent storage of organic P in peat ranged between 2 and 5 $kg \cdot ha^{-1} \cdot yr^{-1}$ under natural levels of P input. Both microbial uptake and soil exchange capacity controlled the amount of P made available for plant growth. Fertilizer additions of 5.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ of P and 17 $kg \cdot ha^{-1} \cdot yr^{-1}$ of N in the fen resulted in no significant ($P < .05$) increase in growth or nutrient uptake by emergent macrophytes as the litter—microorganism compartment (LMC) retained up to 84% of the added P in year 1. A doubling of the P fertilization level resulted in an LMC retention of only 57%. In year 2 the retention of P by the LMC dropped to 67 and 31% for the two fertilizer levels, respectively. Concurrent with decreases in LMC phosphorus retention were increased peat sorption of P, but plant growth responses and P uptake were negligible. Higher level fertilizer additions of 22 and 55 $kg \cdot ha^{-1} \cdot yr^{-1}$ of P and 68 and 170 $kg \cdot ha^{-1} \cdot yr^{-1}$ of N applied with minimal water additions resulted in significant ($P < .05$) increases in net primary productivity and P storage by Carex spp. Narrow—leaved sedge (Carex lasiocarpa, C. oligosperma, and C. aquatilis) removed as much as 61% of the P additions in year 1, with the LMC sorbing an additional 22%. Roots and rhizomes accounted for 81% of plant P storage in the higher fertilizer treatment, when surface water flow rates were reduced and fertilizer additions were sequestered in the root zone. However, seasonal dieback and leaching of P from aboveground standing plant material on the high fertilizer plots resulted in a fivefold increase of P flux to the water compartment. Microcosm ^{32}P studies indicated that most of the P added to the fen ecosystem was removed from the water column within the 1st h by microorganisms and fine sediments, and that sedge uptake was extremely low even 45 d after addition. Thus plant uptake of P is not a major factor in the rapid removal of low levels of newly added PO_4 in the fen. Selective biocide treatments used to separate the P uptake by bacteria and actinomycetes from that of fungi and yeasts in the fen surface water revealed that the latter group of microorganisms was the dominant group responsible for initial P removal. Biological uptake and abiotic sorption of P by the fine sediments in the surface waters were also shown to be of the same order of magnitude, but immobilization of P in the peat soil zone was mainly controlled by chemical sorption. Freezing of peat resulted in P release to the water column upon thawing, but concentrations returned to control levels within 24 h, suggesting minimal ecosystem losses of P in spring runoff. A Freundlich P adsorption maximum of 15 and 38 kg/ha was calculated for a 2 cm and 5 cm depth of peat adsorption, respectively. These soil P adsorption maxima are only 23% (2 cm) and 60% (5 cm) of annual wastewater P additions of 64 ± 14 $kg \cdot ha^{-1} \cdot yr^{-1}$ and may account for the 26 and 42 kg/ha of P exported from the 19.5—ha test area in the fen during the 4th and 5th yr, respectively, of nutrient additions. Collectively, our field research and microcosm studies on the Houghton Lake fen suggest that soil adsorption and peat accumulation (i.e., phosphorus stored in organic matter) control long—term phosphate sequestration. But microorganisms and small sediments control initial uptake rates, especially during periods of low nutrient concentration and standing surface water. Carex P uptake increases later in the growing season during field fertilization, but algal populations in the fen water respond quickly and absorb significant amounts of P in areas where sewage effluent has been added. Both biotic and abiotic control mechanisms are thus functional in the peatland, and the proportional effect of each on P transfers is dependent on water levels, the amount of available P, fluctuating microorganism populations, seasonal changes in P absorption by macrophytes, and P soil adsorption capacity.

Robertson, D. M., G. L. Goddard, D. R. Helsel, and K. L. MacKinnon. 2000. Rehabilitation of Delavan Lake, Wisconsin. *Lake and Reservoir Management* 16:155–176.

A comprehensive rehabilitation plan was developed and implemented to shift Delavan Lake, Wisconsin, from a hypereutrophic to a mesotrophic condition. The plan was threefold: (1) reduce external phosphorus (P) loading by applying Best Management Practices in the watershed, enhance an existing wetlands, and short-circuit the inflows through the lake, (2) reduce internal P loading by treating the sediments with alum and removing carp, and (3) rehabilitate the fishery by removing carp and bigmouth buffalo and adding piscivores (biomanipulation). The first and second parts of the plan meet with only limited success. With minor reductions in internal and external P loading, P concentrations in the lake returned to near pre-treatment concentrations. The intensive biomanipulation and resulting trophic cascade (increasing piscivores, decreased plantivores, increased large zooplankton populations, and limited water clarity). However, now there is extensive macrophyte growth and abundant filamentous algae. Without significant reducing the sources of the problems (high P loading) in Delavan Lake, the increased water clarity may not last. With an improved understanding of the individual components of this rehabilitation program better future management plans can be developed for Delavan Lake and other lakes and reservoirs with similar eutrophication problems.

Robertson, D. M. and D. A. Saad. 2011. Nutrient Inputs to the Laurentian Great Lakes by Source and Watershed Estimated Using SPARROW Watershed Models. *Journal of the American Water Resources Association (JAWRA)* 47:1011–1033.

Nutrient input to the Laurentian Great Lakes continues to cause problems with eutrophication. To reduce the extent and severity of these problems, target nutrient loads were established and Total Maximum Daily Loads are being developed for many tributaries. Without detailed loading information it is difficult to determine if the targets are being met and how to prioritize rehabilitation efforts. To help address these issues, SPAtially Referenced Regressions On Watershed attributes (SPARROW) models were developed for estimating loads and sources of phosphorus (P) and nitrogen (N) from the United States (U.S.) portion of the Great Lakes, Upper Mississippi, Ohio, and Red River Basins. Results indicated that recent U.S. loadings to Lakes Michigan and Ontario are similar to those in the 1980s, whereas loadings to Lakes Superior, Huron, and Erie decreased. Highest loads were from tributaries with the largest watersheds, whereas highest yields were from areas with intense agriculture and large point sources of nutrients. Tributaries were ranked based on their relative loads and yields to each lake. Input from agricultural areas was a significant source of nutrients, contributing ~33-44% of the P and ~33-58% of the N, except for areas around Superior with little agriculture. Point sources were also significant, contributing ~14-44% of the P and 13-34% of the N. Watersheds around Lake Erie contributed nutrients at the highest rate (similar to intensively farmed areas in the Midwest) because they have the largest nutrient inputs and highest delivery ratio.

Robinson, C. 2015. Review on groundwater as a source of nutrients to the Great Lakes and their tributaries. *Journal of Great Lakes Research* 41:941–950.

The role of groundwater in delivering nutrients (nitrogen and phosphorus) to the Great Lakes and their tributaries is not well understood. Consequently, this potentially important non-point source is poorly managed and often neglected. Evaluating nutrient inputs from groundwater requires knowledge of the (i) sources of groundwater nutrient contamination, (ii) physical groundwater discharge flow paths, and (iii) geochemical processes occurring along these flow paths that control the ultimate loading of nutrients to surface waters. Although groundwater quality in the Great Lakes Basin (GLB) is generally good, nutrient concentrations in aquifers can become elevated by a range of agricultural and non-agricultural activities. Nutrients can be delivered from groundwater to the Great Lakes by indirect discharge into tributaries or direct discharge into the lakes. The factors affecting these discharge pathways and their contributions to nutrient loading are distinct. The discharge of nutrients from groundwater to surface water is strongly regulated by zones of high reactivity that exist close to the sediment-water interface (i.e., riparian zone, hyporheic zone). Understanding the functioning of these zones for the landscape and hydrogeological conditions in the GLB is essential for evaluating nutrient loading to the Great Lakes and their tributaries as well as maximizing the benefits these zones can provide for water quality management. The paper concludes with a discussion of key knowledge gaps, challenges, and future research priorities that need to be addressed to evaluate and better manage this complex nutrient input to the Great Lakes and their tributaries.

Scavia, D., J. D. Allan, K. K. Arend, S. Bartell, D. Beletsky, N. S. Bosch, S. B. Brandt, R. D. Briland, I. Dalaglu, J. V. DePintp, D. M. Dolan, M. A. Evans, T. M. Farmer, D. Goto, H. Han, T. O. Hook, R. Knight, S. A. Ludsin, D. Mason, A. M. Michalak, R. P. Richards, J. J. Roberts, D. K. Rucinski, E. Rutherford, D. J. Schwab, T. M. Sesterhenn, H. Zhang, Y. Zhuo. 2014.

Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *Journal of Great Lakes Restoration* 40:226–246. doi:10.1016/j.jglr.2014.02.004.

Relieving phosphorus loading is a key management tool for controlling Lake Erie eutrophication. During the 1960s and 1970s, increased phosphorus inputs degraded water quality and reduced central basin hypolimnetic oxygen levels which, in turn, eliminated thermal habitat vital to cold-water organisms and contributed to the extirpation of important benthic macroinvertebrate prey species for fishes. In response to load reductions initiated in 1972, Lake Erie responded quickly with reduced water-column phosphorus concentrations, phytoplankton biomass, and bottom-water hypoxia (dissolved oxygen b2 mg/l). Since the mid-1990s, cyanobacteria blooms increased and extensive hypoxia and benthic algae returned. We synthesize recent research leading to guidance for addressing this re-eutrophication, with particular emphasis on central basin hypoxia. We document recent trends in key eutrophication-related properties, assess their likely ecological impacts, and develop load response curves to guide revised hypoxia-based loading targets called for in the 2012 Great Lakes Water Quality Agreement. Reducing central basin hypoxic area to levels observed in the early 1990s (ca. 2000 km2) requires cutting total phosphorus loads by 46% from the 2003–2011 average or reducing dissolved reactive phosphorus loads by 78% from the 2005–2011 average. Reductions to these levels are also protective of fish habitat. We provide potential approaches for achieving those new loading targets, and suggest that recent load reduction recommendations focused on western basin cyanobacteria blooms may not be sufficient to reduce central basin hypoxia to 2000 km2.

Scavia, D. J. V. DePinot, I. Bertani. 2016. A multi-model approach to evaluating target phosphorus loads for Lake Erie. *Journal of Great Lakes Restoration*. http://dx.doi.org/10.1016/j.jglr.2016.09.007.

In response to water quality changes in the Great Lakes since implementing the 1978 Amendment to the Great Lakes Water Quality Agreement, the US and Canada renegotiated the agreement in 2012, requiring the governments to review and revise phosphorus (P) load targets, starting with Lake Erie. In response, the governments supported a multi-model team to evaluate the existing objectives and P load targets for Lake Erie and provide the information needed to update those targets.

Herein, we describe the process and resulting advice provided to the binational process. The collective modeling effort concluded that avoiding severe Western Basin (WB) cyanobacteria blooms requires: 1) focusing on reducing total P loading from the Maumee River, with an emphasis on high-flow events during March–July, 2) focusing on dissolved reactive P load alone will not be sufficient because there is significant bioavailable P in the particulate phosphorus portion of the load, and 3) loading from the Detroit River is not a driver of cyanobacteria blooms. Reducing Central Basin (CB) hypoxia requires a CB + WB load reduction greater than what is needed to reach the WB cyanobacteria biomass goal. Achieving

Cladophora thresholds will be challenging without site-specific load reductions, and more research is needed.

Schindler, D. W., S. R. Carpenter, S. C. Chapra, R. E. Hecky., D. M. and Orihel. 2016. Reducing phosphorus to curb lake eutrophication is a success. *Environmental Science Technology* 2016:8923–8929.

As human populations increase and land-use intensifies, toxic and unsightly nuisance blooms of algae are becoming larger and more frequent in freshwater lakes. In most cases, the blooms are predominantly blue-green algae (Cyanobacteria), which are favored by low ratios of nitrogen to phosphorus. In the past half century, aquatic scientists have devoted much effort to understanding the causes of such blooms and how they can be prevented or reduced. Here we review the evidence, finding that numerous long-term studies of lake ecosystems in Europe and North America show that controlling algal blooms and other symptoms of eutrophication depends on reducing inputs of a single nutrient: phosphorus. In contrast, small-scale experiments of short duration, where nutrients are added rather than removed, often give spurious and confusing results that bear little relevance to solving the problem of cyanobacteria blooms in lakes.

Schulte, R. P. O., A. R. Melland, O. Fenton, M. Herlihy, K. Richards, and P. Jordan. 2010. Modelling soil phosphorus decline: Expectations of Water Framework Directive policies. *Environmental Science Policy* 13:472–484. doi:10.1016/j.envsci.2010.06.002.

Depletion of plant-available soil phosphorus (P) from excessive to agronomically optimum levels is a measure being implemented in Ireland to reduce the risk of diffuse P transfer from land to water. Within the

Nitrates and Water Framework Directive regulations the policy tool is designed to help achieve good status by 2015 in water bodies at risk from eutrophication. To guide expectation, this study used soil plot data from eight common soil associations to develop a model of Soil Test P (STP) (Morgan's extract) decline following periods of zero P amendment. This was used to predict the time required to move from excessive (Index 4) to the upper boundary of the optimum (Index 3) soil P concentration range. The relative P balance (P balance:Total soil P) best described an exponential decline ($R^2 = 63\%$) of STP according to a backwards step-wise regression of a range of soil parameters. Using annual field P balance scenarios (−30 kg P ha^{-1}, −15 kg P ha^{-1}, −7 kg P ha^{-1}), average time to the optimum soil P boundary condition was estimated from a range of realistic Total P and STP starting points. For worst case scenarios of high Total P and STP starting points, average time to the boundary was estimated at 7–15 years depending on the field P balance. However, uncertainty analysis of the regression parameter showed that variation can be from 3 to >20 years. Combined with variation in how soil P source changes translate to resulting P delivery to water bodies, water policy regulators are advised to note this inherent uncertainty from P source to receptor with regard to expectations of Water Framework Directive water quality targets and deadlines.

Sekhon, B. S., D. K. Bhumbla, J. Sencindiver, and L. M. McDonald. 2014. Using soil survey data for series-level environmental phosphorus risk assessment. *Environmental Earth Science*. DOI 10.1007/s12665-014-3144-6.

Choosing soil series scale for assessing phosphorus (P) retention and release characteristics may help relate routinely collected series-specific soil survey data with P retention and aid in designing series-specific P management strategies. Phosphorus retention and release characteristics of pedons collected from two benchmark upland soil series (Berks and Monongahela) and two floodplain (Huntington and Lindside) soil series of West Virginia (USA) were assessed by evaluating P sorption capacity (PSC, Langmuir method) and its major determinants, and effect of different levels of degree of P saturation (DPS) and soil test P (STP, Mehlich-1 P) on the desorbable P (0.01 M CaCl2-extractable) concentrations. The PSC of the two floodplain soils, Huntington and Lindside, was similar but lower than PSC of upland Berks and Monongahela soils. However, thicker A horizons of Huntington and Lindside soils may compensate for their lower

PSC. The B horizons exhibited higher PSC than A horizons. However, slow permeability and thinness of such horizons may discount the higher PSC effect. Relationship of PSC with ammonium oxalate extractable Al (AOX-Al) and Fe (AOX-Fe), dithionite–citrate–bicarbonate extractable Al (DCB-Al) and Fe (DCB-Fe), total C, clay content, and pH [soil:water ratio 1:1 (pH-water) and soil:0.01 M CaCl2 solution ratio 1:2 (pH-CaCl2)] showed that in general all except Fe and total C influenced PSC significantly. Aluminum associated with crystalline clay minerals particularly affected PSC, especially of upland soils. Most of the soils did not release considerable P even beyond the conventional critical limit of 25 % DPS for well-drained soils. DPS-desorbable P relationships, though, reflected poor reliability of DPS as an environmental index. At a given DPS and STP, surface horizons released more P than their subsurface counterparts and thus reflected the net sink character of subsurface horizons. Most of the soils did not show considerable release of P even beyond agronomically high STP levels ([23 mg kg-1). The study provides an economical alternative to time and money-intensive lysimetric studies for assessing subsurface P loss. It reveals the workability of integrating environmental P studies with soil survey data and superiority of integrated assessment of environmental indices of P over the use of any single index.

Sharpley, A., H. P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. 2014. Phosphorous legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *Journal of Environmental Quality*. 42(5):1308–1326. doi: 10.2134/jeq2013.03.0098.

The water quality response to implementation of conservation measures across watersheds has been slower and smaller than expected. This has led many to question the efficacy of these measures and to call for stricter land and nutrient management strategies. In many cases, this limited response has been due to the legacies of past management activities, where sinks and stores of P along the land– freshwater continuum mask the effects of reductions in edge-of-field losses of P. Accounting for legacy P along this continuum is important to correctly apportion sources and to develop successful watershed remediation. In this study, we examined the drivers of legacy P at the watershed scale, specifically in relation to the physical cascades and biogeochemical spirals of P along the continuum from soils to rivers and lakes and via surface and subsurface flow pathways. Terrestrial P legacies encompass prior nutrient and land management activities that have built up soil P to levels that exceed crop requirements and modified the connectivity between terrestrial P sources and fluvial transport. River and lake P legacies encompass a range of processes that control retention and remobilization of P, and these are linked to water and sediment residence times. We provide case studies that highlight the major processes and varying timescales across which legacy P continues to contribute P to receiving waters and undermine restoration efforts, and we discuss how these P legacies could be managed in future conservation programs.

Sharpley, A. N., S. Herron, and T. C. Daniel. 2007. Overcoming the challenges of phosphorus-based management in poultry farming. *Journal of Soil Water Conservation*. 62:375–389.

Continued economic and use impacts of accelerated eutrophication of fresh waters caused by elevated phosphorus (P) inputs is placing pressure on agriculture to implement P-based nutrient management strategies, particularly for confined animal feeding operations. As P-based strategies usually have a negative impact on farm operations and economics, current challenges are to define where there is a problem and how big of a problem, to determine how to implement and maintain effective best management practices (BMPs), and to identify the best incentives for farmer adoption. These challenges need to be overcome to develop equitable solutions among those affected (i.e., farming, municipalities, and public). The 1997 US Census showed poultry operations had a higher confined animal unit density (3.23 AU ha^{-1} [1.31 AU ac -1]) than either dairy (0.89 AU ha^{-1} [0.36 AU ac^{-1}]) or swine operations (0.77 AU ha^{-1} [0.31 AU ac^{-1}]).This coupled with the generally greater (two- to four-fold) concentration of P in poultry manure than in other livestock type manure makes P-based management especially challenging for poultry operations. Furthermore, because the N:P ratio in poultry litter or manure (3:1) is much narrower than plants generally need (8:1), there is an inherent long-term increase in soil P and thus, potential for runoff P enrichment when manure or litter is applied to meet crop N needs. Even so, the short-term impacts of land-applying poultry manure or litter can be successfully mitigated with adoption of P-based BMPs. These include feed (enzymes, crop hybrids), manure (chemical and physical treatment, composting, transportation), land (amendments, conservation tillage, critical area targeting, buffers, soil testing), and grazing management (duration and intensity, stream bank fencing). However, developing and planning BMPs at farm and watershed scales is not the single or final solution. Many farmers simply do not have the financial resources to implement and maintain costly remedial measures. Despite many programs to help defray remedial costs, institutional red-tape and conflicting requirements often limit program enrollment and hinder widespread adoption. Obviously, there are still challenges, but if affected parties work together, there is a better chance these challenges can be overcome.

Sharpley, A.N., P. J. A. Kleinman, P. Jordan, L. Bergström, and A. L. Allen. 2009. Evaluating the success of phosphorus management from field to watershed. *Journal of Environmental Quality*. 38:1981–1988. doi:10.2134/jeq2008.0056.

Studies have demonstrated some P loss reduction following implementation of remedial strategies at field scales. However, there has been little coordinated evaluation of best management practices (BMPs) on a watershed scale to show where, when, and which work most effectively. Thus, it is still difficult to answer with a degree of certainty, critical questions such as, how long before we see a response and where would we expect to observe the greatest or least response? In cases where field and watershed scales are monitored, it is not uncommon for trends in P loss to be disconnected. We review case studies demonstrating that potential causes of the disconnect varies, from competing sources of P at watershed scales that are not reflected in field monitoring to an abundance of sinks at watershed scales that buffer field sources. To be successful, P-based mitigation strategies need to occur iteratively, involve stakeholder driven programs, and address the inherent complexity of all P sources within watersheds.

Sharpley, A., H. P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. 2013. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *Journal of Environmental Quality*. 42:1308– 1326. doi:10.2134/jeq2013.03.0098.

The water quality response to implementation of conservation measures across watersheds has been slower and smaller than expected. This has led many to question the efficacy of these measures and to call for stricter land and nutrient management strategies. In many cases, this limited response has been due to the legacies of past management activities, where sinks and stores of P along the land– freshwater continuum mask the effects of reductions in edge-of-field losses of P. Accounting for legacy P along this continuum is important to correctly apportion sources and to develop successful watershed remediation. In this study, we examined the drivers of legacy P at the watershed scale, specifically in relation to the physical cascades and biogeochemical spirals of P along the continuum from soils to rivers and lakes and via surface and subsurface flow pathways. Terrestrial P legacies encompass prior nutrient and land management activities that have built up soil P to levels that exceed crop requirements and modified the connectivity between terrestrial P sources and fluvial transport. River and lake P legacies encompass a range of processes that control retention and remobilization of P, and these are linked to water and sediment residence times. We provide case studies that highlight the major processes and varying timescales across which legacy P continues to contribute P to receiving waters and undermine restoration efforts, and we discuss how these P legacies could be managed in future conservation programs.

Sharpley, A. N., P. J. A. Kleinman, D. N. Flaten, and A. R. Buda. 2011. Critical source area management of agricultural phosphorus: Experiences, challenges and opportunities. *Journal of Environmental Quality*. 64:945–952. doi:10.2166/wst.2011.712.

The concept of critical source areas of phosphorus (P) loss produced by coinciding source and transport factors has been studied since the mid 1990s. It is widely recognized that identification of such areas has led to targeting of management strategies and conservation practices that more effectively mitigate P transfers from agricultural landscapes to surface waters. Such was the purpose of P Indices and more complex nonpoint source models. Despite their widespread adoption across the U.S., a lack of water quality improvement in certain areas (e.g. Chesapeake Bay Watershed and some of its tributaries) has challenged critical source area management to be more restrictive. While the role of soil and applied P has been easy to define and quantify, representation of transport processes still remains more elusive. Even so, the release of P from land management and in-stream buffering contribute to a legacy effect that can overwhelm the benefits of critical source area management, particularly as scale increases (e.g. the Chesapeake Bay). Also, conservation tillage that reduces erosion can lead to vertical stratification of soil P and ultimately increased dissolved P loss. Clearly, complexities imparted by spatially variable landscapes, climate, and system response will require iterative monitoring and adaptation, to develop locally relevant solutions. To overcome the challenges we have outlined, critical source area management must involve development of a 'toolbox' that contains several approaches to address the underlying problem of localized excesses of P and provide both spatial and temporal management options. To a large extent, this may be facilitated with the use of GIS and digital elevation models. Irrespective of the tool used, however, there must be a two-way dialogue between science and policy to limit the softening of technically rigorous and politically difficult approaches to truly reducing P losses.

Sharpley, A. N. and S. J. Smith. 1994. Wheat tillage and water quality in the southern plains. *Soil Tillage Research* 30(1):33–38. doi: 10.1016/0167-1987(94)90149-X.

This study considers the impact of conventional-till (moldboard plow or sweeps) and no-till wheat (*Triticum aestivum* L.) management practices on surface and groundwater quality. Concentrations and amounts of sediment, nitrogen (N), and phosphorus (P) in surface runoff, and associated nutrient levels in ground water were determined for seven dryland watersheds at two locations for periods up to 14 years. In general, annual surface runoff was similar for both tillage practices, ranging from 6 to 15 cm. Compared with conventional till, no-till reduced sediment, N, and P loss an average of 95%, 75%, and 70%, respectively. Concurrently, elevated levels of dissolved P (maximum 3.1 mg $-L^{-1}$) in surface runoff, and nitrate-N in ground water (maximum 26 mg $-L^{-1}$) were observed. About 25% more available soil water was in the no-till soil profiles, but this did not translate into increased grain yield. Instead, no-till grain yields were reduced an average 33% (600 kg ha^{-1}) compared with conventional till, which is attributed to a lower availability of surface applied fertilizer, and increasing cheat *(Bromus tectorum* L.) and associated weed problems. From an overall agronomic and environmental standpoint, our results indicate that the management of no-till systems should include careful fertilizer placement and timing.

Simard, R., S. Beauchemin, and P. Haygarth. 2000. Potential for preferential pathways of phosphorus transport. J. Environ. Qual. 29:97–105. doi:10.2134/jeq2000.00472425002900010012x.

This paper briefly reviews the existing literature and uses evidence from three studies to demonstrate the occurrence of preferential pathways of P transport through soil. Studies conducted in the St. Lawrence lowlands, Canada, indicated that particulate P (PP-i.e., >0.45 I~m) the main fraction of total P (TP) in tile-drainage water generated storm events after periods of low rainfall. In the remainder of the year, the concentration of TP and P forms were related to soil texture, primary tillage intensity and frequency, and showed wide seasonal variations. For a study conducted in the UK under grassland, higher TP concentrations were found in near-surface runoff (0-30 cm) compared with concentrations measured in drainflow. Water passing through the artificial drainage system had a higher proportion of PP (43%) than water passing close to (<30 cm) or over the soil surface (31%). Installation of tile drainage in a poorly draining soil reduces P transfer by improving the infiltration capacity, thereby reducing overland flow volume and allowing P to be retained/sorbed by the soil matrix. Because of the absence of tillage, permanent grasslands accumulate P near the surface. We hypothesize that, if the soil P store is coincident with preferential flow pathways (either artificial mole channels or *natural macropores),* permanent grassland will be vulnerable to transfer large amounts of P through subsurface pathways. Phosphorus transfer through preferential flow pathways may be particularly important after storm events that rapidly follow periods of drought and/or surface P inputs as inorganic fertilizer or manure.

Sims, J., R. Simard, and B. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. *Journal of Environmental Quality*. 27:277–293. doi:10.2134/jeq1998.00472425002700020006x.

The importance of P originating from agricultural sources to the nonpoint source pollution of surface waters has been an environmental issue for decades because of the well-known role of P in eutrophication. Most previous research and nonpoint source control efforts have emphasized P losses by surface erosion and runoff because of the relative immobility of P in soils. Consequently, P leaching and losses of P via subsurface runoff have rarely been considered important pathways for the movement of agricultural P to surface waters. However, there are situations where environmentally significant export of P in agricultural drainage has occurred (e.g., deep sandy soils, high organic matter soils, or soils with high soil P concentrations from long-term over fertilization and/or excessive use of organic wastes). In this paper we review research on P leaching and export in subsurface runoff and present overviews of ongoing research in the Atlantic Coastal Plain of the USA (Delaware), the midwestem USA (Indiana), and eastern Canada (Quebec). Our objectives are to illustrate the importance of agricultural drainage to nonpoint source pollution of surface waters and to emphasize the need for soil and water conservation practices that can minimize P losses in subsurface runoff.

Smith, D. R., W. Francesconi, S. J. Livingston, and C. Huang. 2015a. Phosphorus losses from monitored fields with conservation practices in the Lake Erie Basin, USA. *Ambio* 2015, 44:S319–S331.

Conservation practices are implemented on farm fields in the USA through Farm Bill programs; however, there is a need for greater verification that these practices provide environmental benefits (e.g., water quality). This study was conducted to assess the impact of Farm Bill eligible conservation practices on soluble P (SP) and total P (TP) losses from four fields that were monitored between 2004 and 2013. No-tillage doubled SP loading compared to rotational tillage (e.g., tilled only before planting corn); however, no-tillage decreased TP loading by 69 % compared to rotational tillage. Similarly, grassed waterways were shown to increase SP loads, but not TP loads. A corn–soybean–wheat–oat rotation reduced SP loads by 85 % and TP loads by 83 % compared to the standard corn–soybean rotation in the region. We can potentially attain TP water quality goals using these Farm Bill practices; however, additional strategies must be employed to meet these goals for SP.

Smith, D. R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker, and A. N. Sharpley. 2015b. Surface Runoff and Tile Drainage Transport of Phosphorus in the Midwestern United States. *Journal of Environmental Quality*. 44:495–502.

The midwestern United States offers some of the most productive agricultural soils in the world. Given the cool humid climate, much of the region would not be able to support agriculture without subsurface (tile) drainage because high water tables may damage crops and prevent machinery usage in fields at critical times. Although drainage is designed to remove excess soil water as quickly as possible, it can also rapidly transport agrochemicals, including phosphorus (P). This paper illustrates the potential importance of tile drainage for P transport throughout the midwestern United States. Surface runoff and tile drainage from fields in the St. Joseph River Watershed in northeastern Indiana have been monitored since 2008. Although the traditional concept of tile drainage has been that it slowly removes soil matrix flow, peak tile discharge occurred at the same time as peak surface runoff, which demonstrates a strong surface connection through macropore flow. On our research fields, 49% of soluble

P and 48% of total P losses occurred via tile discharge. Edge-of field soluble P and total P areal loads often exceeded watershed scale areal loadings from the Maumee River, the primary source of nutrients to the western basin of Lake Erie, where algal blooms have been a pervasive problem for the last 10 yr. As farmers, researchers, and policymakers search for treatments to reduce P loading to surface waters, the present work demonstrates that treating only surface runoff may not be sufficient to reach the goal of 41% reduction in P loading for the Lake Erie Basin.

Soil Survey Staff. 1999. *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Features the latest available research data on the taxonomy being used to determine soil maps in the United States and other countries, thus representing the first publication of the complete system and nomenclature. Orders, suborders and subgroups are arranged alphabetically.

Sparks, D. L., 1996. *Methods of Soil Analysis*. Part 3: Chemical Methods, 3rd ed. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin.

This book contains 44 chapters, written by 70 authors from throughout the world. A new chapter on quality assurance and quality control is included. Updated chapters are included on the principles of various instrumental methods and their applications to soil analysis. Additionally, new chapters are included on Fourier transform infrared, Raman, electron spin resonance, x-ray photoelectron, and x-ray absorption fine structure spectroscopies. The application of these methods to analyzing soil chemical reactions is currently one of the major research areas in the soil and environmental sciences. Chapters are included on analyses of soil chemical properties including soil salinity, carbonate and gypsum, soil pH and acidity, lime requirement, cation and anion exchange capacities, and organic matter. Methods for the analyses of soluble, sorbed, and total concentrations of 34 elements are also included. Additionally, these chapters include useful background information on the chemistry of the elements. A new chapter on methods for organic chemical extraction is included.

Spratt, E. D., F. G. Warder, L. D. Bailey, and D. W. L. Read. 1980. Measurement of fertilizer phosphorus residues and its utilization. *Soil Science Society America Journal* 44(6):1200–1204. doi: 10.2136/sssaj1980.03615995004400060013x.

A values and sodium bicarbonate ($NaHCO_3$) extraction soil tests were used to determine phosphorus (P) levels over 8 years on four soils which had been treated with 0, 100, 200, and 400 kg P/ha. The tests correlated highly with each other and indicated the decline of residual fertilizer-P over years as the soils were cropped. Reliable predictions for the duration of the beneficial effects of large amounts of fertilizer-P could be made for the two Manitoba soils where cropping was continuous (wheat-flax) but not for the Saskatchewan soils where fallow was included (wheat-fallow). By using the linear equation of $NaHCO_3$ soil tests vs. time (years), it was predicted that 100, 200, and 400 kg P/ha would last about 6, 9, and 13 years, respectively, before further fertilizer-P inputs were needed to maintain wheat production. Longer durations were predicted for 200 and 400 kg P/ha when curvilinear relationships were used, averaging 11 and 22 years, respectively, giving better economic feasibility. These soil testing techniques may be used on calcareous soils to minimize current fertilizer-P inputs for wheat where residual fertilizer-P has accumulated.

Stamm, C., F. R. Gachter, H. Leuenberger, and H. Wunderli. 1998. Preferential transport of phosphorous in drained grassland soils. *Journal of Environmental Quality* 27:515-522. doi:10.2134/jeq1998.00472425002700030006x.

Phosphorus is the limiting factor for primary production in most freshwater ecosystems. In many areas, diffuse P losses from intensively cultivated land cause severe eutrophication of surface waters. We investigated the P export from two drainage systems under intensively used grassland in a catchment of the Swiss Plateau. Flow rate and nutrient concentrations were measured with a high temporal resolution during discharge events. During most flow peaks, P concentrations strongly increased with increasing flow rates. Concentrations of soluble-reactive P (SRP) reached up to 155 ttmol -1. Phosphorus was mainly transported as soluble-reactive and particulate P. Organic P compounds, as well as P associated with colloids between 0.05 and0.45 tim in effective diameter, were of minor importance. Estimated P loads from the drainage systems were 227 g SRP ha^{-1} within a period of 2.5 mo at site I and 1290 g ha t during 6 mo at site II. Estimation uncertainty was large (~21 and ±36% for the two sites, respectively) due to the weak correlation between discharge and concentration for all data from a given site. Water-extractable P in the soil was concentrated in the uppermost layer of the profiles or, for short periods after spreading of manure, deposited on the vegetation. The discharge-concentration relationship indicated that P was transported through preferential flow paths extending from close to the surface to the drains. Sprinkling experiments with a blue dye confirmed this conclusion. At one site, we observed preferential flow in a downhill direction within the saturated zone.

Stumm W. 1992. *Chemistry of the solid-water interface: Processes at the mineral-water and particle water interface in natural systems*. John Wiley and Sons, Inc. New York, NY, USA.

Provides an introduction to the chemistry of the solid-water interface, progressing from the simple to more complex and applied. Discusses the important interfaces in natural systems, especially geochemistry, in natural waters, soils and sediments. The processes occurring at mineral-water, particle-water and organism-water interfaces play critical roles in regulating the composition and ecology of oceans and fresh waters, the development of soils and plant nutrient's supply, preserving the integrity of water repositories and in such applications as water technology and corrosion science.

Van Bochove, E., J. T. Denault, M.L. Leclerc, G. Theriault, F. Dechmi, S. E. Allaire, A. N. Rousseau, and C. Drury. 2011. Temporal trends of risk of water contamination by phosphorus from agricultural land in the Great Lakes Watersheds of Canada. *Canadian Journal of Soil Sciences* 91: 443-453.

The indicator of risk of water contamination by phosphorus (IROWC_P) was designed to estimate the level of risk of P contamination in water and how the level of risk has changed over 25 yr (1981–2006) in agricultural watersheds of Canada. IROWC_P allows for a qualitative assessment of this risk in comparison with other regions of eastern and western Canada, and the identification of high to very high risk watersheds may require on-site assessment and the development of remedial action plans. This study presents an in-depth analysis of IROWC_P results in the major Great Lakes watersheds of Canada. The risk of water contamination by P remains acceptable (very low to moderate) in most Great Lakes watersheds, but better management practices (e.g., reduced fertilization and manure application rates) and improved control of surface runoff may be required in watersheds which are at increased risk. The Canadian watersheds of the Great Lakes basin showed a 39% reduction in their P applications in excess of crop requirements between 1981 and 2006 bringing the Ontario provincial P balance close to equilibrium in 2006. Vulnerable areas were found south of Kitchener in the Lower Grand River watershed and east of Lake Simcoe.

Van der Valk, A. G. and R. W. Jolly. 1992. Recommendations for research to develop guidelines for the use of wetlands to control rural nonpoint source pollution. *Ecological Engineering* 1:115–134.

Natural wetlands should not be used to reduce rural nonpoint source (NPS) problems. Properly designed restored or created wetlands, however, can be used for this purpose in many agricultural landscapes. Agricultural landscapes in which wetlands can be easily restored are the most suitable areas. Major technical issues that need to be resolved before effective and realistic guidelines can be developed for using restored wetlands to reduce NPS pollution include: (1) the effects of contaminants, particularly sediments and pesticides, on restored wetlands; (2) the fate of organic contaminants in restored wetlands; (3) the development of site selection criteria; and (4) the development of design criteria. There are also many social, economic, and political barriers to using restored wetlands. Social and economic issues that need to be resolved include: (1) what is the most appropriate landscape unit for wetland restoration programs?; (2) where should wetlands be sited?; (3) who will make siting decisions?; (4) how can landowner cooperation for restoration programs be obtained?; (5) who will pay for wetland restorations?; and (6) how cost effective is this approach? Watersheds are recommended as the natural landscape unit for planning, implementing, and administering restoration projects. Eight different research projects are identified: five technical projects (watershed-level demonstration projects, effects of contaminants on wetlands, sustainable loading rates for contaminants, landscape or watershed simulation models, and site selection and design criteria for restored wetlands) and three economic and social projects (attitudes of farmers and rural leaders, legal and public policy implications, and economic costs and benefits).

Vepraskas M. J., M. Polizzotto, and S. P. Faulkner. 2016. *Redox Chemistry of Hydric Soils. In: Wetland Soils: Genesis, Hydrology, Landscapes, and Classification*. M. Vepraskas and C. Craft (eds.). CRC Press.

- A specialized book specifically geared toward environmental consultants and governmental wetland regulators, the text:
- Reviews general properties of wetland soils, including hydrology, redox chemistry, organic matter dynamics and biology.
- Provides examples of major types of wetlands across the United States
- Highlights USDA Hydric Soil Field Indicators, the most current and universal indicators of wetlands soils
- Summarizes technical standards

Evaluates wetland functions, methods of assessment, and restoration techniques.

Verhamme, E. M., T. N. Redder, D. A Schlea, J. Grush, J. F. Bratton, J. V. DePinto. 2016. Development of the Western Lake Erie Ecosystem Model (WLEEM): Application to connect phosphorus loads to cyanobacteria biomass. *Journal of Great Lakes Research*. http://dx.doi.org/10.1016/j.jglr.2016.09.006.

Since the mid-1990s, Lake Erie has experienced re-eutrophication symptoms including harmful algal blooms in the western basin and summer hypoxia in the Central Basin. The 2012 Protocol for the Great Lakes Water Quality Agreement (GLWQA) required phosphorus objectives and management recommendations to be set for all the Great Lakes, beginning with Lake Erie. To inform setting revised loading targets for the Lake Erie portion of the GLWQA, modeling was performed. The development and application of one of those models, the Western Lake Erie Ecosystem Model (WLEEM), is described here. WLEEM is a three dimensional, fine-scale, process-based model that links hydrodynamic, sediment transport, and in-lake biogeochemical and ecological processes. WLEEM was applied here to assess system sensitivity to a range of variables, and ultimately to develop a robust phosphorus load — cyanobacteria response relationship to determine a maximum load of total phosphorus from the Maumee River during the period of March–July that would produce a mild cyanobacteria bloom (b7830 MT cyanobacteria biomass) in Western Lake Erie. The maximum total phosphorus load from the Maumee River for that period to produce a mild bloom was determined to be 890 metric tons. Given the natural variability of systems like this, tools like WLEEM used in a dynamic operational modeling mode, consistent tributary and lake monitoring, and ongoing research will be essential components of effective mitigation and science-based adaptive management of eutrophication in Lake Erie and other nutrient-impacted water bodies.

Wagar, B. I., J. W. B. Stewart, and J. L. Henry. 1986. Comparison of single large broadcast and small annual seed-placed phosphorus treatments on yield and phosphorus and zinc content of wheat on Chernozemic soils. *Canadian Journal of Soil Sciences* 66:237–248. doi:10.4141/cjss86-026.

Yield and P and Zn contents of wheat from plots on a Dark Brown Chernozemic clay soil which received single broadcast P applications and annual seed-placed P applications were compared in a 6-yr study. Broadcast P applications of 20, 40, 80 and 160 kg P ha^{-1} increased the average yield by 9, 24, 33 and 35%, respectively. Yearly seed-placed P treatments of 2.5, 5, 10 and 20 kg P ha^{-1} applied over the first 5 yr of the study increased the average yield by 10, 15, 24 and 29%, respectively. The broadcast application of 40 kg P ha^{-1} increased yields over 5 yr and had an average yield and P uptake similar to that of the annual seed-placed applications of 10 and 20 kg P ha^{-1}. Broadcasting 80 and 160 kg P ha^{-1} increased yields over 6 yr. Soil levels of extractable $NaHCO_3$-P_i indicated future increases may occur. Yields from plots receiving consecutive seed-placed P treatments significantly benefited from the P residues of previous seed-placed applications. Plant zinc concentration was significantly reduced by the broadcast application of 160 kg P ha^{-1} and the seed-placed application of 20 kg P ha^{-1}. Key words: Broadcast P, seed-placed P, residual P, P-Zn interaction.

Wang, N. and W. J. Mitsch. 1998. Estimating phosphorus retention of existing and restored coastal wetlands in a tributary watershed of the Laurentian Great Lakes in Michigan, USA. *Wetlands Ecology and Management* 6:69–82.

Simulation modeling with uncertainty analysis was applied to the question of nonpoint source pollution control through extensive wetland restoration. The model was applied to the Quanicassee River basin, a tributary stream to Saginaw Bay on Lake Huron in northeastern Michigan, USA. An estimate of the role of the existing 695 ha of riverside and lake-side wetlands in the lower Quanicassee River basin suggests that they retain 1.2 metric tons of phosphorus per year (mt P/yr), or 2.5% of the total phosphorus load from the basin. A simple Vollenweidertype model of phosphorus retention by created wetlands, calibrated with 3-years of data from two wetland sites in Midwestern USA, was used to estimate the effect of major wetland restoration in the basin. For a wetland restoration project involving 15% of the Quanicassee River basin or 3,120 ha of wetlands, an estimated 33 mt P/yr could be retained, assuming a proper hydrologic connection between the wetlands and the river. This would represent a reduction of two-thirds of the existing phosphorus load to the Bay from the Quanicassee River basin. Large-scale wetland restoration appears to be a viable management practice for controlling phosphorus and other nonpoint source pollution from entering Saginaw Bay. It is an alternative that meets two major resource goals – developing wetland habitat and controlling pollution to the Great Lakes.

Williams, M. R., K. W. King, W. Ford, A.R. Buda, and C. D. Kennedy. 2016a. Effect of tillage on macropore flow and phosphorus transport to tile drains. *Water Resources Research* 52:2868–2882. doi:10.1002/2015WR017650.

Elevated phosphorus (P) concentrations in subsurface drainage water are thought to be the result of P bypassing the soil matrix via macropore flow. The objectives of this study were to quantify event water delivery to tile drains via macropore flow paths during storm events and to determine the effect of tillage practices on event water and P delivery to tiles. Tile discharge, total dissolved P (DP) and total P (TP) concentrations, and stable oxygen and deuterium isotopic signatures were measured from two adjacent tile-drained fields in Ohio, USA during seven spring storms. Fertilizer was surface-applied to both fields and disk tillage was used to incorporate the fertilizer on one field while the other remained in no-till. Median DP concentration in tile discharge prior to fertilizer application was 0.08 mg L21 in both fields. Following fertilizer application, median DP concentration was significantly greater in the no-tilled field (1.19 mg L^{-1}) compared to the tilled field (0.66 mg L^{-1}), with concentrations remaining significantly greater in the no-till field for the remainder of the monitored storms. Both DP and TP concentrations in the no-till field were significantly related to event water contributions to tile discharge, while only TP concentration was significantly related to event water in the tilled field. Event water accounted for between 26 and 69% of total tile discharge from both fields, but tillage substantially reduced maximum contributions of event water. Collectively, these results suggest that incorporating surface-applied fertilizers has the potential to substantially reduce the risk of P transport from tile-drained fields.

Williams, M. R., K. W. King, D. B. Baker, L. T. Johnson, D. R. Smith, N.R. Fausey. 2016b. Hydrologic and biogeochemical controls on phosphorus export from Western Lake Erie tributaries. *Water Resources Research*. http://dx.doi.org/10.1016/j.jglr.2016.09.009.

Understanding the processes controlling phosphorus (P) export from agricultural watersheds is essential for predicting and mitigating adverse environmental impacts. In this study, discharge, dissolved reactive P load, total P load, and suspended sediment time-series data (1975–2014) from two Lake Erie tributaries, the Maumee and Sandusky rivers, were evaluated to determine whether hydrologic or biogeochemical processes were responsible for observed patterns in P export. Findings indicate that hydrologic processes in these watersheds controlled P loading patterns, as P export was transport-limited (i.e., P loading was strongly correlated to watershed discharge) and P concentrations exhibited effective chemostatic behavior (i.e., low variability in concentration relative to discharge). The nature and behavior of observed P transport likely stems from a large, ubiquitous source of P present within each watershed as results were similar to those found for geogenic constituents (i.e., silica). Results suggest that changes in both precipitation patterns (e.g., precipitation variability) and watershed hydrologic response (e.g., water residence time) are likely explanations for observed increases in water and P loading in the Maumee and Sandusky watersheds. Future P loading in these watersheds should be expected to continue to be proportional to water flux as long as the magnitude and availability of the P source remains at its current level. Current P management strategies may therefore need to be reevaluated to better balance agricultural P requirements and watershed P loadings.

Woltemade, C. J. 2000. Ability of restored wetlands to reduce nitrogen and phosphorus concentrations in agricultural drainage water. *Journal of Soil and Water Conservation* 55.

Runoff from artificially drained agricultural lands is a common source of excessive nitrogen and phosphorus to downstream waters. Restored wetlands receiving crop field drainage water are shown to lower concentrations of both nitrogen and phosphorus. Case studies in Maryland, Illinois, and Iowa indicate that wetlands can remove up to 68% of nitrate-nitrogen and 43% of phosphorus from drainage water, although performance varies considerably. Performance comparison across sites indicates that large wetlands relative to the contributing drainage area most effectively improve water quality. Time series data representing periods of both relatively high and low inflow indicate that performance is highly sensitive to retention time, with greatest nutrient removal during flow conditions that facilitate retention times of at least one to two weeks. Where wetlands are incorporated into forested riparian buffer strips, additional water quality benefits are shown.

Zedler, J. B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. *Frontiers in Ecology and the Environment* 1:65-72.

In the Upper Midwestern region of the US, three ecosystem services (flood abatement, water quality improvement, and biodiversity support) declined when about 60% of the region’s historical wetland area was drained, mostly for agriculture. Some of the lost services could potentially be regained through wetland restoration measures authorized in the 2002 Farm Bill. Because no single wetland can provide all ecosystem services indefinitely, ecologists can help to identify combinations of projects that will best restore ecosystem services within watersheds. “Strategic” restoration would use an adaptive management approach, targeting former wetlands with marginal crop production, and prioritizing the location, size, and type of wetland needed for a watershed to provide optimal levels of all three services. Given that the Farm Bill includes over $1 billion per year to conserve natural resources on agricultural lands, we are in an excellent position to increase the effectiveness of wetland restoration.

Zhang, T.Q., MacKenzie, A. F., Liang, B. C., and Drury, C. F. 2004. Soil test phosphorus and phosphorus fractions with long-term phosphorus addition and depletion. *Soil Science Society America Journal* 68(2):519–528.

The fate of fertilizer P in soil during crop production has to be determined to evaluate the long-term economic value and sustainability of fertilizer practices. We assessed changes in soil test P and soil P fractions with continuous P fertilization and soil P depletion under continuous corn (*Zea mays* L.) in a Ste. Rosalie clay soil (humic Gleysol; fine, mixed, frigid, Typic Humaquept). Soil samples were analyzed for Mehlich-3 P (M-3 P) and P fractions using a modified Hedley's procedure. Soil M-3 P values remained constant in spite of crop removal in soil not receiving fertilizer for 10 yr. Continuous P fertilization at rates from 44 to 132 P ha^{-1} yr^{-1} increased linearly soil M-3 P, with 6.3 kg P ha_1 of net P addition required to increase M- 1 mg P kg-1. Residual fertilizer P in soil resulted from the continuous P addition were found predominately in labile inorganic and moderately labile Pi (MLPi) (NaOH-Pi). Increased P rates favored soil P transformation from LPi to MLPi, indicating enhanced soil P retention. With P depletion, soil M-3 P declined in plots previously receiving 132 kg P ha^{-1} yr^{-1}, with 4.2 kg P ha^{-1} crop P removal decreasing soil M-3 P by 1 mg P kg^{-1}. Continuous crop removal of soil residual P (Res-P) resulted in decreases in soil LPi and increases in MLPi, an indication of increased retention of Res-P with time. However, moderately stable Pi (HCl-Pi) remained constant, both with continuous P addition and P depletion. Conversion of residual fertilizer P to less available P forms in soil was a slow process and thus the fate of the Res-P should be taken into consider- ation when developing soil nutrient management plans.

Ziegler, V. L. 2016. Exploration of the use of treatment wetlands as a nutrient management strategy in Wisconsin. The Nature Conservancy. https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/wisconsin/Documents/LubnerZiegler-treatment-wetlands-nutrient-manage.pdf.

- Phosphorus and nitrogen are naturally occurring elements that, in excess, contribute to poor water quality in aquatic ecosystems worldwide. Strategies have been developed to mitigate nutrient runoff from agricultural fields, a major source of excessive nutrient loads. *Treatment wetlands1* – created or re-established systems that are

man-made and designed to accomplish a pollutant reduction goal – provide one strategy for nutrient management, but there remains a wide range of questions and concerns about their effectiveness and role within nutrient management programs, relative to other strategies.
- The Nature Conservancy engaged partners to explore these issues by conducting a preliminary assessment of the scientific literature, as well as relevant policies and programs. Interviews were conducted with experts in this field on the effectiveness of using wetlands to reduce phosphorus and nitrogen loads to downstream waters as part of a nutrient management strategy in agricultural systems. The objective of this report is to outline the findings from the science and policy literature review and provide recommendations for moving forward with this strategy.
- Numerous variables influence the effectiveness of a treatment wetland to reduce phosphorus and nitrogen, including hydraulic loading, wetland age, season, temperature, and inflow concentration of nutrients. These variables have been assessed in this report, and associated recommendations have been made toward improving site selection, design, and construction. However, due to the complexity and heterogeneity of treatment wetlands as well as inconsistencies in data reporting, assigning specific nutrient reduction amounts to any given treatment wetland remains problematic. More research is needed to fully understand the mechanisms driving phosphorus and nitrogen reduction by a wetland, especially to influence the current policies and programs that do not currently credit wetlands for their treatment capabilities.

This study leads us to three major conclusions. First, the implementation of existing best management practices and reduction of nitrogen and phosphorus applications beyond crop needs, may reduce nutrient loading to surface waters in agricultural watersheds. This will likely result in water quality improvements, and a decrease of time and effort to develop new technologies and strategies if loads were reduced at the source. Second, ensuring effective implementation of existing policies will also aid water quality improvement, especially if supported through expanded and standardized monitoring and assessment efforts. Finally, understanding the potential role of treatment wetlands as part of agricultural nutrient management strategies will take a multidisciplinary approach with engineers, conservationists, ecologists, policy makers, and biologists working together to design and construct the most efficient management practices to reduce phosphorus and nitrogen loading to surface waters.

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14. ABSTRACT

Excess nutrient loading continues to impact water quality within the Great Lakes. The Great Lakes Restoration Initiative (GLRI) seeks to improve water quality through the reduction of phosphorus inputs from surrounding watersheds. Both natural and constructed wetland ecosystems display the capacity to reduce phosphorus inputs in a variety of agricultural and urban settings. However, maximizing the efficiency and benefits of wetlands for phosphorus reduction requires an understanding of nutrient cycles, soil-nutrient interactions, legacy phosphorus, and other factors. The current report synthesizes existing literature related to wetland phosphorus retention, depicts opportunities for improving water quality outcomes, and identifies opportunities for further research.

15. SUBJECT TERMS	Great Lakes (North America)--Water quality Nutrient pollution of water Nutrient cycles	Water--Phosphorus content Wetlands

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