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PHOSPHORUS FATE, MANAGEMENT, AND MODELING IN ARTIFICIALLY DRAINED SYSTEMS

Phosphorus Fate, Management, and Modeling in Artificially Drained Systems

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Abstract

Phosphorus (P) losses in agricultural drainage waters, both surface and subsurface, are among the most difficult form of nonpoint source pollution to mitigate. This special collection of papers on P in drainage waters documents the range of field conditions leading to P loss in drainage water, the potential for drainage and nutrient management practices to control drainage losses of P, and the ability of models to represent P loss to drainage systems. A review of P in tile drainage and case studies from North America, Europe, and New Zealand highlight the potential for artificial drainage to exacerbate watershed loads of dissolved and particulate P via rapid, bypass flow and shorter flow path distances. Trade-offs are identified in association with drainage intensification, tillage, cover crops, and manure management. While P in drainage waters tends to be tied to surface sources of P (soil, amendments or vegetation) that are in highest concentration, legacy sources of P may occur at deeper depths or other points along drainage flow paths. Most startling, none of the major fate-and-transport models used to predict management impacts on watershed P losses simulate the dominant processes of P loss to drainage waters. Because P losses to drainage waters can be so difficult to manage and to model, major investment are needed (i) in systems that can provide necessary drainage for agronomic production while detaining peak flows and promoting P retention and (ii) in models that can adequately describe P loss to drainage waters.

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PHOSPHORUS in drainage waters, particularly subsurface drains such as tile lines, is often mistakenly assumed to be a minor contributor of P losses from agricultural fields. However, it has been the focus of scientific inquiry and management concern for nearly four decades (Sharpley and Seyers, 1979). Around the world, P loss via artificial drainage has been shown to contribute to the accelerated eutrophication of rivers, lakes, estuaries and even coastal waters, including some of the most challenging cases of agriculturally derived eutrophication. High-profile cases of watershed P loss via drainage networks, such as in Western Lake Erie in the United States, have served to bring broader attention to the subject, even raising calls for moratoria on new drainage in agriculture.

Artificial drainage is an essential component of agricultural management in humid regions, where excessive water can limit trafficability and crop production. Even in arid regions, artificial drainage can be an important component to irrigation infrastructure, routing "return flows" away from irrigated lands. In most areas, today's base drainage infrastructure was established or defined by the initial reclamation of land for agricultural production. It should not be surprising, therefore, that modern drainage systems continue to prioritize hydraulic function over water quality management. For instance, in many US states, a local governmental entity, often the county drainage board, is charged with ensuring drainage networks (i.e., agricultural ditches and some large subsurface tile maintained by the drainage board) adequately drain land for agricultural productivity. When these boards were chartered (often more than 100 yr ago), their charge was to remove the water as quickly and efficiently as possible, not to balance nonpoint source pollution and water conservation concerns with drainage concerns.

Two primary methods are used to drain water from agricultural fields, recognizing that variations and combinations of these methods are common and that historical, or outdated drainage methods are also used (e.g., rock drains, mole drains). In finer-textured soils, drainage typically occurs through *subsurface drainage tiles*, originally made of porous ceramic material (hence the name *tile*) but today constructed of perforated plastic pipes. In very flat landscapes with coarser-textured soils that tend to have higher lateral hydraulic conductivity, *open ditches* often

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Abbreviations: BMP, best management practice.

serve as the primary drainage conveyance (Needelman et al., 2007). Water is transported away from the fields via a series of increasingly larger tiles or ditches. Drainage intensity, defined by the spacing, depth, and size of the drains (Blann et al., 2009), generally increases with decreasing soil hydraulic conductivity. Drainage can vary from ephemeral (e.g., shallow, field tiles and ditches, often installed at depths <1 m), to seasonal or perennial flows in deeper ditches.

Despite periodic reviews of leaching and subsurface drainage research on agricultural P loss (Sims et al., 1998; Chardon and Van Faassen, 1999), systematic generalizations regarding the contexts, management, and modeling of P loss in drainage waters remain uneven. This collection of 16 papers seeks to establish a new benchmark in our understanding of the science, management, and modeling of P in drainage waters. The compendium represents the culmination of a symposium arranged by the Organization to Minimize P Loss from Agriculture (Southeastern Regional Information Exchange Group 17, SERA-17) and the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America held at a joint 2013 conference of these organizations in Tampa, FL. This collection of papers includes case studies, field and laboratory experiments, and reviews of P in tile drainage and modeling of P in artificially drained systems authored by researchers from North America, Europe, and New Zealand (Fig. 1).

Contexts of Phosphorus Loss to Drainage Waters

One of the broad goals of this special section is to synthesize the recent contributions to drainage water management and P loss. In that context, King et al. (2015b) provide as part of this special section an extensive review of P losses in drained landscapes. Phosphorus in drainage water occurs in all forms (dissolved, particulate, organic), and during storm flow, the concentrations and forms of P in drainage water are often similar to those in surface runoff, even when discharged from a tile drain. It is well established that soil macropores serve as major conduits for P movement through the soil profile, routing P in the soil or on the soil surface to tile drains (Jensen et al., 1998; Stamm et al., 1998; Simard et al., 2000). Frequently, macropores (earthworm burrows, root channels) serve to bypass the P buffering capacity of the soil matrix (e.g., Shipitalo and Gibbs, 2000).

The concept of hydrologic "connectivity" is key to nonpoint source P concern, with storm water flows driving the majority of P lost in runoff from agricultural soils. Hydraulic engineers, hydrologists, and biogeochemists have found it difficult to determine and quantify the importance of bypass flows on nonpoint source P loss from agricultural fields. The installation of artificial drainage not only increases peak flows, which accounts for the majority of P loss, but also connects areas of the landscape with plumbing and channels where flows were previously more diffuse (King et al., 2015a; Smith et al., 2015). In the process, P that is entrained in drainage water is concentrated along pathways where there is little interaction with the extensive P buffers found in matrix flows or retention times associated with lower hydraulic conductivities (King et al., 2015b).

Fig. 1. Locations of case studies and experiments compiled in the special collection on P loss in artificial drainage.

Trade-offs between P transport in overland versus subsurface flow are frequently highlighted in areas where agricultural P loss is a concern (i.e., do the benefits of reduced surface runoff P losses outweigh the costs of increased P losses in drainage discharge?). In Western Lake Erie, United States, blooms of the cyanobacterium *Microsystis* temporarily overwhelmed the drinking water treatment facilities of the city of Toledo, OH, in the summer of 2014. Two of the case studies in this collection focus on drainage related P losses in the Western Lake Erie Basin. Conducted in intensively cropped areas of Indiana and Ohio, these studies document P losses from lake plain and glacial till soils that are drained by surface inlets, tile drains, and ditches (Smith et al., 2015; King et al., 2015a). Smith et al. (2015) conclude that as much as 50% of the P loads in a tributary of Indiana's St. Joe's watershed may be derived from tile drainage. King et al. (2015a) illustrate the similarities in P loss in tile drainage and surface runoff, with strong correlations between storm hydrographs and chemographs.

Ontario, Canada, borders North America's Great Lakes and is home to intensively tile drained lake plain and till landscapes comparable to those found in the Western Lake Erie Basin. Zhang et al. (2015a) summarize the results of a long-term (>40 yr) cropping systems study in which dissolved forms of P comprised the majority (72%) of total P in tile drainage. Their findings indicate that grassed systems have the potential to lose as much as three times more P through tiled systems than a cropped system (e.g., continuous corn). Differences in P loss in tile drainage between grassed and tilled systems are consistent with greater connectivity between the soil surface and the tile for the no-till grassed system through the preservation of macropores in perennial or no-till crops (Kleinman et al., 2007). In addition, the contribution of dissolved P from lysed plant tissues in the grass systems would be expected to increase loss (Bechmann et al., 2005).

The previously glaciated landscapes of northern Europe are the focus of some of the most extensive long-term studies of P losses via artificial drainage. Bergström et al. (2015) in this issue provide an overview of Swedish research with more than 50 yr of field trial data and more than 25 yr small catchment data. At the catchment scale, soil properties and weather were found to have a greater influence on P loss to drainage waters than did placement of conservation practices. Previous research by Djodjic et al. (2004), determined that P transmission through Swedish soils was greater in leachate from finer-textured soils with strong structural integrity, than in sandier soils. These generalizations are borne out by Kleinman et al. (2015), this issue, who determine that leaching of applied P (from poultry litter) through soils of the mid-Atlantic coastal plain in the United States is greater in fine-textured soils than in coarse-textured soils.

Swedish research also points to the potential for P in the subsoil to contribute to dissolved P losses in leaching waters that contribute to tile drainage. Andersson et al.'s (2015) work in the current issue highlights the potential that subsoil properties (subsoil P concentration, degree of P sorption saturation, and P sorption capacity) can contribute to P loss in leachate from both structured, fine-textured soils and unstructured, coarse-textured soils. Even though the Swedish research focuses on moderately fertilized systems, their findings are consistent with those of Kleinman et al. (2015) in intensively manured soils of the coastal plain region of the mid-Atlantic United States, where historical application of poultry litter has produced much higher levels of P sorption saturation. Kleinman et al. (2015) report significant, positive relationships between P in surface soils (0–5 cm) and P concentrations in leachate but also find subsoil P (45–50 cm), which was lower than P at the surface, to also relate to P concentrations in leachate. Correlation between surface and subsoil P made it difficult to discriminate between the effects of these sources on leachate P concentrations.

With studies dating back to the 1970s (e.g., Sharpley and Seyers, 1979), New Zealand also has a long history of research on P loss in artificial drainage. In the current issue, McDowell and Monaghan (2015) describe recent experiences with the expansion of drainage (open ditch and mole drain) on dairy farms located on marginal lands of the south island of New Zealand. Despite moderate soil P levels, drainage from an organic soil resulted in some of the highest P loads on record (87 kg P ha^{-1} over 18 mo, nearly 60 kg P ha^{-1} yr^{-1}). In comparison, Kleinman et al. (2007) reported loads of 20 to 30 kg P ha^{-1} yr^{-1} in drainage ditches from coastal plain soils of the mid-Atlantic, with a large "legacy P" source (soil P that had accumulated following 30 yr of poultry litter application in excess of crop P requirement). McDowell and Monaghan's (2015) points to the potential for recently applied sources of P to contribute to P in drainage waters from organic soils with low P buffering ability, consistent with the findings of Cogger and Duxbury (1984).

In semiarid environments, return flows from irrigated fields to drainage networks can be source of P to downstream water bodies. However, in the Upper Snake Rock watershed (Idaho) case study described by Bjorneberg et al. (2015) in this issue, water diverted from the Snake River annually supplied 1.1 kg ha^{-1} of total P to the 82,000-ha irrigation tract, while irrigation return flows contributed only 0.71 kg ha^{-1} of total back to the Snake River. The significant reduction of P in the return flows shows the potential for conservation practices to improve water quality in artificial drainage, particularly under highly regulated irrigated systems. For instance, in the Upper Snake Rock watershed, there has been a gradual conversion of irrigation systems from furrow irrigation to sprinkler irrigation. Furrow irrigation contributes high concentrations of sediment and P in return flow (Bjorneberg et al., 2006). In addition, "water quality" ponds designed to mitigate sediment and P losses from the watershed were shown to reduce total P in influent from 36 to 75%, although they had little effect on dissolved P.

Management of Phosphorus Losses to Drainage Waters

It is well recognized that the successful management of artificial drainage requires a systems-level approach in which all aspects of an operation are considered and managed in concert (Strock et al., 2010). The management of P loss in artificial drainage includes the panoply of practices affecting nonpoint source P loss, from balancing P inputs and outputs at catchment, farm and field scales to minimize legacy sources of P (Kleinman et al., 2011) to managing applied sources of P to fields (King et al., 2015b), to agronomic management (Bergström et al., 2015; Han et al., 2015), to drainage water management and filtration (Buda et al., 2012; Nash et al., 2015; Zhang et al., 2015b). While most management studies included in this special section focus on individual practices, it is recognized that the performance of these practices is decidedly site specific. Even so, many of the practices that have been tested show broad promise for mitigating P losses to drainage waters.

Controlling Phosphorus Sources to Drainage Waters

Sources of P to drainage water include recently applied sources (manure, fertilizer), soils, sediments and even vegetation. Growing awareness exists of the role of legacy sources of P to nonpoint source pollutions (Jarvie et al., 2013; Sharpley et al., 2013). In areas where P accumulates due to the concentration of livestock or high value-horticulture and/or vegetable production, accumulation of P in soils and sediments over the long term can create a source of P to drainage water that is extremely difficult to manage. Bergström et al. (2015) review long-term soil fertility trials in Sweden, revealing strong positive relationships between soil P concentrations and dissolved P concentrations in leachate. Strategies are needed to draw down higher levels of soil P so that this legacy source of P to drainage water can be minimized.

Tillage has been proposed as one means of addressing legacy P, by diluting high P concentrations at the soil surface, bringing sources of P sorption capacity from the subsoil to the surface, and breaking macropores that connect the high concentrations at the surface with drainage conduits (Sharpley, 2003; Shipitalo et al., 2000). The results of Han et al. (2015) presented here suggest that in soils with deeper sources of legacy sources, mitigation strategies that address these sources are required to curb P losses in subsurface drainage. They performed simulated tillage (to 20 cm) on 50-cm-deep columns of mid-Atlantic (United States) coastal plain soils with varying textures (from sand to silt-loam) and varying, albeit high, levels of antecedent soil P (Mehlich-3 P at 0–2 cm was 124–283 mg kg^{-1}). Mixing the upper 20 cm of soil to simulate tillage did not substantially reduce soil P concentrations for most of the soils, compared with a control with no mixing. Based on N dynamics in leachate, Han et al. (2015) determined that the simulated tillage did indeed help to decrease solute transfers from the soil surface through macropores and promote matrix flow (applied urea-N leaching was significantly reduced). Therefore, in heavily P saturated soils with legacy sources of P in the subsoil (>20 cm), deeper forms of tillage may be required to see a benefit from this practice.

Recently applied sources of P can serve as acute sources of P in drainage waters. Zhang et al. (2015b) in the current issue evaluated differences in P loss from tile drains following the application of different composts (derived from yard waste or swine manure) to a fine-textured soil over a 4-yr period in Ontario. Substantially greater concentrations (mg L^{-1}) and losses (kg ha^{-1}) of dissolved and particulate P in tile drainage occurred with swine manure compost than with the unamended control or yard waste compost. Elsewhere, Kleinman et al. (2015) point to the soil-specific nature of P leaching from applied sources to shallow groundwater. They broadcast poultry litter (4.5 Mg ha^{-1}) to different agricultural soils of the mid-Atlantic coastal plain. Leachate P losses increased most with poultry litter addition for the finest-textured soils, contributing 41 and 76% of total P loss in leachate from these soils. As noted above, Djodjic et al. (2004) also found that finer-textured soils that preserve structural attributes such as macropores transmit more P from the soil surface than do coarse-textured soils with lesser structural integrity.

Agronomic Management

Considerable opportunities exist to modify agronomic management or to implement practices aimed at curtailing P loss to drainage waters. Bergström et al. (2015) reviewed Swedish studies evaluating best management practices (BMPs) to reduce P leaching losses including catch crops (i.e., cover crops), constructed wetlands, structure liming of clay soils, and manure management. At field and plot scales, the effects of BMPs on drainage P losses could be quite pronounced. For instance, loads of total P in drainage water were reduced by 36% with wetland installation, by 39 to 55% with structure liming [addition of CaO or $Ca(OH)_2$, which improves structure and promotes Ca-P precipitation], and by 50% with incorporation of liquid swine manure into a clay soil instead of leaving the broadcast manure unincorporated. In contrast, experiments with eight different catch crops revealed no clear pattern in P concentrations with practice implementation. At broader, catchment scales, the beneficial effects of BMPs on P losses have been even more elusive to quantify. Long-term trend analysis of water quality from small Swedish catchments in which various BMPs have been implemented since the 1980s revealed no clear pattern with practice implementation.

Control and Treatment of Tile Drainage

Controlled drainage utilizes coffer dams to more precisely regulate artificial drainage and has been shown to dramatically reduce annual drainage losses of N, primarily due to lesser discharge. However, concern has existed over the potential for greater dissolved P losses with controlled drainage due to the reductive dissolution of Fe-P during periods of water stagnation. Indeed, based on simulated conditions in a laboratory study, Sanchez Valero et al. (2007) concluded that elevated water tables produced by drainage water management could increase P export in subsurface drainage following the reductive dissolution of Fe-bound P in waterlogged soils. While issues remain over the timing of discharges under controlled drainage (drains are typically free flowing in the spring, when concern over P discharges is often greatest), field trials with controlled drainage have documented some significant benefits, including reduced P loss and improved yields.

Nash et al. (2015) evaluated the effects of controlled drainage on P loss in tile drains from soils under corn production where seasonal perching of water above a claypan was a concern in New Zealand. They found that flow-weighted dissolved P concentrations from controlled drainage were significantly lower (0.09 mg L^{-1}) than with conventional, free tile drainage (0.15 mg L^{-1}). Dissolved P losses, which were admittedly low compared with some of the other studies reported in this special collection, were reduced by 80% compared with free drainage, consistent with literature reports on nitrogen. Notably, and in contrast with previous research, the lesser dissolved P losses were not solely due to lesser flows from tiles with controlled drainage (63% less than free draining tiles). In particular, during the spring period, when coffer dams were open and flow between controlled drainage and conventional tile drains was similar, concentration of dissolved P in drainage water from the controlled drainage tiles were lower than with conventional, free draining tiles. Nash et al. (2015) speculate that better conservation of controlled drainage water during dry summer months increased crop uptake of water and P, decreasing field sources of P available to drainage later in the year.

Zhang et al. (2015b) compare controlled drainage combined with subirrigation and free drainage on P losses from tile drains in Ontario. Subirrigation is increasingly practiced in the region using tile networks. Zhang et al. (2015b) determined that this creative use of controlled drainage could be an effective means of curtailing all forms of P loss (dissolved and particulate) from tile drainage, both by decreasing flows and by lowering P concentrations. However, these benefits were overwhelmed by the addition of swine compost, pointing to the need to pair nutrient management with drainage management. In addition, monitoring of tile drains across Quebec by Stämpfli and Madramootoo (2006) suggests that subirrigation can substantially increase dissolved P concentrations in tile discharge. Therefore, careful consideration is needed when pairing practices such as subirrigation and tile drainage.

Tile risers are open inlets that connect subsurface tile lines with depressions or internally drained areas of agricultural fields providing a direct conduit for runoff carrying sediment and solutes to surface waters. Feyereisen et al. (2015) herein describe research with "blind" inlets in which previously open surface inlets were capped with soil and gravel to promote filtration without severely restricting drainage. Over 7 yr of paired comparisons between open and blind inlets in Indiana, total P and dissolved P loads were 66 and 50% lower from blind inlets than from open inlets. Total suspended solids loads were 64% lower from the blind inlets than from the open inlets. In Minnesota, the conversion of an open inlet to blind inlets resulted in a decline in median total suspended solids concentrations from 97 to 8.3 mg L^{-1} and a decline of median dissolved P concentrations from 0.099 and 0.064 mg L^{-1}. This promising new technology has an expected service life of at least 10 yr, based on results from the Indiana study.

The treatment of P sources and P in drainage waters to trap or capture particulate and dissolved forms of P has received great attention over the past decade. In parallel, denitrifying bioreactors have emerged as a practice for removing nitrate from tile drainage. In this issue, Bock et al. (2015) evaluated alternative bioreactor designs to couple denitrification with P removal. Nine laboratory-scale bioreactors were evaluated with and without biochar derived from different hardwood and pine materials. The use of biochars in the bioreactors lowered dissolved P concentrations by 65% over 18 h compared with an 8% increase in dissolved P concentrations within the bioreactor with no biochar after 72 h. In addition, these biochars decreased nitrate concentrations, on average, by 86% after 18 h and 97% after 72 h, compared with only 13% at 18 h and 75% at 72 h in the control. While the results of Bock et al. (2015) clearly point to the potential for biochar to expand the benefits of bioreactors to remove P and reduce the design residence time by enhancing nutrient removal rates, it is important to point out that the biochar feedstocks were materials with low antecedent P concentrations. Increasingly, biochars derived from manure are being tested as value-added products for livestock farms. Undoubtedly, the results of Bock et al. (2015) would be different if biochars derived from poultry litter or other high P byproducts were used.

Drainage Ditches

While the focus of this special issue is on tile-drained fields, drainage ditches are also an important and commonly used management practice for removing excess water from agricultural fields. The management of drainage ditches for water quality protection is, however, distinctly different than the management of tile drains. The geometry, or channel characteristics, of a ditch is key to its function in conveying water, sediment, and P. Two-stage ditches, which use a trapezoidal geometry to support a stable bench within the ditch, help to reduce the velocity of drainage flows by widening the ditch and promoting sedimentation on the bench (Powell et al., 2007; Strock et al., 2010). Vegetation also plays an important role through bank stabilization and physical trapping of sediment (Moore et al., 2010; Liu et al., 2013), although vegetation can adversely affect the hydraulic function of a ditch by creating impoundments during peak flows thereby reducing drainage flows.

A growing body of research examines the potential to establish impoundments and diversions in drainage ditches that promote processes of sedimentation and hyporheic exchange that may diminish particulate and dissolved P losses (Pierce and R. Kröger, 2011). Some of these practices fall under the category of constructed wetlands, as many argue that drainage ditches should be considered “entrained wetlands.” Indeed, in the Lake Erie region where very small loads of agricultural P in drainage water discharge are of critical concern (<2 kg ha^{-1}), in-ditch and in-stream options for nonpoint source P mitigation have become a priority focus.

Ditch dredging is frequently cited as a management practice of concern, due to the severe disturbance caused by the activity and instability of banks following dredging. This can result in increased bank erosion (hence particulate P loss) and removal of bed materials with a high P sorption capacity leading to ditches becoming a P source rather than a P sink (Needelman et al., 2007; Sharpley et al., 2007; Smith and Pappas, 2007; Shigaki et al., 2008). In some instances, however, short-term increases in P retention have been observed following ditch dredging (Smith and Huang, 2010). As is the case with tile-drained fields, many questions are still to be answered regarding the use of drainage ditches for effectively removing water from agricultural fields without significantly increasing risks of P loss.

Modeling of Phosphorus Loss to Drainage Waters

Despite the mounting evidence that artificially drained agroecosystems can be significant sources of P loading to P-sensitive water bodies, the development, implementation, and evaluation of P fate and transport models in these systems is lacking. For models to be effective tools, they must accurately capture the important processes governing P fate and transport in the system of interest. It is important, therefore, that research be directed at better understanding the processes controlling P in artificially drained agroecosystems and that models specifically designed for these systems are developed and tested. In addition to these priorities, there remains a need for more data to calibrate and test models in artificially drained systems and for reasonable estimates of uncertainties in model predictions (Radcliffe et al., 2015).

In the current issue, Radcliffe et al. (2015) first identify the critical processes controlling P loss in artificially drained systems (Fig. 2), then review the following models that have been used, or have the potential to be used, for modeling P losses in artificially drained fields: the P Index, ADAPT, APEX, DRAINMOD, HSPF, HYDRUS, ICECREAMDB, PLEASE, and SWAT. With the exception of the ICECREAMDB model, the models reviewed by Radcliffe et al. (2015) were not developed specifically for predicting P loss in artificially drained agroecosystems. Not surprisingly, ICECREAMDB is deemed by the authors as the best option for modeling P losses in artificially drained systems. In addition, some important limitations in applying the remaining models to artificially drained systems are highlighted and recommendations are given on how some of these models could be improved. Several of the models do not directly account for artificial drainage but rather simulate drainage indirectly (APEX and HSPF). Important limitations in the P routines are also noted for most of the models, including omission of important P loss pathways such as leaching through the soil matrix (SWAT), transport through macropores (APEX, PLEASE, SWAT, and nearly all versions of the Phosphorus Index), and particulate P losses in surface runoff or through the soil matrix (HSPF, HYDRUS, PLEASE); DRAINMOD and HYDRUS currently lack P specific routines. P Indices were deemed too simplistic to adequately represent fate and transport of P in artificially drained systems.

Also in this issue, Que et al. (2015) present results from their study using the Annualized Agricultural Nonpoint Source model (AnnAGNPS) to predict effects of controlled drainage on nutrient and sediment loads in a 3900-km^2 agricultural river basin in Ontario. While the model-predicted changes in runoff due to controlled drainage were generally consistent with changes in runoff measured from small (250 and 470 ha) paired watersheds within the basin under controlled and conventional drainage, the model-predicted changes in P loading only agreed with observed changes from the paired watersheds 50% or less of the time. The authors hypothesize that the ability of AnnAGNPS to predict P losses in flat tile-drained landscapes could be improved by modifying the model to account for P transport in the subsurface and in tile drainage; they caution,

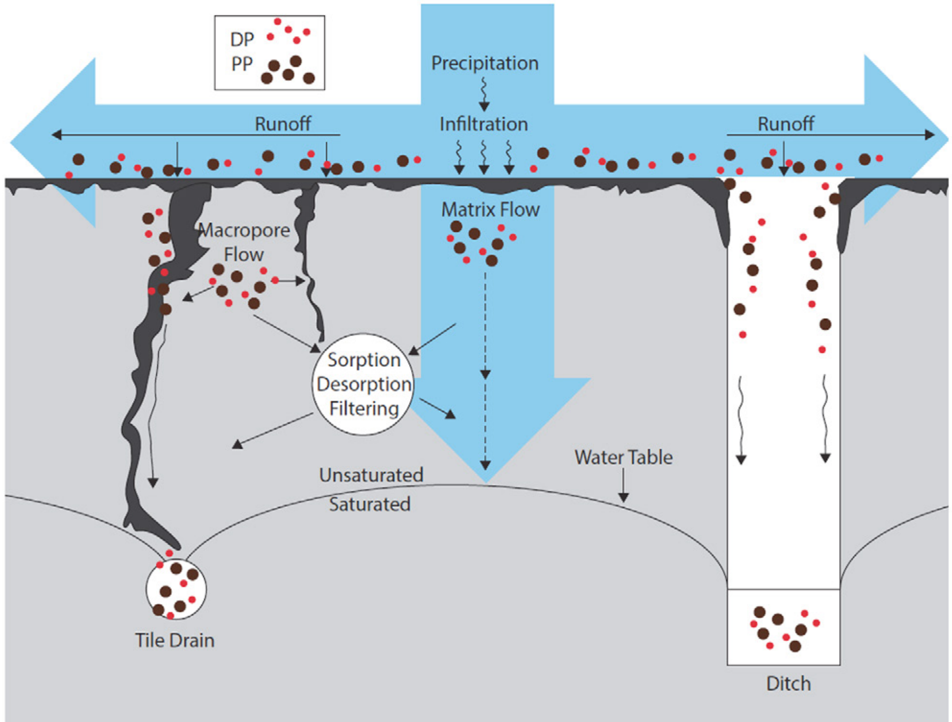

Fig. 2. Representation of processes controlling P losses in artificially drained systems. DP, dissolved phosphorus; PP, particulate phosphorus. Adapted from Radcliffe et al. (2015).

however, that modeling at large spatial scales, particularly in mixed-use watersheds, requires parsimonious parameterization.

Improving the Science, Management, and Modeling of Phosphorus in Drainage Waters

Artificial drainage in agricultural landscapes is fundamental to the productivity of agriculture in many areas of the world, but it increases the connectivity of fields to downstream water bodies and can increase P losses from agriculture. Strategies to mitigate P loss through artificial drainage must weigh trade-offs between increased production and potential increases in P loss. Following roughly four decades of research on P in drainage waters, a solid foundation of knowledge exists on factors controlling the fate and transport of P in artificial drainage. Even so, the site-specific nature of P mobility can confound generalizations regarding P in drainage waters. By the same token, trade-offs associated with drainage must be better documented to inform farmers, action agencies, and watershed management organizations. For instance, trade-offs between greater connectivity of agricultural fields with intensification of tile drainage and lesser contribution of surface runoff to watershed discharge must be better quantified. From this collection of papers, we have identified the following priorities for improving the science, management, and modeling of P in drainage waters.

Knowledge Priorities

- Decisions on whether to intensify drainage require a clear understanding of the trade-offs between P losses in overland flow versus losses in tile or ditch flow. Techniques that discriminate between surface and subsurface sources of P in drainage water are needed to better target management practices.

Management Priorities

- Determining the trade-offs of cover crops on different forms of P loss in artificially drained systems is needed to ensure benefits in particulate P control are not overwhelmed by greater dissolved P losses.
- Quantifying trade-offs of tillage management on P sources and P transport in artificial drainage (no-till, strip till, conventional tillage) is necessary to define the correct mix of practices.
- Developing filters that maintain hydraulic function of drainage systems but remove P (particulate and sediment) that can be widely adopted.
- Irrigation systems need to be developed that minimize P loss to drainage waters.

Modeling Priorities

- Field studies designed to increase our understanding of the mechanisms controlling P fate and transport in artificially drained systems are needed to correctly formulate and parameterize models.
- Watershed- and field-scale models for artificially drained systems must be tested against measured P losses in drainage waters.

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