THE STATE OF THE SCIENCE OF PHOSPHORUS

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THE STATE OF THE SCIENCE OF PHOSPHORUS

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THE ROLE OF PHOSPHORUS MANAGEMENT IN THE GREEN PASTURES AND BLUE WATERS PARADOX

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INTRODUCTION

Recent high profile harmful algal bloom outbreaks and an inability to meet water quality goals and targeted load reductions have increased attention on agriculture's role in contributing phosphorus (P) to surface water impairment and the effectiveness of current and future conservation strategies designed to mitigate such loads. Research on the sources and pathways of P loss predates most of us, yet we still deal with unintended consequences of some conservation measures. To a large extent, these concerns are fueled by a public debate of the wise use of conservation funding, an underlying desire for "quick fixes," and an underestimation of the legacies of prior nutrient management. These problems are not unique to the Chesapeake Bay Watershed nor are our options for future P management. As a result, lessons can be learnt and regional and national research, demonstration, and extension efforts can guide approaches towards sustainable P management and conservation systems.

Until the much publicized occurrences of *Pfiesteria* in the Chesapeake Bay in the mid-1990's, there was a continuing emphasis on managing the land application of manures and compound fertilizers for nitrogen (N) to meet annual plant needs and secondarily to limit nitrate leaching to ground waters. This management philosophy was supported by the 60's school of thought that land application of P was akin to putting money in the bank, and that P was bound to soil and not going *anywhere*, except being there for the next crop or forage plant to take it up. Our knowledge and message that as soils became more saturated with P, P could more be easily released to surface runoff waters or leach through the soil, was not heeded by land managers nor did we properly translate the information to the farming community. The end result, however, was the continued application of manure P at levels greater than crop uptake, increased soil P and consequent risk of off-site movement. However, as recent events in several watersheds across the U.S. highlight, there are many other site, weather, and management factors that influence these losses.

Here, there is a brief description of recent efforts to manage agricultural P in the face of water use impairment for three locations in the U.S., spanning a wide range in scale from the Mississippi River Basin (MRB) to Lake Erie Watershed to the Eucha-Spavinaw Illinois River Watershed in northwest Arkansas. These three efforts illustrate lessons pertinent to current and future P management in the Chesapeake Bay Watershed.

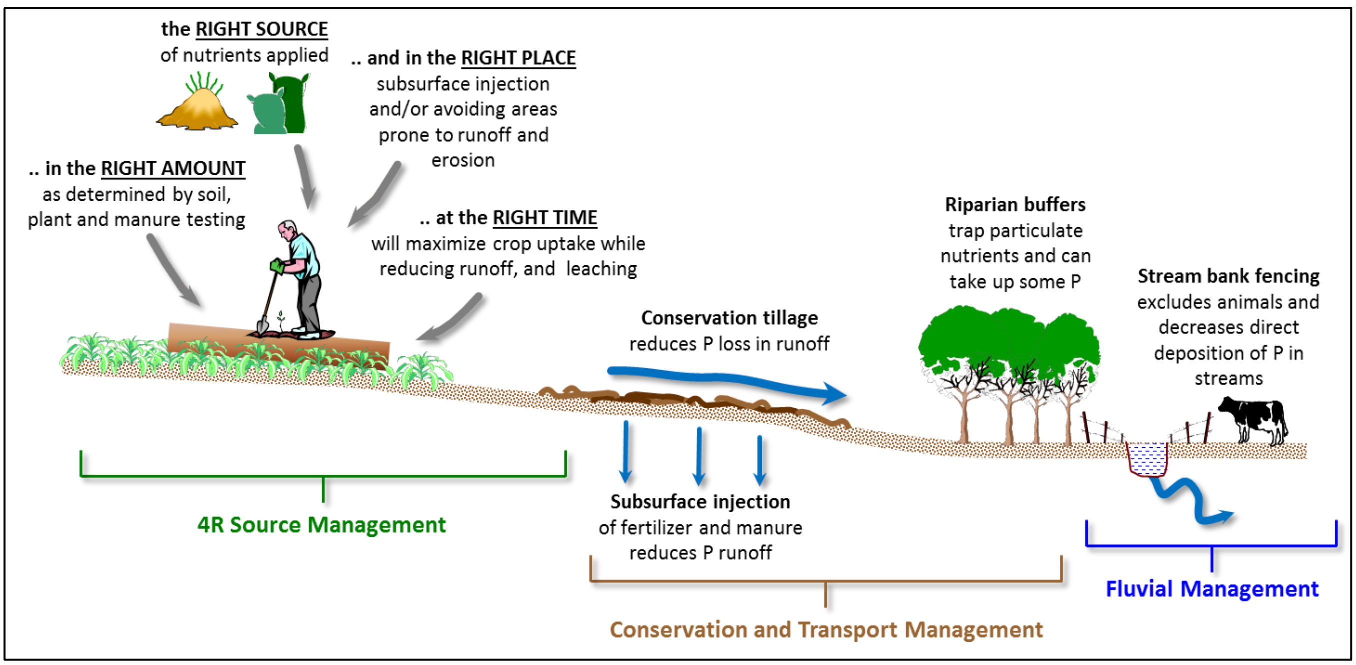

Figure 1. "4R" source management and conservation management of P in agricultural production systems.

MISSISSIPPI RIVER BASIN

The MRB drains 41% of the 48 contiguous U.S. states (or 1,245,000 $miles^2$). Thus, spatially expansive sources of P and the relative contributions of municipalities, industries, and agriculture, create system complexities that should not limit action by any one entity. Recent model estimates (USGS-SPARROW) suggest that up to 85% of the P and N entering the Gulf of Mexico originate from agriculture. While these estimates are based on large-scale modeling within the MRB, there have been few farm-scale studies of P and N loss from agricultural production systems in the Basin. Even so, NRCS used model estimates to prioritize allocation of conservation cost-share funding under the 2009 Healthy Mississippi River Basin Initiative (MRBI; $320 million over 5 years) to 41 of the top contributing 12-digit watersheds in 13 states along the Mississippi River corridor. One unique aspect of this program was the provision for financial incentives to producers to conduct edge-of-field monitoring under NRCS Conservation Practice Standard 201 and 202.

Since MRBI, NRCS has implemented similar initiatives in other watersheds. These initiatives have been very successful in getting conservation systems approaches implemented on a large acreage of agricultural lands to help producers avoid, control, and trap P, N, and sediment and address water quality concerns. However, a transparent framework is needed to document and verify on-the-ground conservation practices to ensure agricultural stakeholders are credited with accurate reductions. This need will only grow in importance and urgency over the coming years, in light of recent litigation against individual farms and farming communities in MRB states of Arkansas, Iowa, Minnesota, and Wisconsin, with the intent of halting perceived source water impairment related to P and N inputs (see Related Reading for additional information).

LAKE ERIE WATERSHED

The richly documented history of Lake Erie water quality, outbreaks of harmful algal blooms and land management in the Lake Erie Watershed over the last 50 years, provides an excellent example of how well-meaning conservation strategies, can result in intended and unintended consequences on P fate and transport within the watershed continuum. Steady declines in P inputs from predominantly agricultural watersheds were measured between 1980 and 1995 with the adoption of best management practices (BMPs) such as increased nutrient management planning (NMP) that reduced fertilizer and manure applications to corn and soybeans and a transition to no-till cropping.

However, increased P inputs from agricultural runoff, mainly in the biologically available dissolved form, over the last decade, have resulted from complex, dynamic, and yet predictable factors. These include the accumulation of P at the soil surface, fall application of fertilizer, continued broadcasting of P, a focus on implementing BMPs for particulate P loss, rapid rise in tile drainage fuelled by higher grain prices, and release and remobilization of fluvial P. For instance, more fields with tile drainage that connect to ditches and streams have increased, contributing source areas of legacy P to Lake Erie. The combination of these factors created a "perfect P loss storm," which along with more intense summer rains increased P inputs to Lake Erie to record levels in 2010, culminating in the 2014 toxic bloom and water crisis in Toledo, OH. However, scientifically valid remedial strategies were not likely to be readily adopted by farmers due to several logistical, practical, and cost limitations. Clearly, the research community needs to work closely with the farming community to generate innovative support, stewardship, reward, and trading program that will empower change.

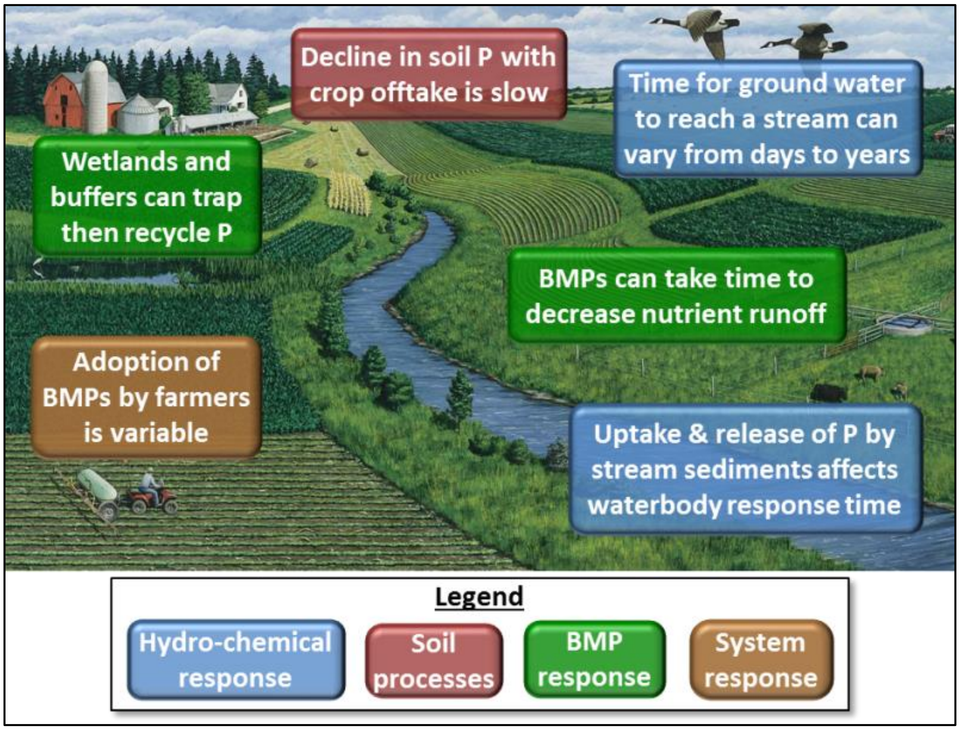

Figure 2. Conceptual representation of legacy P processes.

EUCHA-SPAVINAW AND ILLINOIS RIVER WATERSHEDS

The Eucha-Spavinaw and Illinois River Watersheds (ESIRW) have the unfortunate distinction of having the application of any form of P to agricultural land, tightly litigated. A rapid, five-fold increase in the population in Northwest Arkansas over the last 20 years has coincided with the expansion of confined poultry broiler operations, which now produce over 2 billion birds annually, nearly 25% of the total broiler production in the U.S. In 2001, the City of Tulsa, Oklahoma and in 2004 the Attorney General of Oklahoma filed lawsuits to mitigate the accelerated eutrophication of municipal water supplies and Eucha-Spavinaw reservoirs, and Lake Tahlequah, respectively. As part of settlement for the 2001 lawsuit, in 2004 the Judge mandated the use of a P Index developed specifically for the watershed, required at least a third of the generated litter be exported out of the watershed, and imposed a soil P ceiling for litter application, preventing application to soils with a Mehlich-3 > 300 mg kg^{-1} (see Additional

Reading for litigation and Index information). As part of a court settlement agreement in 2013, this threshold was cut in half, making it much more restrictive: no P can now be applied to soils with a Mehlich-3 > 150 mg kg^{-1}. A decade on from the initial agreement, P management and water quality outcomes provide examples of the intended and unintended consequences of these actions, which are relevant to the Chesapeake Bay Watershed.

Since the required NMP process was set in place, land application of poultry litter has decreased from an average of 2.5 tons ac^{-1} before litigation to 1.2 tons ac^{-1} in 2014. In addition, 80 to 90% of the produced litter has been transported out of the Eucha-Spavinaw Watershed (~75,000 tons $year^{-1}$) and about 40% out of the larger Illinois River Watershed (~100,000 tons $year^{-1}$) since 2006. In other words, a lot less poultry litter is now being applied to pastures, which has greatly reduced the amount and risk of P runoff. As is usually the case, there is a consequence to using so much less litter on pastures in ESRIW, where beef grazing operations have had a symbiotic relationship with poultry operations, using litter as a low-cost source of N and P, allowing a more profitable cattle production than before the chickens came. In fact, the ability to land apply less litter has led to a slow decline in beef herd size and pasture productivity.

Despite initial concerns that restrictions placed by the court case would force poultry growers out of the litigated watersheds, poultry farmers have adapted to the P-based regulations, in part through subsidies supporting manure export. Even with subsidies, a key component of the success of the manure export program are the ties made between the fertilizer industry, particularly distributors, and the livestock industry so that mutual goals are achieved. In order to maintain the economic viability of all farming enterprises, not just the poultry farms, it has become clear that the NMP process must go beyond addressing poultry litter application rates and environmental risk and include educational efforts to help farmers develop sustainable farming operations.

Have all these changes in P and litter use in ESIRW translated in an improvement in water quality? Given that lower point P inputs from wastewater treatment plant upgrades have also occurred in the last 10 years, it is not possible to definitely say yes. Further, annual variations in stream flow, means lower concentrations of P have not led to a statistically significant decrease in annual P flux. However, the implementation of a threshold total P concentration of 0.037 mg L^{-1} as water flows from Arkansas into Oklahoma in the Illinois River, currently dictates the success or failure of water management and conservation efforts. While the 0.037 mg P L^{-1} standard is not yet met on an annual mean flow-weighted basis, concentrations have decreased by a third compared with pre-2003 levels (i.e., 0.29 mg P L^{-1} in 2002 to 0.07 mg P L^{-1} in 2013). Clearly, progress is occurring.

In the three examples given here, there has been little attempt to quantify legacy sources of P from past management practices and to determine their relative contribution to current fluxes of P and the potential of legacy P sources to mask conservation benefits. Thus, this leads us to P management paradoxes.

CONCLUSIONS

Common threads interweave among the examples given, which show the pressures placed on farmers to maximize yields in response to increasing demand for cheap food, feed, and fuel. To a large extent this has occurred through the development and use of fertilizer products. At the same time, there is increased pressure being placed on farmers to be environmental stewards. However, despite a long history of soil and water P research, management questions still exist and water-use impairment continues as a result of P enrichment of soil-water systems.

Thus, we need to accept that current research knowledge should be translated and transferred better to farmers, while at the same time realizing that farm management decisions are largely driven by competitive economics. This leads to four current P paradoxes relevant to this discussion.

1) <u>Blue – green paradox:</u> An increasingly affluent population is becoming more demanding of cheap, reliable food sources and wanting inexpensive clean, safe water for many essential and recreational uses. As we have moved from nutrient management that improves crop production to the environmental quality arena, we face many challenges in balancing competing demands for protecting and restoring water quality and aquatic ecology, with sustainable and efficient agricultural production. It is important to recognize that market prices do not always motivate farmers to manage nutrients in an environmentally sustainable way. Consumers can be given a choice about which products they buy, with premiums paid to farmers who provide more environmentally friendly products. However, after the low hanging fruit of remedial measures are adopted, remaining BMPs become increasingly less cost beneficial and raise the old dilemma "who benefits and who pays?"
2) <u>Conservation legacy P paradox:</u> Many conservation practices have been implemented to trap and retain P on the landscape rather than enter waterways. Yet, the capacity of those practices to retain is finite and there are more and more examples of conservation practices (e.g., buffers, wetlands, reservoirs - Conowingo Dam) transitioning from P sinks to P sources. Research that better quantifies the sinks and sources of nutrients as they are transported through a watershed, and the legacies and

lags from past land use, will help develop realistic expectations for BMP use and the timescales for aquatic ecosystem recovery.

3) Soil health paradox: Many important NRCS initiatives are rightly promoting improved soil health as a major goal of future agricultural management practices. However, some of the claims that improved soil health will stop nutrient runoff and leaching are misguided. For instance, practices such as no-till can lead to a surface accumulation of applied P, which can enrich dissolved P runoff, as well as a greater potential for leaching through intact macropores, unless there is either a concomitant change in fertilizer and manure management or occasional soil destratification.
4) The grain for fuel paradox: With increasing pressures to meet biofuel mandates, 42 and 25% of the corn and soybean grown in the U.S. was used to produce biodiesel in 2012. In some areas, CRP and environmentally sensitive lands were allowed to go back into grain production; large tracts of land have been tiled drained, increasing source areas and connectivity of soils directly to streams and bypassing the soil matrix where P might have otherwise been sorbed; and in other areas crop residue is removed as biomass fuel increasing the potential for runoff and erosion.

Clearly, agricultural P issues facing the Chesapeake Bay Watershed are neither new nor specific to the Bay Watershed and lessons can be gleaned from other remedial efforts in the U.S. This Symposium "The State of the Science of Phosphorus," will highlight some of the P-effective BMPs, where and when on the landscape they would be most effective, and how response to change will occur.

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IMPACT OF PHOSPHORUS ON WATER QUALITY

Walter Boynton, University of Maryland Center for Environmental Science Chesapeake Biological Laboratory, Solomons, Maryland

This presentation summarized the current understanding of the role of phosphorus in estuarine eutrophication, a process largely driven by excess amounts of both phosphorus and nitrogen entering these ecosystems. Relatively simple conceptual models have been developed to capture the various water and habitat quality impacts of nutrient enrichment. More recently, strong feedback mechanisms have been identified wherein ecosystem health can change rapidly when these feedback systems come into play. In the case of phosphorus in aquatic ecosystems, low dissolved oxygen conditions, elevated water pH and salinity all play a role enhancing phosphorus mobilization from sediments. Field and laboratory studies and simulation modeling all indicate rapid phosphorus responses to changing environmental conditions and a longer "system memory" for phosphorus than for nitrogen.

Key points:

- The basic model of nutrient enrichment and restoration is solid…stay with it!
- The Duel Nutrient reduction strategy is sound…both Phosphorus and Nitrogen play powerful roles in Bay water and habitat quality
- Substantial reductions of Nitrogen and Phosphorus result in improved water quality and better habitat conditions

- The pathways estuaries follow during degradation and restoration often involve time delays (lags), abrupt changes (thresholds) and other things not yet known or fully understood

- Restoration trends (and hints of trends) have been observed in both small and large Chesapeake systems…very good signs!

AGRICULTURAL PHOSPHORUS SOURCES – THE OBVIOUS AND THE OBSCURE

Pete Kleinman, USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania and Doug Beegle, Penn State University

The persistence of agricultural phosphorus management concerns can be attributed to many causes, but, at its core, is the product of fundamental processes that are often undeterred by conventional conservation practices. When viewed through the lens of agricultural development, or basic soil fertility management, phosphorus can be seen as a limiting macronutrient that is so inherently sticky in nature that large amounts are needed just to overwhelm the basic buffering capacity of soils. Indeed, the majority of our soils still need to be approached with this perspective in order to ensure that our crop production keeps track with demand. It is from this perspective that the quantity-intensity relationship was first understood: for every unit of phosphorus that we hope to reside in the soil solution (where crops can readily access it), at least ten times that amount must be sacrificed to the various binding agents in soils. All food, organic or conventional, owes its phosphorus to our ability to overcome the fundamental inequality of phosphorus chemistry. Indeed, overcoming this inequality is at the foundation of our civilization, regardless of whether it is recognized by society.

It is therefore not surprising that many of us were educated with the generalization that the water quality problems of phosphorus stem from erosion – the single largest reserve of phosphorus in our landscapes is that which resides in soils. Conserve the soil and one prevents phosphorus from running off of our lands. To a large extent, this generalization remains true. However, a closer inspection of phosphorus in soils reveals complexity in its distribution that readily roasts old chestnuts. Phosphorus is most concentrated in the finest particles of soils, those with the greatest surface area and most prone to erosion. These particles are increasingly selected as erosion is controlled, a phenomenon known as phosphorus enrichment. Improve soil conservation and the sediment that does erode is more concentrated with phosphorus than the sediment that dislodges from poorly conserved soils. Go figure.

Most vexing is the problem of dissolved phosphorus release to runoff. Here, focusing on the “intensity” component of quantity-intensity relationships offers perspective, and hope, in management. At its simplest, the more phosphorus in the soil the greater the concentration in runoff. This can be described with new “environmental” soil tests or with old fashioned agronomic tests. Although agronomic tests tend to offer sufficient perspective into soil sources of P, the concept of soil phosphorus saturation can be an important educational device that may even be estimated from existing sources of data without requiring new expense.

Soils are three dimensional resources that must be managed accordingly. Vertical stratification, i.e., the accumulation of phosphorus in a thin veneer at the soil surface, occurs so readily that it can be observed over just a few crop rotations under the right conditions. As a result, standard soil testing protocols are prone to underestimating the edaphic sources that are available to runoff waters. Furthermore, in the wrong location, a small amount of soil phosphorus will enrich runoff waters with every event. When phosphorus leaching is a concern, this may mean that low concentrations at deeper depths, too deep to manage and too low to be of normal concern, can be a source.

The fact that many of our greatest watershed phosphorus concerns are tied to areas of intensive livestock production and land application of manure is no coincidence. While manures may enrich soils and indirectly contribute to runoff concerns of soil phosphorus release, they may also contribute directly to runoff, particularly over the short term. “Wash off” or “incidental transfer” of manure phosphorus is related to many factors, including the inherent concentration and form of phosphorus in manure. Great strides have been made in lowering manure P concentrations for all livestock, arising from feed additives and formulations. However, these advances have not necessarily transferred to hobby and equine operations, which account for a substantial quantity of the manure produced in the Chesapeake Region (almost 10% of the manure dry matter in the watershed derives from horses). Adjusting the solubility of phosphorus in manure has proven to be productive, particularly with poultry where it can be tied to ammonia management in barns.

Manures do not only have to be brown. One of the least appreciated sources of phosphorus is vegetation. When plants senesce or are killed with herbicides, they release dissolved phosphorus from their cells that can enrich runoff water. Case studies from Scandinavia to Ohio raise concern with dissolved phosphorus from cover crops. But cover crops help to conserve soils and capture soil nitrate. Considering these trade-offs, particularly in areas where dissolved phosphorus is a primary concern to water quality, is a challenge that must not be taken lightly.

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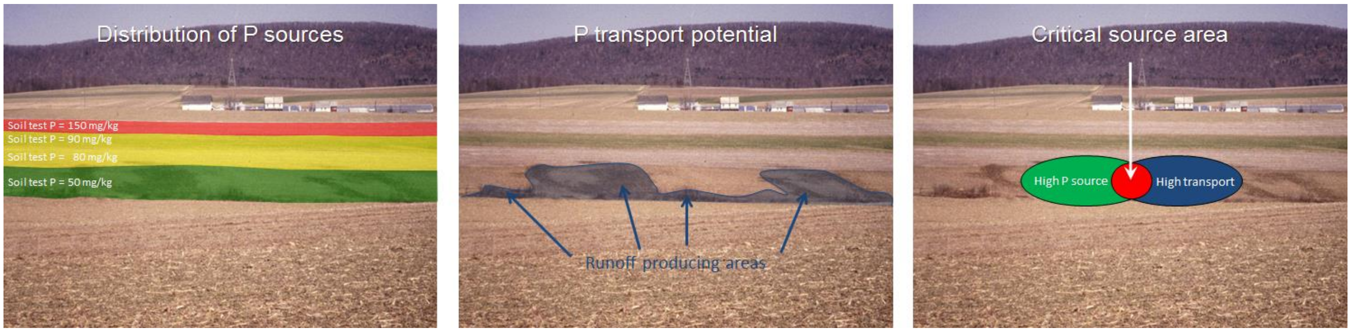
THE ROLE OF HYDROLOGY IN CONNECTING AGRICULTURAL PHOSPHORUS SOURCES TO SURFACE WATER

Anthony R. Buda, Research Hydrologist, USDA - Agricultural Research Service, Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania

Minimizing the risk of phosphorus (P) loss from land to water represents one of the most important priorities of nutrient management in the Chesapeake Bay watershed. Simply put, for P to pose a water quality problem, there must be a source of P that can readily be connected to surface water by hydrologic transport processes. Areas with high P sources that lack hydrological connectivity do not typically constitute a water quality risk. By the same token, areas with high hydrological connectivity that do not link to high P sources also pose little threat. While the role of hydrological connectivity in P loss is simple to articulate, uncertainty arises when we try to observe the hydrological processes and landscape features linking P sources to receiving waters, to model and represent these processes in risk assessment tools, and to control them with targeted management measures. Indeed, recognizing and addressing these uncertainties is central to advancing the science of P management across the Chesapeake Bay watershed.

The critical source area concept is perhaps the most recognizable illustration of how hydrological connectivity has been incorporated into P management, most notably the P Index. The critical source area concept posits that areas of the landscape posing the greatest risk to P loss are those where high P sources and high transport potential coincide (as shown below).



In upland areas of the Bay watershed, variable source area hydrology dominates such that small areas of watersheds are responsible for the majority of surface runoff. These runoff generating zones, typically found near streams and in lower landscape positions, expand and contract during storms and over seasons as a result of interactions between ground and surface water, storm characteristics, and soil properties. It is from this perspective that distance to receiving water has oft been viewed as one of the best proxies for hydrological connectivity in nutrient management.

While the greatest risk of P loss in upland regions is usually confined to variable source areas near streams, a host of hydrological processes can modify and enhance hydrological connectivity, thus activating distant P source areas that otherwise would not normally contribute to P loss in agricultural watersheds. Chief among these are preferential flow pathways, including macropores, soil pipes, and fractures, as well as shallow lateral flows induced by the presence of soil or bedrock confining layers. While digital soil mapping, near-surface geophysics, and tracer studies can offer insight into the spatial arrangement and extent of preferential flow paths, the activation of these pathways in time and space remains dynamic and threshold-dependent (e.g., affected by variable rainfall characteristics and antecedent conditions), which complicates our ability to adequately represent these flow paths in P risk assessment tools. Even when we have good knowledge of preferential flow networks and their hydrological behavior, determining whether they are linked to P source areas is often hindered by fact that P sources (edaphic and applied) are rarely, if ever, mapped in detail across agricultural landscapes.

Farm infrastructure and daily farming activities also play a role in shaping the hydrological connectivity of agricultural landscapes. For example, impervious surfaces such as barnyards, roads, and roofs can rapidly generate stormwater runoff and connect P sources on the farm with nearby receiving waters. This problem may be especially acute in areas where farms are intensifying operations by adding significant infrastructure. Soil compaction by heavy farm machinery and animal activity, as well as practices that orient soil roughness features parallel with topographic slope (e.g., the direction of plowing and cropping patterns) also create concentrated flow pathways that increase the risk of P loss. Animal heavy-use areas, including streamside dairy and beef cattle loafing areas, offer a notable example of how compacted soils and high P sources combine to produce a significant risk of P loss in concentrated runoff. While some success has been achieved in applying filters with P sorbing materials to remove P from stormwater generated in loafing areas, low hanging fruit such as improved water management on the farm may be the best long-term strategy to reducing offsite P losses in barnyard runoff.

Artificial drainage represents an area of heightened concern with regard to hydrological connectivity and P loss, particularly on the flat, poorly-drained soils of the Delmarva Peninsula. Here, networks of open ditches, and to a lesser extent, buried tiles lines, are commonly used to drain fields for crop production. In many cases, fields on the Delmarva Peninsula possess soil P levels well in excess of crop requirements. Recent evidence highlights the importance of macropores and soil cracks as conduits for preferential flow, allowing P from surface soils to leach to shallow groundwater, where it can then move laterally to nearby ditches or streams. At present, most water quality simulation models are ill equipped to simulate these shallow preferential flow pathways, pointing to the need for new experiments that provide insight into P contributing areas and hydrological connectivity in near-ditch zones. At the watershed scale, determining the intensity of artificial drainage (depth and spacing) is critical to assessing the connectedness of the landscape and its capacity for delivering P to surface waters. Unfortunately, information on the geometry and spatial patterns of field-scale artificial drainage networks are rarely mapped, precluding our ability to reliably capture this risk in P site assessment tools.

Looking to the future, we would be remiss to ignore the fact that hydrological connectivity affects and is affected by changes that occur well beyond the farm or small watershed scales that dominate our P management concerns. One such example is the Conowingo Dam, which has served to trap P-rich sediments in the Susquehanna River for the past 85 years, thereby reducing downstream losses of particulate P to the Bay. As the capacity of the dam has been reached, particulate P losses have begun to trend upward again, particularly during large storm events, suggesting that the pool of legacy P stored in sediments behind the dam will once again be reconnected with the Chesapeake Bay. Projected changes in climate also portend potential changes in hydrological connectivity throughout the Bay watershed as extreme storms, shifting rainfall patterns and intensities, and longer dry spells alter the hydrological processes that mobilize and transport P. Short and long-term hydroclimatic forecasting tools will be needed to help farmers and nutrient managers anticipate changes in hydrological connectivity that increase the risk of incidental and chronic P losses in runoff, and adapt their management accordingly.

ADDITIONAL READING

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CURRENT COMPUTER MODELS FOR AGRICULTURAL PHOSPHORUS MANAGEMENT

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INTRODUCTION

Since the 1970's, non-point pollution of surface waters by agricultural P has been studied to understand interactions between land management and natural hydrology and biogeochemistry processes. The number of possible interactions that deserve study are far more than what can be physically measured given our typical time and resources limits. Computer models have been developed to simulate interactions that cannot be studied and to predict P loss for future management and weather scenarios. Now, models are frequently used to assess P loss in the absence of measured data. Models are also important because they force us to formalize and test our understanding of P loss processes, and identify knowledge and data gaps. Given the role that models are playing in P research and management decisions, we need to be sure they are up to date with the science, are well tested and proven, and can be improved in the future.

MODEL TYPES

There are many models that predict P loss at the field edge, transport through a stream or drainage network, and delivery to surface waters. Some models are simple and simulate only edge-of-field P loss, while others are very complex and simulate very large watersheds. Models can differ widely in how they calculate P loss, how they represent physical and management differences in the landscape, whether they simulate single storms or weather across many years, and whether they simulate changes with time or long-term, average conditions.

On one end of the modeling spectrum are simple, user-friendly P Indexes. P Indexes are generally tables of rules or guidelines that assess the average risk of P loss from a single field. They assess P loss risk based on P sources (soil P, fertilizer, and manure), and transport processes (erosion and runoff). Only a few studies have used measured P loss data to test if P Index output is reliable, while other studies have identified short-comings of P Indexes. The P Index is best at showing land managers if certain practices will increase or decrease P loss, but may not accurately quantify the magnitude of P loss. Also, most P Indexes deliver a relative risk of P loss but cannot predict water quality beyond the field edge.

There are a few examples of field-scale models that have the user-friendly approach of a P Index but use process-based equations to quantify edge-of-field P loss. These include the Annual Phosphorus Loss Estimator (APLE), the Wisconsin P Index, the PPM model from Oklahoma, and the TBET model in Texas. These models quantify P loss from sediment bound and dissolved P in runoff at the field edge, but may not simulate management practices outside of the field. These models have generally been better tested than P Indexes because their output can be directly compared to measured P loss data.

Beyond these user-friendly examples, P loss models are typically much more complex and difficult to operate. More complex models like EPIC, APEX, GLEAMS, and IFSM use similar equation as simpler models like APLE, but can simulate more processes and can operate at the farm or small watershed scale. To quantify the impacts of P loss at larger scales or to assess management implemented outside of fields, watershed scale models such as SWAT or HSPF are necessary. Watershed scale modeling is substantially more complex and challenging. Significant experience is needed, and models need to be calibrated, which requires a lot monitoring data to compare with model output. Because these complex models can be calibrated to agree with measured P loss data, it may seem like they correctly simulate P transport and fate processes. However, because watershed models have many parameters that can be adjusted, it is easy to get the "right" answer for the "wrong" reasons. Therefore, it can be difficult to accurately assess the real effects of management practices, especially those that require specific landscape positioning to be effective. Instead, current watershed models are best for assessing impacts of large-scale changes (e.g., conversion from corn to alfalfa, or changes in P application rates), but may not be appropriate to determine what practices to implement at the field scale to reduce P loss or to assess practices that require specific locations in the landscape.

MODEL APPLICATIONS AND SHORTCOMINGS

The 10 points below can help guide someone to know which model to use or if model output is reliable. Important model characteristics include:

1) Does the model accurately represent true P loss and reductions?
2) Does the model operate at an appropriate scale and resolution?
3) Can the model simulate local conditions and agricultural practices?
4) Do model data requirements match availability?
5) Are model sensitivity and uncertainty appropriate relative to the magnitude of desired P loss reduction?
6) Does the model represent current science, and has it been well developed and tested?
7) Does the model deliver information in the units and on a timescale needed?
8) Is model user-friendly enough and will it give consistent results across multiple users for the same scenarios? Is the model practical and economical to set up and apply?

9) Is the model transparent enough so model equations are understandable and simulations can be followed?
10) Does the model have adequate support to be applied and updated as needed?

No single model may meet all of these criteria, and a model user will have to decide which ones are absolutely critical. Also, while a model may appear to meet certain criteria, it may not do it very well. Failure to meet many of the criteria may mean a particular model should not be used or needs to be improved. Failure of most available models to consistently meet criteria may mean a whole new modeling approach is needed.

Models can always be improved, and weaknesses should not necessarily prevent a model's use, especially because using a model is one of the best ways to learn how to improve it. If model weaknesses are understood, then a P loss program can be designed to account for them. Weaknesses are understood by knowing how models work, their equations and algorithms, and not just how to make them run and give output. While this is obvious, some models can be so complex that it is difficult for anyone except a model developer to know how they work. This is truer for watershed models than field models. In such cases, it is up to developers to communicate how models work, and their strengths and weaknesses. However, it is up to model users to know how reliable their models are.

Below is a discussion about principles of model development and function, which can help show what kinds of errors models have. There are four areas of model development:

1) The perceptual model, which is our understanding of how a system behaves.
2) The conceptual model, which is the mathematical equations used to describe the system.
3) The procedural model, which is how equations are written into computer code.

4) Model calibration and validation, which is how we test how well a model works.

Model errors can exist in all four areas. A poor ***perceptual model*** may be when we do not understand what controls P fate and transport, or what we think controls them is not correct. Even when a P model is perceptually correct, the way it is translated into equations, or the ***conceptual model***, can be incorrect, perhaps because of a lack of data or modeler inexperience. This may be true of P Indexes. Also, mathematical equations may be used differently in different models, giving rise to errors in the ***procedural model***. This can happen if model developers understand an equation differently or have to make it fit differently into an existing model. This can make two models give different predictions for the same scenario. Finally, how we decide to run and test a model in ***calibration and validation*** can determine how well we think it performs and expose or hide model weaknesses. Testing a model with limited data over short periods or few scenarios may not show its weaknesses. Models that have too many errors should be avoided, even though they are advertised as robust and dependable. Some priorities for model improvement include:

1) Current models are better at field scale than watershed scale P loss predictions, especially for fast, affordable estimates that minimize the expertise and resources needed to run the models. Linking field practices to watershed outlet impacts is at the edge of scientific understanding, but remains a priority for P modeling.
2) The translation of science into models often lags years and even decades behind current scientific understanding. Some model weaknesses can be readily and rapidly improved by addressing this situation.
3) The computing foundation of many P loss models has not been updated for 20+ years. Model formats need to be kept up to date with computing technology,

including spatial and online possibilities, and user-friendly interfaces. However, fancy technology does not improve a model's accuracy.

4) Other specific model improvements include:

   a. Runoff: Alternatives to the Curve Number approach should be developed and implemented (e.g. TOPMODEL).
   b. Erosion: Improvements to the USLE family of models are needed.
   c. In-stream processes: Better nutrient cycling and especially sediment transport predictions are needed.
   d. Nutrient cycling in soil is generally well simulated, but incremental improvements can be made, especially to reflect technology changes in farm management and scientific understanding.
   e. Estimates of uncertainty are needed for full confidence in model predictions.

Current efforts to establish policies and make management decisions require being able to predict P loss at field to watershed scales. The best way for model development to proceed is through interdisciplinary collaborations and communication between experimentalists, model developers, and model users. An interconnected framework of experimentation and model development should advance agricultural P management and environmental protection beyond what the two proceeding alone can achieve.

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LEGACY PHOSPHORUS

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In recent years, phosphorus (P) loadings have led to eutrophication of water bodies such as Lake Erie and Chesapeake Bay. Since the 1980's, great efforts have been made to decrease sediment, and many thought by proxy the P to these waters. In the case of Lake Erie, total P loads have declined since the 1980's while soluble P showed an initial decline over this period. However, in the mid-1990's soluble P began to increase again.

The lack of improved water quality may be in part due to legacy P (Jarvie et al., 2013; Sharpley et al., 2013), defined as that P that has accumulated in soils, water, or sediments within a watershed. Much of the P within an agricultural landscape can be considered legacy P until it is removed from the watershed through crop or meat production or removed hydrologically in water or sediment.

Many conservation programs within watersheds have been implemented with short term monitoring programs (i.e. 2-5 years), often with no discernable differences between the pre- and post-conservation implementation periods. This can be in part due to lag times in P transport (Meals et al., 2010). Lag times depend upon the source of P (i.e. direct deposit of animal manure to a stream versus residual high soil test P, STP), the pathway (surface runoff versus groundwater transport), the distance the conservation activities occur from the monitoring point and the scale of the monitoring (field versus large watershed).

Legacy P in soil includes the fraction in excess of what is necessary for crop production. In many regions where animal production has occurred, the chronic application of manures at waste disposal rates as opposed to agronomic rates has led to very high STP levels. The area around manure storage facilities can also be highly elevated in STP. Phosphorus release from soils can be related to the ratio of P to iron plus aluminum (Maguire and Sims, 2002), referred to as the P sorption ratio, degree of P saturation (DPS) or P saturation ratio (PSR). Initially, P release from soils should be relatively low, until the PSR exceeds 20-25%, at which time a change point occurs and much greater P losses can occur. Drawdown strategies can reduce the STP levels to an agronomically acceptable range if P applications are ceased; however, this can take from several years to decades.

Groundwater P concentrations sufficient to induce eutrophication have been observed on the eastern shore of Maryland (Kleinman et al., 2007). Groundwater residence times in the Chesapeake Bay can range from months to decades (Phillips and Lindsey, 2003). Unless practices are designed to intercept and treat this source (i.e. Penn et al., 2007), groundwater may continue to mask the water quality benefits of other practices for the decades to come.

Stream and ditch sediments are also known to serve as a source or a sink for P in the water, although this source is often ignored. For example, P related water quality problems were being blamed solely on the poultry industry. However, one study showed waste water treatment plants were not adequately treating effluent for P and that one such plant was discharging sufficient P to saturate the stream sediments and elevate stream P concentrations 30 km downstream (Haggard et al., 2001). With P saturated sediments in the streams or lakes, it may take years to remove enough P to return the stream water quality to an acceptable level. In another example, a hurricane in North Carolina resulted in swine lagoons flooding, which saturated stream sediments with P. Two months after the lagoon breech, P concentrations in the affected river were an order of magnitude higher than samples collected upstream of the affected reach (Burkholder et al., 1997), which further illustrates the importance of sediments as a P source.

In artificially drained landscapes, drainage districts are obligated to ensure adequate drainage throughout the land base in their region. One of the practices employed by drainage districts to ensure adequate drainage has been dredging or dipping agricultural ditches. This process has been shown to affect nutrient transport within the ditch networks (Smith et al., 2006). In Indiana and Ohio, immediately after dredging, the sediments in the ditch bottom were less able to remove P from the water column than prior to dredging. However, after a few months and up to a year after dredging, a dredged drainage ditch in Indiana was able to remove P from the water such that there was a decrease in the P mass as it passed through this 3 mile reach (Smith and Huang, 2010). P removed by the ditch and contained in its sediment in that study would be considered legacy P. Generally, sediments or spoils dredged from ditches are left on the ditch banks or spread in adjacent fields. These spoils can contain hundreds or thousands of pounds of P, which is potentially available for transport back into the ditch network unless removed from the watershed.

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AGRICULTURAL BEST MANAGEMENT PRACTICES TO MINIMIZE PHOSPHORUS LOSS

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The Chesapeake Bay Model identifies agriculture as the leading source of phosphorus (P) to the Chesapeake Bay (USEPA, 2015). This has led to considerable investment in policies and practices to reduce agricultural P loading. Much of the discussion has focused on local P imbalances and ways to increase P use efficiency. However, increases in P recovery efficiency are not likely to result in reduced P loading to surface water – particularly in the short term. Improving agricultural P recovery efficiencies might help avoid future legacy P losses that result from elevated soil P concentrations. However, meeting short term water quality objectives will also require a holistic approach that aims to interrupt the field to water transport continuum by targeting P management practices and conservation measures to site-specific P sources and transport conditions.

Site characteristics including hydrology, soil characteristics, and manmade features (e.g. tile drainage, ditching, terracing) combine with P source (e.g. fertilizer, manure, soil P) to determine the potential for P loss from an agricultural field. Phosphorus management must aim to maximize crop uptake and soil storage of applied P, while minimizing P exposed to transport processes. One example of a management practice that might limit P loss and increase P use efficiency is the use of starter fertilizer banded below the soil surface. In this situation the quantity-intensity relationship that controls P availability to crops is manipulated by placing less total P in a concentrated band, thereby limiting fertilizer exposure to soil sorption processes. However, there are many examples in the literature where management impacts P loss independently of P use efficiency (Daverede et al., 2003, 2004; Buda et al., 2009; Kaiser et al., 2009; McGrath et al., 2010). In most situations management reduces P loss by decreasing the exposure of a source to transport processes or directly interrupts transport pathways, while having little effect on P use efficiency. Examples include incorporation or direct injection of P fertilizer sources (inorganic and organic), tillage to dilute surface soil P concentrations, or maintaining soil cover to minimize soil-water interaction.

Repeated P applications beyond crop removal can result in elevated soil P concentrations. This "legacy" P source can be particularly difficult to manage, especially in areas with high hydrologic connectivity to surface water. Strategies should focus on minimizing water export and reducing P concentrations in runoff and drainage water. Practices such as drainage control (in tile or ditch drains), land-application of P sorbing materials, or direct removal of P from drainage waters using treatment structures can help meet short-term water quality goals (Penn and Bryant, 2006; Grubb et al., 2011; Buda et al., 2012; Penn and McGrath, 2014; Penn et al., 2014) Over the long-term, continuous crop production can remediate high soil P concentrations, however, this can take decades or longer in many situations.

The 4R Nutrient Stewardship approach (The Fertilizer Institute, 2015) provides a framework for implementing practices to meet multiple performance objectives. It centers on the use of the right rate, right timing, right source, and right placement of nutrients and management practices. However, it is important to keep in mind that in agriculture there is often a push pull relationship between multiple objectives. For example, often the highest net profits are realized when some nutrients are discharged to the environment, particularly in areas with concentrated livestock production. Furthermore, spatial and temporal variability in management practice effectiveness demands a site-specific approach to implementation. These tradeoffs, along with uncertainty surround practice efficacy must be weighed in the context of multiple, competing performance objectives when developing management strategies that optimize crop production and minimize P loss to surface water.

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IMPLEMENTATION OF AGRICULTURAL PHOSPHORUS MANAGEMENT POLICY IN MARYLAND

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For decades, it has been recognized that many surface waters in Maryland are impaired by excessive inputs of nutrients. Inputs of both nitrogen (N) and phosphorus (P) have stimulated algal growth in the degraded waters, thus decreasing water clarity and depleting dissolved oxygen levels. Both N and P contribute to water quality impairment, with freshwater systems being particularly sensitive to P inputs. Currently, data from water quality monitoring programs combined with assessment of the sources of nutrient inputs have identified drainage from agricultural landscapes as the largest source of P inputs to the Chesapeake Bay.

Based on the U.S. EPA Chesapeake Bay Program watershed models, P input to the Chesapeake Bay from municipal wastewater treatment has declined by 70% since 1985. Today, according to Chesapeake Bay Program models, wastewater discharge now accounts for 18% of the P that enters the Chesapeake Bay as a result of human activities and is roughly equal to the P loading from urban storm water runoff (19%). Over the same time period, P inputs from agricultural sources also have been reduced, but at a much slower rate (6% reduction) and, currently, the Chesapeake Bay Program models attribute 64% of the human-influenced P that enters the Chesapeake Bay as originating from agricultural landscapes.

Beginning in the late 1980's, the State of Maryland adopted various policies and developed voluntary agricultural nutrient management programs aimed at reducing P loading of surface waters. In swift response to a popularized Chesapeake Bay fish kill during the summer of 1997 that was attributed to the suspected nutrient-stimulated toxicity of the dinoflagellate *Pfiesteria piscicida*, the State of Maryland passed the Water Quality Improvement Act of 1998, which phased in mandatory N and P-based nutrient management planning regulations for Maryland farmers. The P management provisions of these aggressive regulations were fully implemented by 2005.

In an effort to further alleviate water quality impairments and accelerate reductions of P inputs to the Chesapeake Bay from agricultural sources, President Obama issued Executive Order 13508 in May 2009 that declared the Chesapeake Bay a “national treasure” and ushered in a new era of federal oversight and accountability. In 2010, under the existing provisions of the Federal Clean Water Act of 1992, the U.S. EPA developed Total Maximum Daily Load (TMDL) limits for P entering the Chesapeake Bay. The Chesapeake Bay TMDL prescribed the amount of P input that can be tolerated by the Bay ecosystem and not result in impaired water quality. A 2025 deadline was established by which time each of the Chesapeake Bay watershed states was legally obligated to achieve the TMDL P load reductions necessary to alleviate water quality impairments. By 2025, total P loading to the Chesapeake Bay must be less than 14.5 million pounds P/year and P loading from Maryland’s tributaries to the Chesapeake Bay must be no greater than 2.8 million pounds P/year. The TMDL implementation plan allows for half of Maryland’s total load, or 1.4 million pounds P/year, to originate from agricultural sources. In order to achieve the 2025 TMDL mandate, overall P loading from Maryland tributaries will need to be reduced by 15% and P loading from agricultural sources will need to be reduced by 12%, relative to today’s estimated loading rates.

Phosphorus in eroded sediments, runoff water and subsurface drainage is a function of the concentrations and forms of P present in the soil, the type of soil, field management, and hydrologic connectivity. While Maryland soils do have a large capacity to retain P, at some point a specific soil’s P retention capacity may become saturated and dissolved P losses with field drainage water may rapidly increase. Assessment of all potential P sources, including newly applied P, residual soil P and long-term legacy P, and evaluation of off-field transport pathways are essential elements of a comprehensive P management strategy.

In 1994, research began on the development of a tool designed to identify site-specific risk for P loss from farm fields and provide guidance for adoption of management practices to reduce the risk for P loss. The resulting risk assessment tool was tailored to Maryland's soils, agricultural management practices, climate, topography, and hydrology. Phosphorus loss risk assessment tools have been implemented widely in Maryland's agricultural nutrient management planning process since 2000 and have been revised, updated and improved along the way, most notably in 2005 and 2013. The current version, the Phosphorus Management Tool (PMT), has incorporated the most reliable science into a method that has improved the ability to identify sites for potential P losses from the agricultural landscape and identify targeted management practices for mitigating P loss.

The science of P dynamics in the agro-ecosystem will continue to evolve. Undoubtedly, new and refined field management practices will be developed to help minimize P losses from agricultural production systems. In some specific locations where P losses are particularly egregious due to combinations of past management, elevated legacy P concentrations, and accelerated hydrologic connectivity, adjustment of current field management practices may not be sufficient to result in a significant reduction in P losses. In such cases, active remediation techniques such as purposeful crop drawdown of soil P reserves, chemical immobilization of soil P, installation of P trapping filters in drainage ditches, and intensified drainage water management may be required to reduce P losses from identified high risk sites.

BIOGRAPHIES

Dr. Walter Boynton, University of Maryland Center for Environmental Science

Dr. Walter Boynton is a Professor at the Chesapeake Biological laboratory (CBL), University of Maryland Center for Environmental Science and has been a faculty member at CBL since 1975. Boynton's research expertise is estuarine ecology, particularly issues related to eutrophication and ecosystem restoration. He has published over 100 scientific papers and many more technical reports related to water quality, habitat and restoration issues. Dr. Boynton currently has funding from Sea Grant, Maryland Department of Natural Resources, Maryland County and city government and the National Science Foundation. All of this research involves coastal and estuarine eutrophication and restoration of these ecosystems. Dr. Boynton serves on boards of the Patuxent Riverkeeper, the Maryland-DC Chapter of The Nature Conservancy and the Patuxent River Commission. He has served on several EPA Science Advisory Board panels reviewing the state of the hypoxic zone in the Gulf of Mexico, Florida nutrient criteria, an EPA workgroup developing national water quality standards for estuarine systems and, more recently, worked with the Department of Justice on Gulf of Mexico issues. He served on Maryland Governor O'Malley's transition team for environmental issues and is currently a member of the science advisory panel for the Chesapeake Bay Trust Fund. He was awarded the Odum Award for Lifetime Achievement from the Coastal and Estuarine Research Federation and was elected president of this scientific society. More locally, he served as the vice-chair of the Calvert County Zoning Appeals Board for more than a decade and in this position has been involved in many Maryland Critical Area decisions. He teaches a graduate ecology course and seminar that ties together the ecosystems of Maryland from the western mountains to the coastal ocean.

Dr. Anthony Buda, USDA Agricultural Research Service

Dr. Anthony Buda is a hydrologist with the USDA Agricultural Research Service (ARS) Pasture Systems and Watershed Management Research Unit (PSWMRU) in University Park, PA. He joined the unit in 2007 after receiving a PhD in Forest Hydrology from Penn State University. Dr. Buda works collaboratively with teams of physical, natural, and social scientists to address critical water resource challenges facing agriculture. His field research program applies a variety of tools, including conservative hydrologic tracers, near-surface geophysics, and hydrometric monitoring, to understand factors connecting nutrient sources on the landscape with surface water and groundwater. He works with action agencies and farmers to develop decision support tools for nutrient management, most notably the Fertilizer Forecaster, which leverages hydrologic modeling and weather forecasting to guide daily decisions by farmers on the timing and placement of nutrients. He also conducts research to understand how changes in land management and climate impact hydrology and water quality in agricultural watersheds. Dr. Buda serves on the editorial board of Soil Science Society of America Journal, and has received research recognitions from the American Society of Agronomy, Soil Science Society of America, American Water Resources Association, and USDA's North Atlantic Area.

Dr. Frank Coale, University of Maryland

Dr. Frank J. Coale is Professor and Extension Specialist for agricultural nutrient management in the Department of Environmental Science & Technology at the University of Maryland. Dr. Coale also serves as Director of the Gemstone Honors Program in the Honors College at the University of Maryland. The Gemstone Honors Program is a unique and prestigious multidisciplinary four-year research experience for selected undergraduate Honors students of all majors. Dr. Coale received his B.S. degree in Agronomy from the University of Maryland and his Masters' degree in Crop Physiology and his Ph.D. in Soil Fertility and Plant Nutrition from the University of Kentucky. After 7 years on the faculty at the University of Florida, Dr. Coale joined the faculty at the University of Maryland in 1993. His research and extension programs concentrate on efficient agronomic and environmental management of applied nutrients and nutrient management policy development in the Chesapeake Bay watershed. Dr. Coale has published 50 refereed journal articles and 167 Extension publications. He has delivered nearly 200 scientific presentations with published abstracts and has given over 500 Extension Education presentations. Dr. Coale has mentored 31 graduate students and has supported his programs with over $15 million in external grant funding. Dr. Coale served as Chair of the Department of Environmental Science and Technology at the University of Maryland for six years. He has received recognition awards for his contributions from his university, the State of Maryland, and federal agencies. Dr. Coale is Fellow of the American Society of Agronomy (2012) and Fellow of the Soil Science Society of America (2014).

Dr. Peter Kleinman, USDA Agricultural Research Service

Dr. Peter Kleinman is a soil scientist with USDA's Agricultural Research Service and the research leader of the Pasture Systems and Watershed Management Research Unit in State College, PA. He obtained his PhD from Cornell University in 1998. His research aims provides tools to farmers, resource managers and policymakers to improve the stewardship of nutrients in agriculture. He has worked to advance the Phosphorus Index and other decision support tools, including the Fertilizer Forecaster which provides daily forecasts of when and where to apply nutrients. He has spear-headed efforts to bring new manure application technologies to farmers, from liquid manure injectors to dry manure applicators. He and his team have developed new filtration technologies to remove phosphorus from manures and from runoff waters. He leads and advocates for collaborative, consensus based science at regional, national and international scales. He has learned that, as a scientist and as an advisor to watershed and farming programs, conveying the trade-offs of management options is more important than promoting any single approach. He is a recent member of the Chesapeake Bay Program's Science and Technology Committee. He is a fellow of the Soil and Water Conservation Society, American Society of Agronomy and Soil Science Society of America, serves on the editorial boards of Journal of Environmental Quality and Journal of Soil and Water Conservation.

Dr. Joshua McGrath, University of Kentucky

Dr. Josh McGrath joined the Department of Plant and Soil Sciences, University of Kentucky as Associate Professor and Soil Management Specialist in July of 2014. Dr. McGrath's research and extension activities focus on agricultural productivity and environmental quality as they relate to soil fertility, nutrient management, and water quality. He has published and conducted research on in-situ treatment of agricultural drainage; sensor-based variable-rate nitrogen; manure management in no-till; manure storage to reduce nutrient losses; environmental persistence of manure-borne anti-microbial compounds; and phosphorus forms and cycling in manure and soil. Prior to joining the faculty at the University of Kentucky, Dr. McGrath was an Associate Professor and Extension Specialist at University of Maryland and was heavily involved in Chesapeake Bay water quality issues and policy development. Dr. McGrath routinely speaks throughout the United States on issues related to agriculture and the environment. He has secured over five million dollars in external funding for his research and extension activities, has advised and mentored numerous graduate students, post-doctoral researchers, and undergraduates, and has authored or co-authored 39 peer-reviewed publications and five book chapters in addition to presenting at numerous scientific meetings. Dr. McGrath was born and raised in Smyrna, Delaware, graduated with a Bachelor of Arts from Johns Hopkins University in Environmental Earth Sciences, and earned his Ph.D. in Plant and Soil Sciences from the University of Delaware.

Dr. Andrew Sharpley, University of Arkansas

Dr. Andrew Sharpley joined the Department of Crop, Soil and Environmental Sciences, University of Arkansas, Fayetteville in 2006. He is Distinguished Professor of Soil and Water Sciences, Director of the Discovery Farms for Arkansas Program, and Chair of the Division of Agriculture's Environmental Task Force. He received degrees from the University of North Wales and Massey University, New Zealand and spent 25 years with the USDA-ARS in Oklahoma and then Pennsylvania. His research investigates the cycling of nutrients (primarily phosphorus) in soil-plant-water systems in relation to soil productivity and water quality and includes the management of animal manures, fertilizers, and crop residues. He also evaluates the role of stream and river sediments in modifying phosphorus transport and response of receiving lakes and reservoirs. He helped developed decision making tools for agricultural field staff to identify sensitive areas of the landscape and to target management alternatives and remedial measures that have reduced the risk of nutrient loss from farms. He is the Editor-in-Chief of the Soil Science Society of America, in 2008 was inducted into the USDA-ARS Hall of Fame and in 2012 received the Christopher Columbus Foundation Agriscience Award. Dr. Sharpley serves on National Academy of Science Panels and EPA's Scientific Advisory Board.

Dr. Doug Smith, USDA Agricultural Research Service

Dr. Doug Smith is a soil scientist with USDA-ARS at the Grassland, Soil and Water Research Laboratory. He obtained his BS (1997) and MS (1999) degrees from Texas A&M University - Commerce and a PhD from the University of Arkansas (2002), where he worked on dietary modification and manure amendment strategies to decrease P losses from swine and poultry production. Dr. Smith has worked on P fate and transport in the tile drained landscapes of the Western Lake Erie Basin for 12 years while a soil scientist with the USDA-ARS National Soil Erosion Research Laboratory. He has conducted novel research at bench, plot, farm field and small watershed scale to elucidate the impacts of management activities on nutrient losses in agricultural landscapes. He has authored or coauthored more than 60 peer-reviewed publications and mentored 18 graduate students and postdocs. Dr. Smith is incoming Chair of SERA-17, an organization for agricultural phosphorus management, and has served on the editorial board of the Journal of Environmental Quality.

Dr. Peter Vadas, USDA Agricultural Research Service

Dr. Peter Vadas is a soil scientist with USDA-Agricultural Research Service at the Dairy Forage Research Center in Madison, WI. He obtained M.S. (1996) and Ph.D. (2001) degrees from the University of Delaware, where he worked on field and modeling research for phosphorus management on the Delmarva Peninsula. His research focuses on nutrient management in agricultural production systems, and especially with developing tools and models for phosphorus management. He has conducted lab and field research to generate the data needed to improve existing field, farm, and watershed scale models that are used to help manage agricultural phosphorus. Notable modeling advances include better simulation of phosphorus loss from field-applied manures and fertilizers, and the Annual Phosphorus Loss Estimator (APLE), which is a user-friendly model that quantifies annual phosphorus loss from cropped fields, grazed pastures, and cattle barnyards and feedlots. APLE is being used to help improve Phosphorus Indexes in several states, including Maryland. Dr. Vadas is active in the SERA-17 organization for agricultural phosphorus management, and has served on the editorial boards of the Journal of Environmental Quality and the Soil Science Society of America Journal.

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