Managing legacy and new sources of phosphorus to reduce leaching in Mid-Atlantic soils

Application of phosphorus (P) fertilizers and animal manures to P-rich soils due to the historic use of P inputs can lead to greater P losses. In these soils, we need to manage legacy and new inputs of P in a way that they do not lead to P loss. Studies were conducted to (i) determine the effect of soil type on P leaching and (ii) investigate if changes in dairy and poultry diets can lead to lower P in manures and loss when manures are land applied. Earn 2 CEUs in Soil & Water Management by reading this article and taking the quiz at www.certifiedcropadviser.org/certifications/self-study/799.

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In contrast to phosphorus (P)-deficient soils in the tropics (Toor and Bahl, 1997, 1999; Toor, 2009), the intensive animal production areas in many developed countries are saturated with P due to the lack of economically viable uses of manures for decades, which has resulted in application of virtually all surplus manure to agricultural soils (Toor et al., 2006). This has occurred despite the fact that agronomic soil P tests often clearly indicate that no crop response to added manure P could realistically be expected. Consequently, in much of southern Delaware and eastern Maryland today, soil test P values are well above the optimum values needed for the major crops grown in the area (Sims et al., 1998). Research has shown that P loss increases if there is a buildup of soil test P to excessive levels, which saturates P sorption sites present in soils (e.g., clay, Al and Fe oxides) and increases dissolved P loss (Sims et al., 1998; Sinaj et al., 2002). Thus, agricultural practices that accelerate P loss are of environmental and ecological concern since P leads to decreased water quality. The recent legislation and policy changes in the USA have resulted in more stringent control and management of animal manures for land disposal, with several states (e.g., Delaware and Maryland) advocating application of manures on the basis of total P content (Coale et al., 2002). Recent lawsuits such as Oklahoma State vs. Arkansas poultry integrators (DeLaune et al., 2006) are an indication of the changes in the perspectives of policymakers on the need to exploit

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doi:10.2134/cs2016.49.0512

Abbreviations: DRP, dissolved reactive phosphorus; DUP, dissolved unreactive phosphorus; M3-PSR, Mehlich 3 phosphorus saturation ratio; TPP, total particulate phosphorus other means of use of animal manures to decrease nonpoint pollution.

Reducing P loss from soil to water is a complex and difficult task. Currently, two approaches are receiving considerable attention in the U.S. First, identify soils where the risk of P loss is the greatest and reduce or eliminate P inputs to these soils. In the past, most studies were focussed on the transport of P via surface pathways because of the belief that any P leached would be strongly fixed by subsoil. Thus, the processes to identify and manage soils where P losses by erosion and surface runoff are of concern are reasonably well established. However, less is known about the leaching of P to shallow groundwater and the lateral subsurface flow of P to surface waters. Recent research has shown that P leaching can be a major pathway of P transfer in some situations, e.g., free draining irrigated soils, deep sandy soils, high-organic-matter soils, or soils with a history of long-term P application (Sims et al., 1998; Toor et al., 2004a,b). Related to this, when alternatives to land application of manures do not exist or are limited, manure use should be prioritized on soils where the risk of P loss is the lowest. This is the goal of the P Site Index now widely used in many states to assess the risk of P loss from fields (Sharpley et al., 2003).

Second, in watersheds where animal production is a vital component of the economy, such as the Chesapeake Bay, strategies should be developed to reduce the amount of P (total and soluble) in manures. The most promising option for this to date is dietary modification, where using dietary additives (e.g., phytase and vitamin D_3 metabolites) for poultry and reducing P content in feed for both poultry and dairy have been shown to decrease total P in manures. Recent research has shown that these dietary modifications can cause reductions of total P in dairy manures and poultry litters by 40% (Angel et al., 2005; Toor et al., 2005a,b). This decrease in manure P, in turn, will reduce the amount of P when manures are applied to land. At the same time, we need to evaluate the impact of manures produced by dairy- and poultry-modified diets on P leaching. In the past, concerns have been raised that inclusion of phytase in poultry diets will increase the amount of soluble P in manures and the risk of P loss by surface runoff. Research has consistently shown that if the addition of phytase in poultry diets is accompanied by appropriate reductions in non-phytate P (or mineral P), it does not increase the manure soluble P (e.g., Toor et al., 2005c) and runoff P loss, but no information is available on the effect of dairy and poultry dietary modifications on P leaching.

There are extensive areas of sandy soils in southern Delaware and eastern Maryland overlying shallow water tables, and in some portions of the watershed, an extensive system of drainage ditches exists to transport surface and subsurface runoff to tributaries of the Chesapeake Bay. Many watershed soils are now sufficiently saturated with P to be of environmental concern, and fresh applications of P inputs are made each year. Given this, we need information on the effect of soil properties on P leaching if we are to accurately identify the “critical source areas.” This is where P transfer to surface waters by subsurface processes is of most concern and where P-based management should be implemented to protect and improve water quality. Reducing the risk of P loss to surface waters is a complex and difficult task in these settings.

Methods

We collected 54 undisturbed lysimeters (12 inches diameter and 20 inches deep) from three major soil series, widely distributed in the Mid-Atlantic, using a mechanical, tractor-mounted soil-coring machine (Fig. 1). The soils were (i) a well-drained Matapeake silt loam, (2) a

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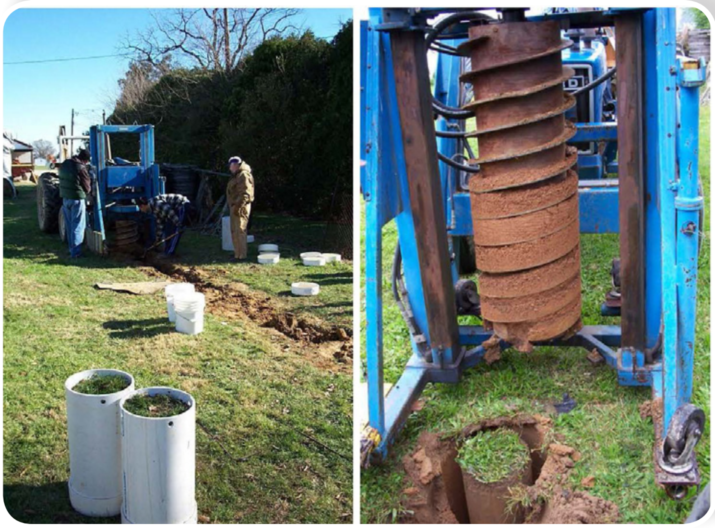

Fig. 1. Tractor-mounted soil corer was used to collect undisturbed lysimeters (12 inches diameter and 20 inches deep).

moderately well-drained Woodstown sandy, and (3) a very poorly-drained Pocomoke sandy loam. Sims et al. (2002) used a Mehlich 3 (M3) soil test to define four soil P saturation categories based on the molar ratio of M3-P to M3-[Al+Fe]. Two sets of lysimeters were obtained from each soil series with corresponding M3-P saturation ratio (M3-PSR) values in the topsoil horizon (upper 6 inches) of *below optimum or optimum* (M3-PSR of 0.06 to 0.11) and *environmental* (M3-PSR of >0.15).

Lysimeters were irrigated with the equivalent of ~2 inches of water each week for a total of 16 weeks (total applied water was 32 inches). Lysimeters received reverse osmosis water for first eight weeks. Before irrigating lysimeters during Week 9, six treatments were applied at 187.4 lb total P/ac, and lysimeters were irrigated for another eight weeks. This application rate is similar to the amount of P added when a range of different manure types are applied to meet the nitrogen (N) requirements of most crops. The treatments were no P (control), P fertilizer (triple superphosphate; $Ca(H_2PO_4)_2$), two dairy manures generated from low (0.36% total P) or high (0.53% total P) P diets (Toor et al., 2005a), or two broiler litters generated from normal or reduced non-phytate P and phytase-amended diets (McGrath et al., 2005). The corresponding total P contents in dairy manures were 0.57% for the low-P manure and 0.84% for the high-P manure (Toor et al., 2005a). The total P was 1.36% in normal broiler litter and 0.97% in modified broiler litter (McGrath et al., 2005).

Total P concentrations in leachate can provide useful information about the relative effects of soil type, hydrology, and nutrient management practices on the potential of P transport from land to water. Because of this, we first measured total P concentrations and loads in leachate from all lysimeters. However, recently there has been growing interest in better understanding the various forms of P in leachate as we have learned more about the differential bio-availability of P species to aquatic organisms. Consequently, we used a fractionation scheme to separate leachate total P into three categories:

Dissolved reactive P (DRP)—includes orthophosphate soluble in water and some easily hydrolyzable organic P forms such as labile monoesters (sugar phosphates and mononucleotides) and diesters (DNA, RNA, phospholipids);

Dissolved unreactive P (DUP)—thought to primarily contain organic P compounds, such as monophosphate esters, nucleotides and nucleic acid, phospholipids, phosphonates, and polyphosphates, but may include some inorganic compounds such as polyphosphates; and

Total particulate P (TPP)—a more recalcitrant form of P that is not readily bio-available but may provide a long-term source of P in water bodies. Note that TPP includes (a) particulate-reactive P, which is insoluble in water but may contain P sorbed on the surfaces of colloidal-sized clay, Fe, Al, or Ca oxides and hydroxides (e.g., Toor et al., 2005a) and (b) particulate-unreactive P; the nature of P compounds in this fraction are relatively unknown but may include P sorbed on mineral-humic acid complexes or inositol hexaphosphate (Toor et al., 2003).

Results and discussion

Properties of soils

All soils were moderately acidic with <2.1% organic matter, typical of soils in the Mid-Atlantic Coastal Plain. For all soils, M3-P was 76–734 lb/ac in the surface horizon (0–10 inches) and 14–74 lb/ac in the subsurface horizon (10–20 inches). The lower M3-PSR values (0.01–0.04) of the subsurface horizon suggest that subsoils may have sufficient capacity to sorb P. Overall, from the results of soil chemical analyses and P sorption experiments, it was apparent that M3-PSR is an equally good predictor of P sorption capacity of soils as compared with P sorption batch indices that are more time consuming. Consult Toor and Sims (2015) for a detailed discussion on soil properties.

Total drainage from the lysimeters

Total amount of water leached from three soils ranged from 25 to 27 inches, which was equivalent to 79–86% of applied water. The higher leachate in the fine-textured Matapeake soil (86%) as compared with Woodstown and

Pocomoke sandy loam soils (79–82%) suggests that some form of bypass/preferential flow occurred in the Matapeake soil. In well-structured soils such as the Matapeake, stable macropores that can facilitate leaching of water and dissolved solutes are more common than unstructured sandy soils where matrix flow generally predominates (e.g., Toor et al., 2005d). The remainder of the irrigation water (14–21%) was likely retained in the soil profile and/or evaporated.

Influence of soil types on phosphorus leaching in different forms

The greater P leaching from the Matapeake and Pocomoke soils can be explained by rapid P transport through preferential flow paths. This notion is supported by the patterns of P leaching losses, which often showed short-term peaks in P concentrations, especially following application of P inputs. Presumably, preferential flow caused a proportion of the applied water to flow through the macropores, thereby by-passing some of the soil matrix. This limited interaction of water (and leached DRP) with soil P fixing constituents resulted in rapid transfer of P from the soil profile and caused greater DRP leaching loss.

In contrast, DRP leaching from Woodstown soil was small and very similar for the control, superphosphate, dairy manures, and broiler litters treatments, suggesting a similar environmental risk of P leaching from all P sources. The lack of preferential flow in Woodstown soil may have allowed DRP to diffuse into soil matrix, which effectively retained DRP resulting in lower leaching loss irrespective of different treatments, but this may be partially offset once P fixation sites are saturated due to repeated applications (e.g., Toor and Sims, 2015).

Both dissolved (DRP and DUP) and particulate (TPP) forms of P were found in the leachate from all soil types. However, the relative proportions of each form in the leachate primarily depended on P sorption properties of individual soils and preferential flow pathways. For example, Woodstown soil had lower P sorption capacity than Matapeake because of lower contents of Fe and Al in the subsoils, but most of the applied P (from superphosphate and manures/litters) was retained, resulting in lower DRP loss in Woodstown soil. Sorption would have removed much, if not all, of the DRP from applied P sources, thereby leaving primarily unreactive P (i.e. DUP) and organic P sorbed to colloidal material (i.e., TPP) in the soil solution where it would be susceptible to leaching. This pattern was observed for Woodstown soil where DUP losses were much higher than DRP even for the superphosphate treatment. In earlier studies (Toor et al., 2003, 2005d), unreactive P was >70% of total P leached from light-textured soils treated with dairy slurry.

Overview of phosphorus forms in the leachate

Total phosphorus in the leachate. The background total P concentrations in the leachate were consistently higher from environmental M3-PSR soils than agronomically optimum M3-PSR soils. These values further increased after fertilizer application more in the environmental M3-PSR soils while a little change was initially noted in leachate total P for soils in the optimum M3-PSR. The sharp peaks in the leachate total P immediately after fertilizer application in the Matapeake (5,915 ppb) and Pocomoke (1496 ppb) soils indicate that some form of bypass flow, which minimizes interactions between dissolved solutes and the soil matrix, occurred in the initial leaching event for these two environmental M3-PSR soils. No such peak in leachate total P was observed for the Woodstown soil, suggesting that matrix flow, which enhances P sorption in the soil profile, predominated. Overall, for soils in the environmental M3-PSR category, mean concentrations of total P significantly increased after fertilizer application.

Dissolved reactive phosphorus in the leachate. Unlike total P, concentrations of DRP in leachate, before fertilizer application, were not significantly different between soils or M3-PSR categories but were consistently higher than the eutrophication limit of 10 ppb DRP for freshwater suggested by USEPA (1994). As with total P, fertilizer application caused an immediate and significant increase in leachate DRP for soils in the environmental M3-PSR but not for those in the optimum M3-PSR range. Concentrations of DRP in the leachate from soils in the environmental M3-PSR declined with time but were still elevated relative to water quality standards.

Based on the factors known to increase P sorption in soils such as high clay and Al contents and sorption maxima, the capacity to sorb DRP from leaching waters should be greatest for the Matapeake soil followed by the Pocomoke, and Woodstown soils. The fact that DRP concentrations in leachate followed an opposite trend with these three soils supports the existence of preferential flow pathways in the Matapeake and Pocomoke soils, which limited the interaction of DRP with P-sorbing soil constituents as compared with the Woodstown soil.

For the dairy manure treatments, DRP concentrations in leachate were generally slightly higher in the low-P than high-P dairy manure treatments. Mean concentration of DRP was two- to fourfold higher in the lysimeters (Pocomoke and Matapeake) that received normal broiler litter compared with phytase broiler litter. In the Woodstown soil, DRP was similar in the control, superphosphate, dairy manure, and broiler litter treatments.

Dissolved unreactive phosphorus in the leachate. In most cases, the majority of leachate P was found as DUP or TPP. This suggests that organic and colloidal forms of P play a major role in the downward movement of P through Mid-Atlantic soils; a similar observation was reported by other researchers in other parts of the world (Toor et al., 2003, 2005d). The higher losses as DUP in these soils are also of environmental concern as the organic P compounds present in the DUP fraction have been reported to be rapidly utilized by aquatic organisms.

Concentrations of DUP were higher than DRP in all control treatments. Among dairy manure treatments, concentrations of DUP were greater in the low-P than high-P dairy manure amended lysimeters. Similarly, concentrations of DUP were generally higher in the normal than in the phytase broiler litter treatments. In Woodstown lysimeters, concentrations of DRP were low and similar whereas DUP was greater and more variable.

Total particulate phosphorus in the leachate. The proportion of TPP in leachate was 10–47% across soils. The recalcitrant nature of TPP compounds (P associated with Ca, Fe, and Al and inositol phosphates) means that these fractions are scarcely bio-available and might not constitute a direct threat to surface water quality. However, these may be critical to the long-term P cycle and are important in supplying P to aquatic organisms when labile P species are depleted.

In all treatments, concentrations of TPP were lower than DRP and DUP. Like DUP, TPP was generally less than <100 ppb from all lysimeters except for a few events. However, TPP was 100–718 ppb immediately following the application of P inputs (superphosphate and normal broiler litter only), especially in the Matapeake and Pocomoke lysimeters. These two soils had existence of preferential flow pathways, which likely resulted in rapid transport of TPP.

Relating soil phosphorus saturation with leachate phosphorus concentrations

When M3-PSR was plotted against leachate DRP and total P concentrations, a linear but non-significant relationship was observed. This is due to the higher proportion of DUP and TPP in leachate from these soils as M3-PSR is directly related to the ability of the soils to fix inorganic P (i.e., DRP). Further, the lower proportions of the DRP in the present study (typically <25%) likely resulted in a weak relationship between M3-PSR and DRP. For instance, subsurface horizons of all soils had M3-PSR values <0.04. Therefore, it could be assumed that most of the P leached from surface horizons would be retained by subsurface horizon, which in case of Woodstown sandy loam, resulted in lower P leaching losses. The Matapeake and Pocomoke soils did not behave according to this pattern and had larger P leaching losses than what would be expected from their subsurface horizon P sorption capacities (0.01 M3-PSR for both soils). Although the M3-PSR of soil is useful to understand the relative P retention capacity of different soils and potential P release, it should not be used alone to indicate the risk of P leaching, but it can be used with subsurface physical properties (e.g., preferential flow pathways) to account for the released P that may be lost from the soil profile. It can be assumed that low M3-PSR in the subsurface horizon of Woodstown sandy loam reduced P concentrations in the percolating water and resulted in low P losses; whereas, the existence of preferential flow pathways in the subsurface horizon of Matapeake and Pocomoke soils probably lead to greater losses of P.

Even though the correlation between M3-PSR values and actual P leaching loads was weak, an increase in soil M3-PSR beyond the optimum level is not desirable. Continuous over-application of P inputs can eventually overcome the ability of the soil to keep P within the profile, especially for soils with low P sorption capacity. High-P leaching from soils and sites with different M3-PSR (Matapeake and Pocomoke) and low-P leaching from soils with considerable P retention capacity (Woodstown) emphasize the importance of both physical and chemical properties of the whole soil profile that should be used to design appropriate risk assessment strategies.

Effect of animal manures generated with modified diets on phosphorus leaching

The higher (~100%) water solubility of P in the superphosphate resulted in greatest leaching of DRP in the superphosphate-amended lysimeters, whereas the lower P solubility (<30% water-extractable P) in dairy manures or broiler litters resulted in lowest DRP leaching. Most of the P leaching (>60% of total) from all soils occurred in dissolved (DUP>DRP) rather than particulate (TPP) fractions. In manure and litter amended Matapeake soil, most of the P was leached as DUP (35–44%) and TPP (18–41%) as compared with superphoshate-amended soils (DUP: 30%, TPP: 11%). This is attributed to both the larger proportion of organic P applied and greater mobility of organic P forms applied with manures/litters compared with superphosphate (Toor et al., 2003, 2005d). Consult Toor and Sims (2016) for a detailed discussion on impacts of modified diets on P leaching.

Influence of dairy manures application on phosphorus leaching. Although total P in leachate was higher in the low-P than high-P dairy manure amended soils, these were not statistically different. The exact reason for discrepancy in P leaching from both dairy manure amended soils is unclear but probably relates to the different amounts of manure addition. This caused application of variable amounts of C and influenced P sorption and desorption in soils. For example, the lower contents of total P in low P dairy manure resulted in a higher addition of manure due to the application of similar rate (187.4 lb total P/ac) for both treatments. As total P in low P dairy manure was 54% lower than high P dairy manure, the low P dairy manure amended lysimeters received 54% higher manure amount than the high-P dairy manure lysimeters. Moreover, 45% more total C was added with low-P dairy manure than high-P dairy manure. In this regard, the higher leaching of P from the soils treated with low-P than high-P dairy manure were probably because of higher C addition with low P dairy manure addition. This may have resulted in greater transport of P in association with C, similar to the findings of Toor et al. (2005d). Thus, introducing organic matter with manures in soils will positively affect soil structure, increase water-holding capacity, and affect fate and transport of P. Higher organic matter will also promote the activity of soil microorganisms and earthworms, which feed on the organic matter. This may help to keep the soil macropores open because of the greater activity of earthworms and maintain the water flow paths through which P can leach to lower depths. In addition, inorganic forms of P can be present as organo-mineral complexes (such as TPP), which were also leached from the soils because of their greater mobility thereby contributing to higher total P losses. Because of these factors, the largest differences in total P were recorded in Matapeake lysimeters. Thus, variations in the amount of C added together with greater preferential flow in Matapeake soil, which restricted interaction of applied P with soil P fixing constituents, facilitated higher P losses. The similar concentrations of total P in leachate from dairy manures amended Woodstown and Pocomoke soils suggest less abundance of preferential flow and rapid fixation of soluble P by soil matrix.

Influence of normal and phytase broiler litter application on phosphorus leaching. Among all P forms, most of the P leaching occurred as DUP in the broiler litter amended lysimeters. Higher but not statistically significant total P concentrations were observed from Matapeake lysimeters amended with normal broiler litter (553 ppb) than phytase broiler litter (310 ppb). For the Woodstown soil, total P was slightly higher, but non-significant, in the phytase broiler litter compared with normal broiler litter amended lysimeters. Lower losses of DRP from phytase compared with normal broiler litter amended soils showed that phytase addition did not cause an increase in P leaching. Similar to dairy manures, a higher amount (66%) of broiler litter was added in the phytase amended broiler litter than normal broiler litter. We contend that P leaching would have been significantly lower if the same amount of litters was applied in both treatments because this would have resulted in lower amount of P applied in phytase amended broiler litter. Thus, poultry diet modification using phytase is a sound management practice to reduce the amount of P addition and lower P leaching.

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Implications and recommendations for phosphorus management in phosphorus saturated soils

Even before fertilizer application, total P concentrations in leachate from these three soils frequently exceeded 100 ppb, the value used by USEPA (1994) as an indicator of surface water quality problems. Initial leachate DRP from lysimeters paralleled total P concentrations and was also high relative to USEPA criteria of 10 ppb DRP. After superphosphate application, leachate total P concentrations were 15–60 fold higher for soils in the environmental M3-PSR category and five–sixfold higher for soils in the optimum M3-PSR category than the USEPA guideline value of 100 ppb. The major forms of P in leachate from all soils were DUP and DRP, with DRP becoming more significant after P inputs. Preferential flow appeared to be a factor in the differences in P leaching between soils and most important in the Matapeake silt loam although water and P movement by bypass flow likely also occurred to some extent in the Pocomoke soil. Matrix flow appeared to predominate in the very sandy Woodstown soils. In summary, our results indicate that P leaching will be most significant in the Mid-Atlantic soils that are P saturated and in soils where preferential flow can rapidly transport P to subsoil horizons. It is important to note that for leached P to impact water quality, subsurface flow paths that link subsoils and surface waters must also exist.

These results indicate that total P loss from both optimum and environmental M3-PSR categories of soils are of environmental concern and that environmental M3-PSR soils are more prone to P leaching following fresh addition of P inputs. On the other hand, the lower losses of total P from optimum M3-PSR sites in comparison with environmental M3-PSR sites, even after fertilizer application, suggests that these soils still have sufficient capacity to retain P.

Overall, it is recommended that management strategies need to be developed for land application of P inputs which minimize P leaching losses from the soils by synchronizing applications with crop uptake and maximizing nutrient removal through reaction with soil colloids. The knowledge about P speciation in leachate can provide invaluable information about the environmental fate of these forms in the water bodies. This can be used to assess the short- and long- term effects on water quality. Importantly, we need to develop strategies to control the loss of P, in particular species that are most bio-available such as DRP, and not simply targeting total P reductions. For example, DRP is known to be immediately available to aquatic biota, whereas DUP may become available over a short period of time and the TPP over a longer period of time. It is apparent that in some settings, such as environmental M3-PSR soils, dissolved P losses can be of as much, or more, of a concern than the particulate P losses. For example, in the present study, up to 90% of total P loss occurred in the dissolved fractions (DRP and DUP). Therefore, in these soils, we need to develop management practices that specifically mitigate the movement of dissolved P from soils to drainage ditches and connected surface waters.

Take home messages

Influence of soil P saturation on P leaching

The pattern of DRP and total P loss from Mid-Atlantic soils was influenced by degree of P saturation in soils. For example, environmental M3-PSR soils had much greater P losses, which significantly increased following fertilizer application. This indicates that these soils do not have sufficient capacity to retain P and any future addition of P inputs would result in greater P leaching. In contrast, in the optimum M3-PSR soils, there was an opportunity for a proportion of P to be fixed by soil constituents that reduced P leaching loss.

Effect of future P application in P saturated soils

Concentrations of DRP and total P in the leachate from superphosphate, dairy manures, and broiler litters amended lysimeters were much greater than the environmental threshold limits. This suggests that P leaching in soils with a legacy of animal manures application is a concern, especially with fresh addition of manures. Rapid sorption of DRP by the subsurface horizon of all soils removed much, but not all, of the DRP applied with superphosphate, thereby leaving primarily DUP and TPP in the soil solution that was also lost.

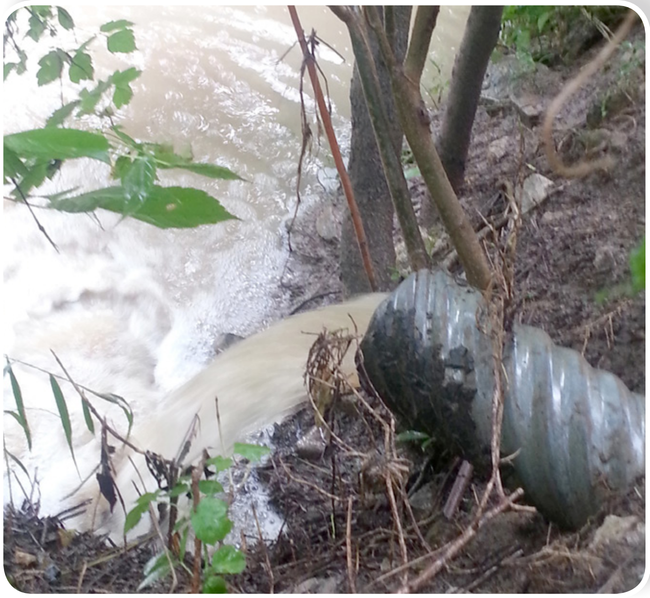

Photo by Aubrey Bunch, USGS.

Water movement in soils controlled P leaching

In soils with matrix flow, such as Woodstown sandy loam, greater interaction between soil particles and percolating water resulted in low P leaching. However, if water transport through the subsoil occurs rapidly through preferential flow pathways, such as Matapeake silt loam, the buffering effect of the subsoil may be reduced and it can result in larger leaching losses. Therefore, P leaching is of much concern in the Matapeake silt loam and Pocomoke sandy loam due to existence of preferential flow pathways. While for the Woodstown sandy loam soil, concerns about P leaching are minimum if soil P saturation remains below the saturation point.

Soil texture not indicative of P leaching

The traditional thinking that P leaching is of greater concern in coarse- than fine-textured soils may not apply in all settings, especially in soils with existence of preferential flow pathways such as Matapeake soil. It appears that P leaching from Matapeake and Pocomoke soils following P application inevitably poses environmental concerns, and risks appear to be augmented by rapid preferential flow leaching. For Woodstown sandy loam soil, concerns about P leaching following application of P inputs are lower, which highlight the important role that soil physical and chemical properties can play in mitigating P leaching.

Predicting and managing P leaching

We suggest that both M3-PSR and information about existence of preferential flow pathways should be used to predict the risk of P leaching when soil test P values exceed the agronomic optimum thresholds. Central to our efforts to reduce P leaching from the soils with long-term history of P applications is the use of manures generated with new dietary modifications. These dietary modifications are an effective tool to reduce P concentrations in animal manures and thus should reduce the extent of P leaching from soils.

This article was adapted from the following two articles:

1. *Toor, G.S., and J.T. Sims. 2015. Managing phosphorus leaching in mid-Atlantic soils: Importance of legacy sources. Vadose Zone J. 14(12). http://dx.doi.org/10.2136/vzj2015.08.0108.*
2. *Toor, G.S., and J.T. Sims, 2016. Phosphorus leaching in soils amended with animal manures generated with modified diets. J. Environ. Qual. 45(4): 1385–1391. http://dx.doi.org/10.2134/jeq2015.10.0542.*

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