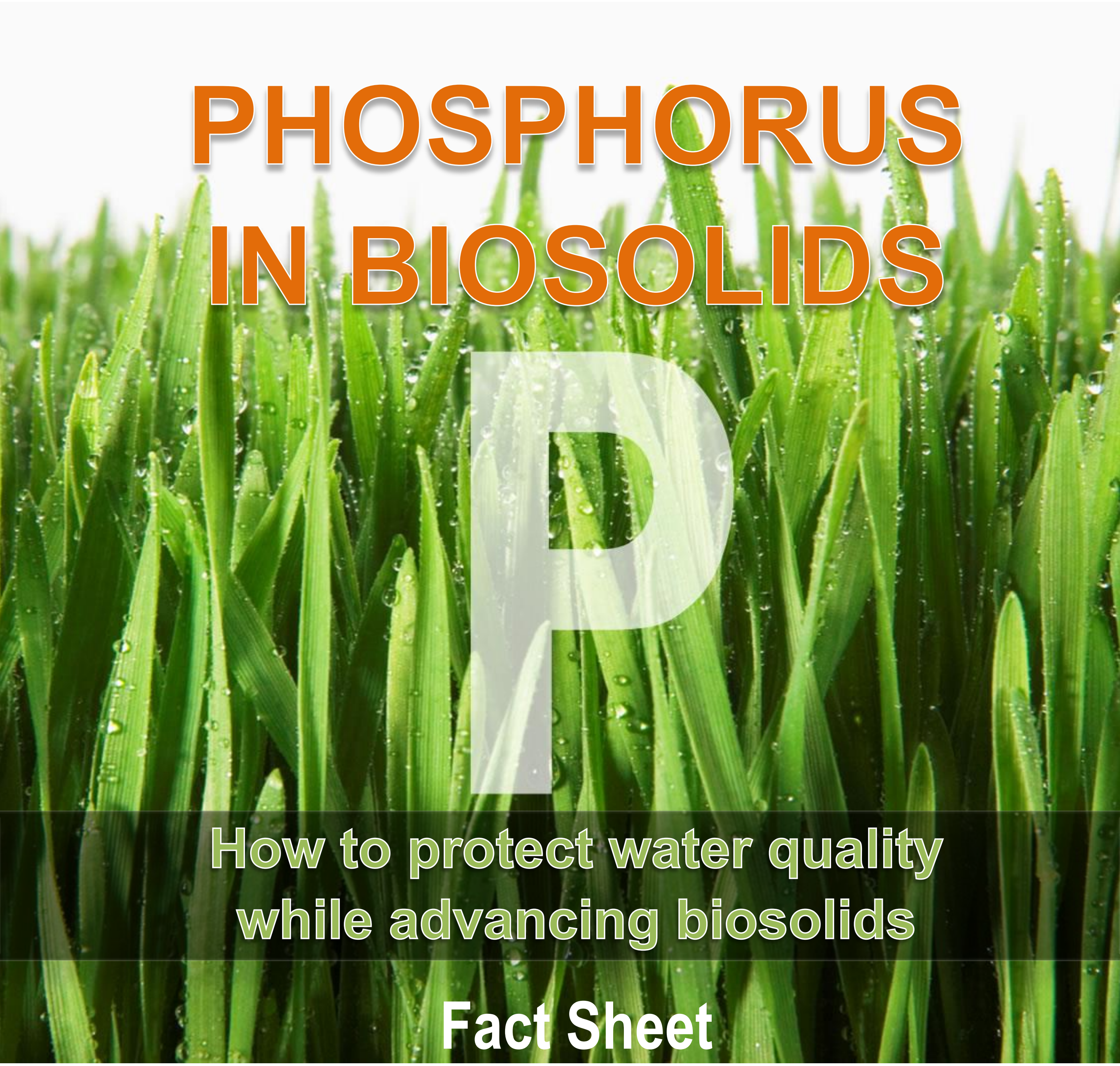
Water Environment Federation
the water quality people®

NATIONAL biosolids PARTNERSHIP



PHOSPHORUS IN BIOSOLIDS

How to protect water quality while advancing biosolids

Fact Sheet

FACT SHEET – MAY 2014
Copyright © 2014 Water Environment Federation. All rights reserved.

Acknowledgments

Principal Authors

Lisa Boudeman, Material Matters Inc.
Ben Davis, Renda Environmental Inc.
Andy McNeill, Denali Water Solutions
Ned Beecher, New England Biosolids and Residuals Association
Robert Rubin, Ph.D, Professor Emeritus, North Carolina State University
Brenda Stephanoff, Indiana Department of Environmental Management
Kari Brisolara, ScD, MSPH, Louisiana State University, School of Public Health

Final Reviewer

Herschel (Chip) Elliott, Ph.D., Penn State University

Phosphorus Fact Sheet Team Members

Robert Bastian, Ph.D., United States Environmental Protection Agency
Ned Beecher, New England Biosolids and Residuals Association
Lisa Boudeman, Material Matters Inc.
Kari Brisolara, ScD, MSPH, Louisiana State University, School of Public Health
Ben Davis, Renda Environmental Inc.
Conor Dennehy, O2 Environmental
Herschel (Chip) Elliott, Ph.D., Penn State University
Jason Fleury, WeCare Organics
Diane Garvey, Garvey Resources Inc.
Isabel Lima, Agricultural Research Service, United States Department of Agriculture
Lisa McFadden, Water Environment Federation
Mike McKee, Progress Environmental
Andy McNeill, Denali Water Solutions
Mike Moore, Resource Recovery Strategies
Lynne Moss, P.E., BCEE, CDM Smith
William Mullin, Lystek International Inc.
Chris Peot, P.E., DC Water
Christine Polo, Black & Veatch
Robert S. Reimers, Ph.D., Tulane University
David T. Rosnagel, Trinity River Authority
Robert Rubin, Ph.D, Professor Emeritus, North Carolina State University
Brenda Stephanoff, Indiana Department of Environmental Management
Aaron Stephens, Material Matters Inc.

Water Environment Federation
Residuals and Biosolids Committee
Sustainable Residuals Use Subcommittee

Ben Davis, Renda Environmental Inc., Chair

Copyright © 2014 Water Environment Federation. All rights reserved.

Fact Sheet Contents

Copyright © 2014 Water Environment Federation. All rights reserved.

Phosphorus in biosolids: how to protect water quality while advancing biosolids use

Setting the Stage: Background

What is Phosphorus?

Phosphorus (P) is an essential element for life. Most significantly, P is a component of nucleic acids (DNA and RNA), the biological molecules critical for all known forms of life. Phosphorus is also an important element in adenosine diphosphate (ADP) and adenosine triphosphate (ATP), the energy storage and transfer molecules in cells, and it functions as a building block of phosphoproteins and phospholipids, the macromolecules that form cell membranes (Beegle, 2012).

In modern agriculture, P is one of the most critical nutrients for crop and livestock production due to its vital role in root growth and seed (grain) production (Sharpley et al., 2003)(Figure 1). Therefore, an adequate supply of P is essential to maintain and promote optimum crop growth and, in turn, profitable agriculture (PSU, 2007). In fact, without fertilization from P, it is estimated that wheat yields would be reduced by more than half - from four to less than two tons per acre (Soil Association, 2010).

The advent of regionally specialized agriculture (and concentrated animal feeding operations) in the mid-1900s has led to an abundance of phosphorus-rich organic soil amendments (i.e. manure) in some areas, and, in turn, the application of P in excess of crop uptake. This results in an accumulation of P in the soil which, in turn, has the potential to be transported in runoff to surface waters by means of surface runoff and, in course-textured low P-sorbing soils, leaching through the soil profile. Although P applied beyond crop needs will not adversely affect crop yields, nutrient enrichment of surface waters can promote the rapid growth of algae, followed by depletion of dissolved oxygen during algal decomposition (Figure 2). This leads to organic enrichment of the water body, or eutrophication, a natural aging process of surface waters that is accelerated by excess nutrients and increased biological productivity (Carpenter et al., 1998). Eutrophication causes an overall degradation of water quality for aquatic life and for human activities (more costly treatment for drinking water purification, reduced fishing and recreational availability, and reduced aesthetic value). In fact, two of the main causes of eutrophication, organic enrichment and nutrient loading, are cited by the U.S. Environmental Protection Agency (USEPA) as two of the top five leading causes of water quality impairment in U.S. surface waters (U.S. Environmental Protection Agency, 2009). As a result of degraded water quality, especially in prominent national resources such as Chesapeake Bay, nutrient management standards – including new P-based management – have gained increasing traction in recent years.

Figure 1: Inadequate phosphorus supply can hinder pollination and kernel development, resulting in portions of cob tissue without kernels. Source: *http://agcrops.osu.edu/*

Copyright © 2014 Water Environment Federation. All rights reserved.

Figure 2: Dymers Creek and the Chesapeake Bay. Eutrophication, the proliferation of algae in nutrient enriched water bodies, is apparent along the coastline. Source: http://www.annmeekins.com/pages

Sources of P in the Environment

Phosphorus is widespread in the environment, where it undergoes a natural cycle between plants, animals, rocks, minerals, and water. As depicted in Figure 3, humans have greatly accelerated the natural P cycle by

- mining mineral phosphate rock (the mineral form of P) and converting it to fertilizer,
- land-applying organic soil amendments (i.e. manure and biosolids) in concentrated areas, and
- discharging wastewater directly into surface waters.

Human-induced movement of P into the environment is grouped into two categories; *point sources* and *non-point sources*.

A point source is a single identifiable channel, such as a pipe, from which P is discharged. Point sources include discharges (effluent) from water resource recovery facilities (WRRF), industrial pretreatment facilities, agricultural operations (e.g. confined animal feeding operations (CAFOs)), and municipal and industrial stormwater collection facilities. In recent years, point sources in many states have felt the pressure to reduce discharges of P through substantial reductions in effluent discharge permit limits. Some WRRFs are being required by USEPA and states to reduce P discharges to less than 1 mg/L. In Pennsylvania, for example, prior to 2010, only the largest WWRFs had permitted P discharge limits set at 2.0 mg/L; now the vast majority of WWRFs in the Chesapeake Bay watershed have permitted maximum P discharge limits set at 0.8 mg/L. Although targeting point sources for P management is relatively straightforward with modifications to discharge permits, tightening permit limits does not proportionately improve water quality, because the major source of excess P entering surface waters originates from non-point sources (Parry, R. 1998). In fact, USEPA (2009) identified agricultural nonpoint source pollution as a leading contributor to nutrient pollution of rivers and streams.

Non-point-source P comes from an area(s) with undefined boundaries, and, therefore, management of non-point-source P has proven to be quite challenging. The three major contributors of non-point-source P to surface runoff are soils, plant material, and applied fertilizers, manures, and biosolids (Vadas et al., 2004). Although soil and plant material contribute to runoff P, soil P is primarily environmentally unavailable and plant material contains just a small fraction of the total P in these three sources. As such, environmentally available P is primarily added to the environment via inorganic mineral fertilizers and organic amendments (manures and biosolids).

Copyright © 2014 Water Environment Federation. All rights reserved.

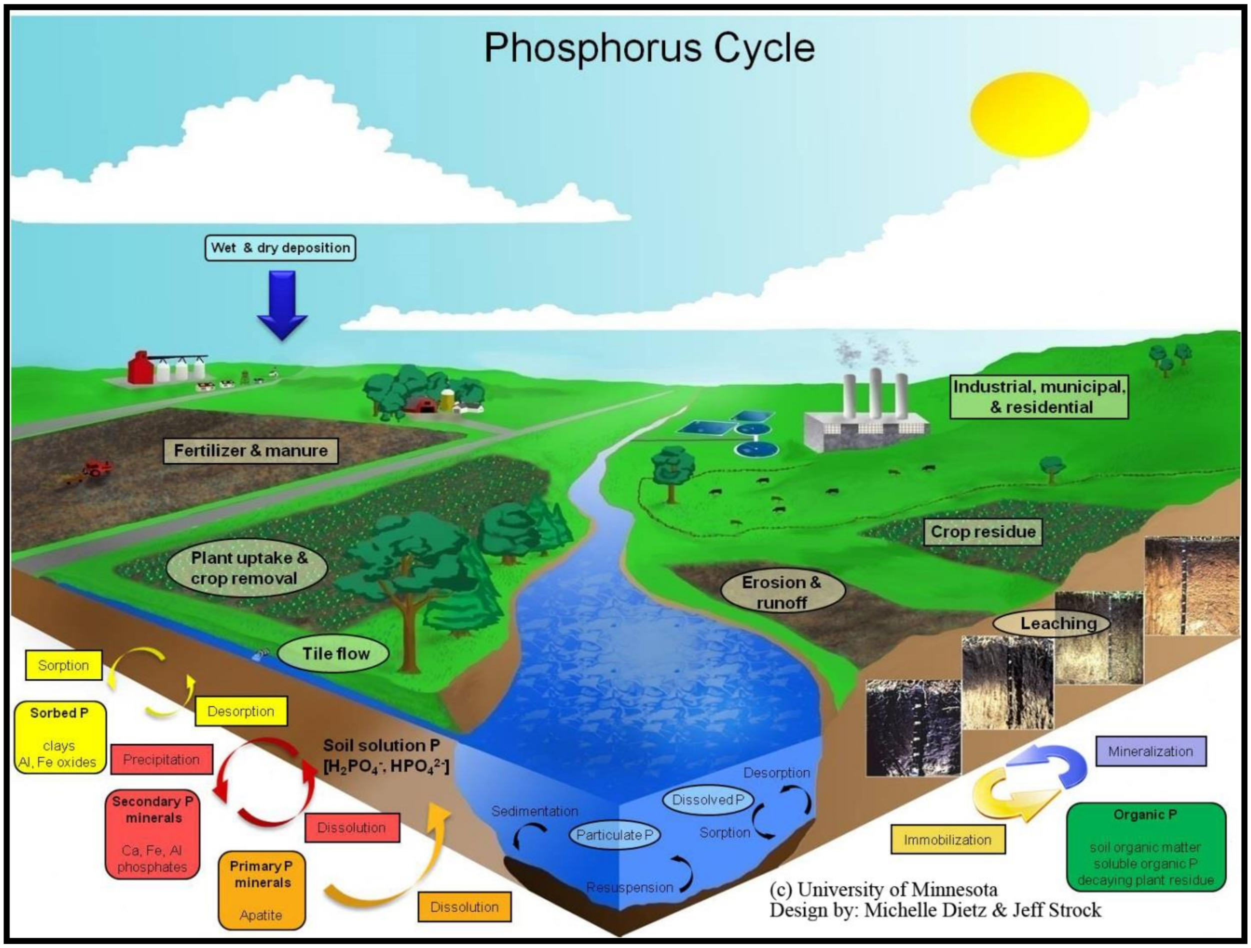


Figure 3: Phosphorus Cycle. P naturally cycles in different forms in the environment. However, human have accelerated the movement of phosphorus by mining and land-applying phosphate fertilizers, land applying organic soil amendments, and discharging concentrated sources of P directly into water bodies. Source: *http://swroc.cfans.umn.edu/ - reprinted with permission.*

Mineral Fertilizers

Because P is one of the three critical macronutrients required for healthy plant growth, it has long been a substantial ingredient in many fertilizers. Most fertilizers are formulated and labeled based on their macronutrient content; for example, a common kind of commercial fertilizer is “10-10-10,” meaning it contains 10% nitrogen (N), 10% phosphate (P_2O_5), and 10% potash (K_2O) by weight. The commercial source of mineral phosphate is “phosphate rock”, the name given to natural calcium phosphates. Millions of tons of phosphate rock are mined every year for use in mineral phosphate fertilizers (Soil Association, 2010).

Although fertilizers containing mineral phosphate are commonly used across the United States, farmers tend not to over apply P from mineral fertilizers, because doing so is economically impractical (Beegle, 2012). But even when mineral P fertilizers are applied at crop P uptake rates – meaning that the P applied is mostly removed in the crop when the crop is harvested – certain farming practices (i.e. conventional tillage or fertilizer application immediately prior to a precipitation event) have been shown to lead to P transport to ground and surface waters via leaching (particularly in sandy soils) and sediment runoff (Gascho, et al., 1998). Because of this, and because agriculture is a large user of mineral P fertilizers, the U. S. Department of Agriculture (USDA) and other advisors have focused considerable attention over the past two decades on managing P use more carefully, including recommending – and, in many areas, requiring – nutrient management plans that limit P applications. Mineral phosphate is also widely used in markets independent of conventional feed and fiber agriculture. In some of the more densely populated parts of North America, mineral phosphate fertilizer is commonly applied to turf grass, including parks, sports fields, golf courses, and residential and commercial lawns. In Maryland, for example, it is estimated that 44% of chemical fertilizer sold in the state is used for these purposes (Maryland Dept. of Agriculture, 2013). Due to the challenges of properly managing P in these settings, state laws and regulations have been enacted throughout much of the Northeast that prohibit or significantly limit the use and/or sale of P for lawn maintenance (NEIWPCC, 2012).

Manure

Using manure as a fertilizer for crops is common throughout much of North America (Figure 4). Most often, manure is applied to meet the nitrogen (N) needs for the desired yield of the planted crop. Because the N/P ratio of manure (2:1 to 6:1) is lower than that in crop uptake (7:1 to 11:1), N-based manure management results in more P being added to the soil than the crop requires. This results in a buildup of P in soils (Maguire et al., 2002), and in turn, may increase concentration of dissolved P in surface runoff or lateral subsurface flow.

Copyright © 2014 Water Environment Federation. All rights reserved.

In recent years, the trend towards intensive livestock operations on relatively small areas of land has exacerbated this nutrient imbalance in some areas. In the past, traditional farming practices involved feeding animals with crops grown on the farm and then returning their manures to the fields whence the crops came, thus generally maintaining a balance of nutrients within the farm boundaries. In contrast, today's concentrated animal feeding operations (CAFOs) import food (nutrients) into relatively small areas where many animals are fattened, resulting in an accumulation of manure and an excess of nutrients in these localized areas (Gburek et al., 2000).

Biosolids

Biosolids, the nutrient-rich organic materials resulting from the treatment of sewage sludge, is used as a fertilizer for feed and fiber crops throughout most of the United States. Traditionally, biosolids are applied to meet the nitrogen (N) needs for the yield goal of the planted crop. As with manures, most biosolids are an "unbalanced" fertilizer: N-based biosolids nutrient management results in the application of P at a rate 5-10 times greater than the crop need (Maguire et al., 2000). In turn, continual application of biosolids to meet crop N needs can noticeably increase total and environmentally available soil P.

It is important to note that although continuous biosolids application can result in an accumulation of soil P, the percent of "labile" (mobile) P in biosolids (24%) is significantly smaller than other amendments (55-70%), and therefore may be less likely to be environmentally available and significant compared with other fertilizers and soil amendments (Ajiboye et al., 2004).

Phosphorus Behavior in the Environment

The dynamics of P in soils and the environment are complex, and research continues to advance understanding of this critical aspect of soil chemistry. However, what is known is that the P found in soils consists of a large variety of compounds that make the P either more or less environmentally available, and, therefore, more or less likely to cause undesirable eutrophication of surface waters. But, in general, regulatory agencies charged with protecting surface water quality are concerned when there are high levels of total P in soils adjacent to water bodies.

Soil P exists in organic and inorganic forms, and each form consists of a continuum of many P compounds, existing in equilibrium with each other and ranging from solution P (which can be taken up by plants), to "labile P" (potential to be converted to solution P by microbial action), to very stable compounds (unavailable to plants) (Figure 5). In most soils, 50 to 75% of the P is in the unavailable, inorganic form, meaning it is bound in mineral complexes (Penn State Univ., 2001). There are several factors that influence P dynamics in soil including soil texture, and most notably, pH (Frossard et al., 2000). In soils, P binds strongly to iron and aluminum at mid to low soil pH. At high pH, P binds to calcium. The optimal pH for making P available to plants is 6.5 (Havlin et al., 2004).

Figure 4: Application of dry poultry manure as a fertilizer. Land application of animal manures to recycle valuable nutrients and enhance soil productivity has been common practice in the agriculture community for many years. Source: *http://www.ipm.iastate.edu*

Copyright © 2014 Water Environment Federation. All rights reserved.

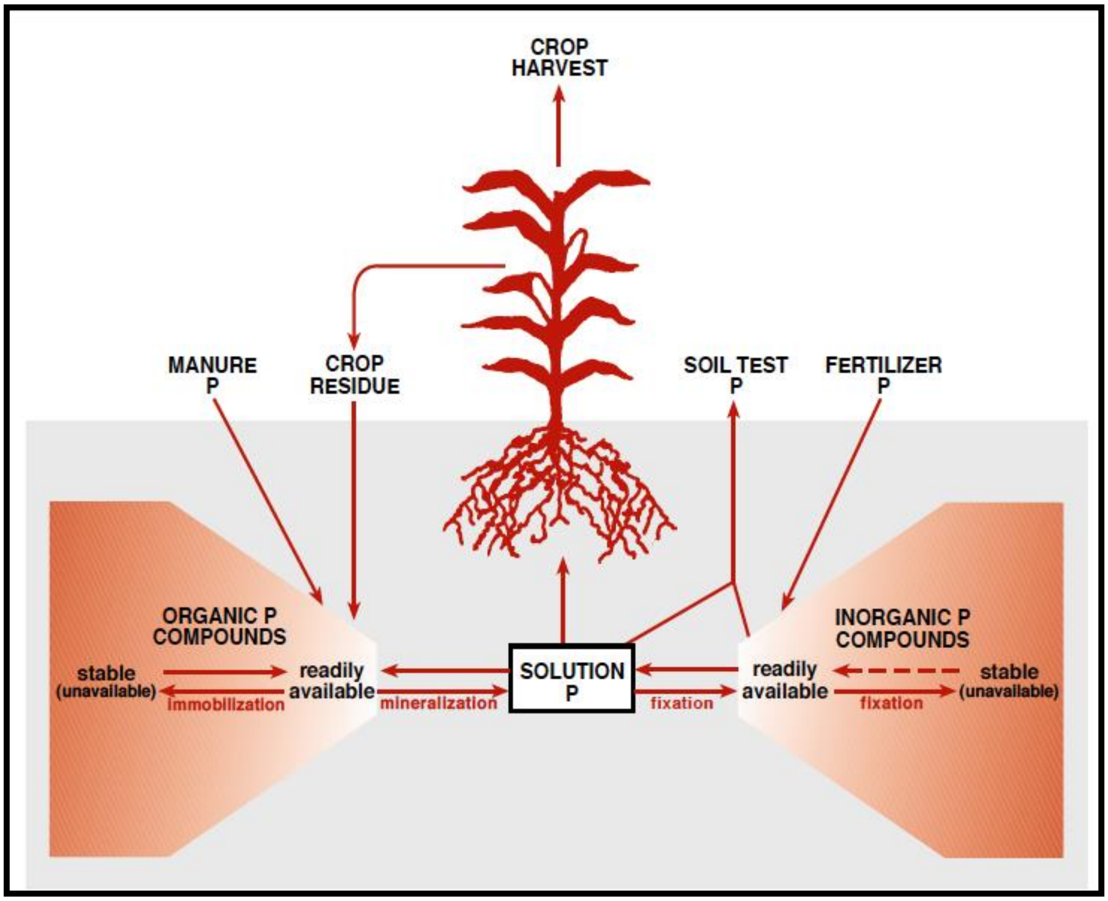


Figure 5: The complex dynamics of phosphorus (P) in the soil/farming system. Source: *CIWEM, 2012*

As discussed previously, P enters the environment from many sources; fertilizers and soil amendments are some of the larger sources. On agricultural lands, P can be removed from soils via wind erosion, runoff, or, preferably, by crop uptake and removal when harvested.

Concerns about P in soils focus on the potential for transport of P to surface waters. The two most significant pathways of P transport are:

- *Dissolved P in stormwater runoff.* A variety of studies have found a significant correlation between the concentration of dissolved P in runoff water and the soil P content, as measured by P agronomic soil tests Sharpley, 1995 (see below for information on P test methods).
- *P adsorbed in soil particles*. This form of P can move to surface water when the soil particles are eroded. According to Penn State University (2001), up to 90% of the P transported from cropland is attached to sediment. Thus, erosion control is of prime importance in minimizing P loss from agricultural land.

Because P adsorbs readily to soil particles, P does not leach downward in significant quantities in most soil types, and, in turn, relatively little P is found in lower soil horizons (Penn State Univ., 2001; Sharpley, 1995). Thus leached P, which can move in shallow groundwater to surface water, is not an important pathway in most situations. If P does not leave a site as dissolved P in surface water runoff, via erosion of sediment containing P, or via plant uptake, it remains in the topsoil, where it tends to become part of increasingly stable mineral complexes. In fact, according to Penn State, up to 90% of inorganic P can become fixed within 2 to 4 weeks of being added to soil (Penn State Univ., 2001).

Similarly, organic forms of P, found in biosolids and manures, are also “fixed” but will slowly become available as microorganisms break down the organic matter. Once transformed into soluble P, soil pH, temperature, soil texture and other factors mentioned below will determine its fate.

Understanding the behavior P in the environment can help farmers meet the P needs of crops while avoiding release of excess P to surface waters (Frossard et al., 2000). The science is still developing regarding whether or not P that is labile in soil and available to plants, but not readily water soluble, presents a significant risk to surface water quality. According to Kukier et al (2010) it appears that the size of the labile pool of an element in soil does not directly correlate in a simple way into element concentration in plant shoots. A complexity of other factors, such as soil pH, plant physiology, competition between elements for absorption sites at the root surface, element speciation in soil solution, and the kinetics of sorption/desorption and precipitation/dissolution processes, all play a role in the P uptake by plants and the movement of P into the surrounding environment.

Codling (2013) reported that P added to soil via biosolids continues

Copyright © 2014 Water Environment Federation. All rights reserved.

to be available to plants for many years after application. However, others argue that this pool of labile P may be plant available, but it is unlikely to escape the soil system and impact surface water quality (Codling, 2013).

In summary, for P to adversely impact water quality, it must be present and there must be a method by which it is transported to a surface water body (especially ones that are susceptible to eutrophication). Research has demonstrated that high levels of soil P far from water bodies are, in general, not a threat and soils with low levels of P near susceptible water bodies present little threat (however, ideally, such soils should be managed to avoid build-up of excess P). The risk of P impacts on surface waters increase with higher levels of soil P, proximity of surface waters, and well-defined pathways for transporting soil P to surface waters. These are the factors that are considered in phosphorus indices, tools that help manage the risk of non-point P pollution from agriculture, which are described below.

Measuring Phosphorus in Soils

Assessing the particular potential risk of soil P affecting nearby surface waters depends on measurements of P in the soil. There are several different soil tests for P. They include:

Total P

This test involves use of a strong acid to strip as much P as possible from all minerals and molecules to which it is bound. Total P is a poor indicator of the potential for water quality impacts, because, in a field setting, much of the P it measures is bound to soil particles and is not available (i.e. not easily water soluble).

Plant-Available (or simply “Available”)

This is the most commonly used measure of P in soil, because it measures the phosphorus that is most likely available for uptake by plants. This includes P that is easily water soluble, as well as some that is less soluble, but labile. There are four standard tests that all aim to measure plant-available P: Bray, Olsen, Mehlich 3, and Modified Morgan. All report P in the P2O5 (phosphate) form, which relates stoichiometrically to Total P in this way: P_2O_5 = 2.291 * Total P. Most fertilizer recommendations and regulations use this measure of P (i.e. phosphate, P_2O_5).

The Bray, Olsen, Mehlich 3, and Modified Morgan tests differ in several ways, such as the concentration and makeup of the solution added to extract the P and the amount of time the sample is shaken (Sawyer, 1999). Each was developed to address different agronomic needs; for example, Bray was originally developed for Midwest soils, Mehlich 3 was developed for acidic Southeast soils with low cation exchange capacity (CEC), and Morgan (later modified) was developed as a more universal test for acid soils typical of the Northeast.

All of the above P test methods were developed to assess the level of P in a soil in order to develop recommendations for P fertilizer needs that will ensure best crop growth. But, soil P tests conducted for crop-growing recommendations do not correlate with potential environmental impacts of P to surface waters. Thus, a soil test result indicating an “optimum” level of P for a crop does not necessarily indicate if the level of P in the soil is likely to negatively impact surface water quality or not (Penn State Univ., 2001).

Water extractable P (WEP)

More recent research indicates that the P in biosolids and other materials that is of concern with regards to potential water quality impacts is only that portion of P that is water soluble, known as water extractable P (WEP). The remaining P is adsorbed strongly enough that it is unlikely to run off or leach and affect surface waters. As noted above, some of this P may still be labile (i.e. it may be undergoing transformations from being bound in one compound to being bound in another more plant-available compound) (Chaney, 2013; Chaney and Codling, 2005; Codling et al., 2000), but it is unlikely to escape the soil system and impact water quality. While not completely understood, when biosolids are involved, the reduced availability of P is likely due to the high levels of P binding constituents – such as aluminum or iron – in the typical biosolids. This reduced availability of P in biosolids is now accounted for through P source coefficients used in P indices (see below).

When regulations and best practices are developed, the type of test used to measure P is a critical consideration. Currently, different jurisdictions require different test procedures, resulting in significantly different restrictions on rates of application of P in various fertilizers and soil amendments.

Copyright © 2014 Water Environment Federation. All rights reserved.

Figure 6: Phosphate mining site near Tampa, Florida. In Florida, phosphate rock is extracted by an energy-intensive process called strip-mining, in which sandy topsoil is completely removed, exposing the phosphate matrix below. Source*: http://www.startribune.com/business/*

Biosolids: A Sustainable P fertilizer in Agriculture

Biosolids is an environmentally and economically responsible alternative to mined phosphate rock. All biosolids contain P and putting this P to use reduces the demand for mined phosphate rock, an energy-intensive and expensive product. Biosolids-borne P is a source of P typically closer to farms that need P, and it is provided to the farmer at low or no cost, thus reducing farm costs. Additionally, using biosolids as a fertilizer rather than disposing of it in a landfill will generally reduce the biosolids management costs for municipalities, save landfill space, and reduce the demand for more mined P, thus extending the availability of this critical natural resource. Although biosolids have these advantages over other sources of P, they must be managed responsibly to prevent impairment of surface waters.

Phosphorus: A Finite and Environmentally Damaging Resource

Phosphate rock, the primary source of commercially produced P fertilizer, is a finite resource with substantial environmental costs (Figure 6). In 2009, 67% of phosphate rock was mined in only three countries – China (35%), the USA (17%) and Morocco and Western Sahara (15%). "In the United States, only four states mine phosphate rock: Florida, North Carolina, Utah and Idaho, and Florida and North Carolina account for approximately 85% of the phosphate rock mined" (Minerals Education Coalition, 2013). Due to the high demand and limited supply of mined phosphate, the price of rock phosphate has risen dramatically in recent years, and the United States has actually stopped the export of phosphate. It is estimated that the supply of phosphorus from mined phosphate rock could peak as soon as 2033 and U.S. sources may be depleted within 25 years (Soil Association, 2010).

In addition to the challenge of a growing deficit between phosphate supply and demand, mining mineral phosphate poses its own environmental challenges. For example, according to the Soil Association (2010), for each ton of phosphate processed to produce fertilizer (via dissolving in sulfuric acid), 5 tons of a toxic by-product containing uranium and radium is generated and must be disposed of as a radioactive waste. Additionally, mining phosphate ore is energy intensive, requiring energy to mine the ore (found about 15-50 feet below the earth's surface), transport the ore (generally transported as a slurry many miles to the processing plants), and crush and process the ore to separate the phosphate from sand and clay.

Recycling phosphorus in manures and biosolids not only meets the increasing global need for P fertilizers, but also avoids significant environmental impacts associated with mined phosphate.

Copyright © 2014 Water Environment Federation. All rights reserved.

Biosolids Phosphorus: Lower Solubility and Environmental Availability

The solubility in water of phosphate derived from biosolids is lower than that of other P fertilizers. Many peer-reviewed studies (Tabbara, 2003; Gaudreau, et al., 2002, Brandt, 2003) generally support the conclusion that biosolids are less likely to produce P in runoff or leachate than synthetic fertilizers and animal manures due to differences in P solubility (Figure 7); others (Easton and Petrovic, 2004) reach the opposite conclusion. Many states have developed and implemented the P-index tool to assess the risk of P transport to aquatic systems and provide assistance with environmentally responsible P management.

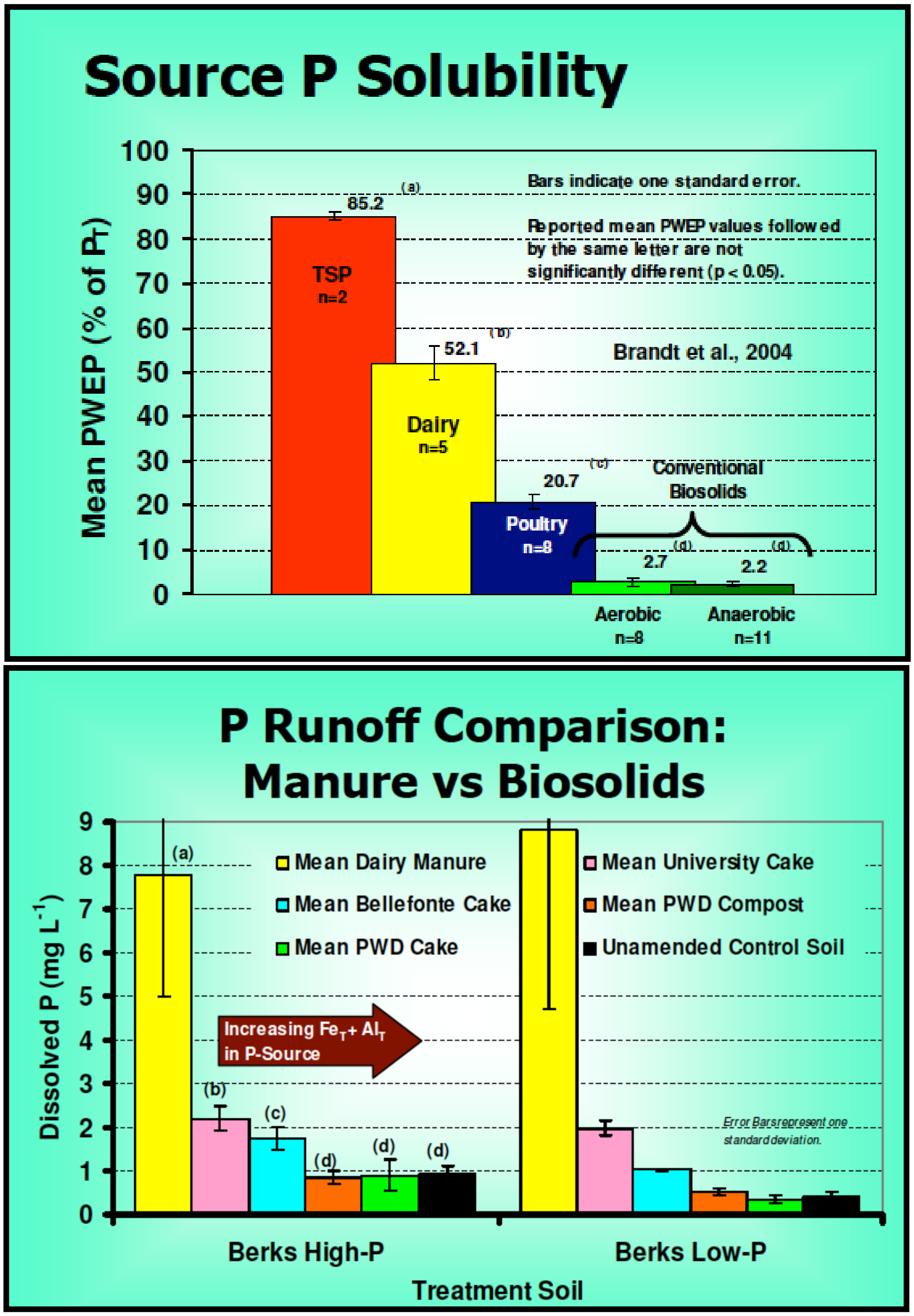


Figure 7: (A) In a 2004 study, Brandt et al. found that both aerobically and anaerobically digested biosolids have significantly lower water-extractable "available" phosphorus, than poultry litter, dairy manure, and triple-super-phosphate (a synthetic fertilizer). (B) In the second phase of the study, it was demonstrated that the concentration of dissolved P in the runoff of the soil treated with dairy manure was significantly greater than any of the soils treated with biosolids treatments. The study also found a correlation between dissolved P concentrations in the runoff and the concentration of iron (Fe) and/or aluminum (Al) in the P source.

Copyright © 2014 Water Environment Federation. All rights reserved.

The P index: a Valuable Tool

Application of P at rates greater than the uptake of the crops may be done responsibly by utilizing a P Index. A P Index tool is a scoring matrix for the dynamic phosphorus system at a particular site. It brings together site-specific data on sources of P ("source factors") and data on mechanisms by which P may move to surface waters ("transport factors").

The source factors commonly included in P Indices are:

- Soil test phosphorus (STP)
- Method of Application
- Rate of Application
- Amount of P applied under N-based application

And the transport factors that may be included in P indices are: Soil erosion potential

- Subsurface drainage
- Irrigation
- Distance to surface water
- Surface runoff class
- Riparian buffers

State Guidelines

Most state P indices assume that the solubility and runoff and leaching potential of P are the same for chemical fertilizers, manures, biosolids, composts, and other soil amendments. But research has clearly demonstrated that this is not the case. The source of the P has significant impact on the potential risk it poses to surface water quality (Brandt et al., 2004). Since the solubility and runoff and leaching potential vary with the source of P, some states include tabulated "phosphorus source coefficients" (PSCs) to account for the differential P-loss potential of fertilizers and soil amendments. Because organic P sources defy rigid categorization, methods have been developed for quantifying source-specific PSCs based on simple testing of the water extractable P (WEP) content of the material to be land applied (Elliott et al., 2005).

When a state P index treats biosolids like any other source of P, by assigning to them source coefficients that are the same as chemical fertilizers, the land application of biosolids may not be allowed on many sites or may be limited to very small application rates. In those states that have adopted lower coefficients for biosolids, land application will remain viable.

The inclusion of PSCs in P indices improves their ability to identify sites vulnerable to P loss (Elliott et al., 2005). This is especially important for biosolids, since research suggests that biosolids have lower WEP and P source coefficients because of the relatively high levels of aluminum and iron they contain (Elliott, 2002; Chaney, 2013). Pennsylvania is an example of a state that has included source coefficients in its P index (Penn State, 2007).

National Guidelines

Natural Resources Conservation Service (NRCS) Code 590 creates a *national* guideline for nutrient management, which can help to make P indices more consistent from state to state. However, there will continue to be significant differences, because Code 590, released in December, 2011, assumes interpretation and implementation at the state level will be based on local needs and conditions. A key provision of Code 590 is that applications of manures must take into account the level of P risk at any particular site, which is calculated using a state-developed and NRCS-approved P index. This provision is applied to biosolids as well. Originally, the P index was intended to be an educational tool, "intended to help *producers* understand important site and management factors" (Brandt, 2013). It has, however, gone well beyond that and become a policy and regulatory tool.

Some of the differences between state P indices are being addressed. For example, a current NRCS-CIG-funded project has the goal of harmonizing nutrient management to the Code 590 standard and developing consistency amongst the states in the Chesapeake Bay Region (Brandt, 2013).

State Regulations of Phosphorus and the Impact on Biosolids Usage

Due to mounting concerns regarding the adverse effects of excess nutrients in surface waters , many states have implemented—or are in the process of implementing--laws and guidelines that impact the feasibility to land apply biosolids products and other P-containing residuals. For example, P fertilizer on turfgrass is being banned or significantly reduced by the majority of states in the northeast, unless a soil test shows need for P. Additionally, some states have implemented P-indices with very restrictive P allowances, resulting in reduced P fertilizer usage even in agriculture. Some states have even adopted numeric nutrient criteria. As a result of these laws, successful biosolids programs have been significantly influenced, leaving biosolids managers facing fewer end-use options.

Bulk Agriculture Fertilizers Regulations

A key component of the federal biosolids regulations (40 CFR Part 503) is the requirement that Class B, bulk, land applied biosolids be applied at the agronomic rate for nitrogen (N). As discussed previously, biosolids are an unbalanced fertilizer, in that when applied to meet the N needs of the plant, the P will be applied in excess. In recent years, some states have implemented nutrient management requirements for agricultural operations that strive to avoid or reduce the build-up of P in the soil. Based on the features of the particular site, these management practices require nutrient application to meet the P needs of the crop or, if indicated by high soil P tests, may prohibit P fertilizer application altogether. Many of these state nutrient management requirements rely on a state P index to determine if amendment application rate must be limited to satisfying the crop P requirement.

Turf-grass Fertilizer Regulations

At least 15 states have laws and/or regulations related to turfgrass fertilizers, including 11 states that have completely banned the use or sale of P for lawn maintenance. While most of these are in the mid-Atlantic, Northeast, and upper mid-West (bordering the Great Lakes), Florida is also a leader in this area (dispatch.com, 2013). Many of these laws/regulations have been adopted in the past few years and

Copyright © 2014 Water Environment Federation. All rights reserved.

are still in the process of being implemented. In general, these state restrictions on turf fertilizers include:

- focus on P, but, in many cases, nitrogen as well;
- definitions of specific materials (e.g. fertilizers, composts) to which the restrictions apply;
- prohibitions on particular uses and/or permissions for particular uses;
- site and management restrictions (e.g. setbacks from surface waters, no application to impervious surfaces or frozen or saturated soils); and
- requirements regarding labeling and display of P-containing fertilizer products at the point of sale.

While the underlying theme of these turfgrass fertilizer regulations is generally consistent, the specific details vary a good deal among states. Some states completely prohibit use on turfgrass of fertilizer or P-containing fertilizer – defined either as having no measurable P or having less than 0.67% P. Some states have specific restrictions for applications during winter months. As a result, Scotts removed P from most of its Turf Builder lawn fertilizers. Because Scotts is a leader in the fertilizer marketplace, any companies that have not already done so will likely remove P from their regular lawn fertilizer products as well (Columbus Dispatch, 2013b).

Figure 8: Source: *http://www.extension.umn.edu/*

Many states do not include golf courses in their new restrictions, although some require conditions for golf course use. While all states allow P-containing fertilizer to be used when a new lawn is being started or when a soil test shows a need for P, only some states specify that P fertilizer use on flower and vegetable gardens is allowed. Some states have developed different criteria for homeowners and for certified professional applicators, assuming that the latter will apply scientific standards more precisely.

The New England Interstate Water Pollution Control Commission (NEIWPCC) has compiled a summary of state turf fertilizer regulations for states in the Northeast as part of its final recommendations to states and fertilizer applicators regarding best practices (NEIWPCC, 2014).

What You Can Do – Monitor and Enhance Fertilizer Regulations

While it is recognized that new P regulations may be inevitable in areas where eutrophication is a major problem, many of the state laws being developed have imprecise or incomplete definitions, or they reference existing agricultural laws and regulations containing definitions of “fertilizer,” “commercial fertilizer,” “soil amendment,” “soil conditioner,” “organic fertilizer,” etc. In many instances, it remains unclear what definitions apply to biosolids and other organic residuals, and even state regulatory agency staff interpreting the laws and applying the regulations are uncertain.

Therefore, it is critical for wastewater and biosolids managers to:

- discuss the details of these laws and regulations as they apply to biosolids with the appropriate state regulatory agencies (especially during public comment periods);
- urge the integration of P source coefficients in regulations and the state P index;
- pay attention to the type of P test being required in assessing the level of P in a fertilizer, soil amendment, or soil. Water Extractable P tests should be used to assess the potential for environmental impacts from P, while other tests can continue to be used for evaluating the agronomic need for P; and
- educate lawmakers and agricultural advisors (e.g. Cooperate Extension and NRCS staff) about the benefits of using biosolids, including the enhancement of soil properties, the environmental benefits of recycling (not landfilling), greenhouse gas reductions, and benefits to local economies and jobs. Emphasize the fact that the nutrients in biosolids – including P – are already in the local region and should be used instead of importing nutrients from afar. Providing such arguments may improve the flexibility and efficacy of fertilizer laws and regulations to allow for continued use of biosolids in bulk agriculture and as turf fertilizer.

Best Biosolids Management Practices to Reduce P Losses

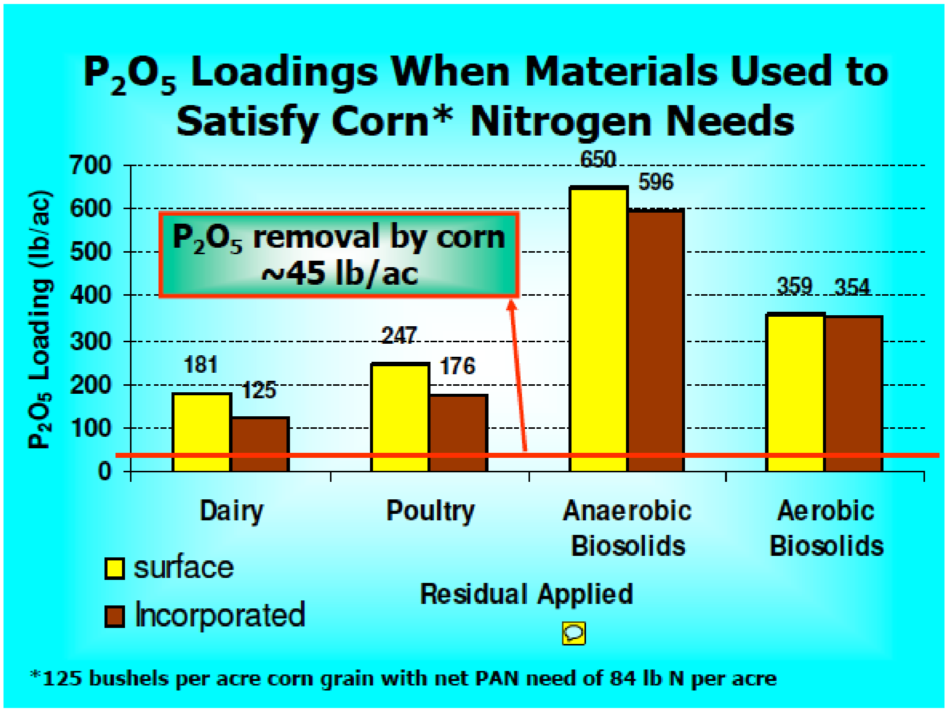
With proper management, land application of biosolids is an environmentally responsible practice that will produce minimal nutrient runoff into surface waters. Best management practices include:

- matching biosolids application rates with crop P needs or using a 3 to 5-year application cycle,
- maintaining an up-to-date nutrient management plan,
- implementing farming practices that minimize erosion,
- maintaining robust and adequately-sized vegetative buffers,
- storing biosolids properly, and
- applying other residuals to reduce P solubility.

Copyright © 2014 Water Environment Federation. All rights reserved.

Matching Biosolids Application Rates with Crop P Needs

Best nutrient management practices with biosolids are challenging because biosolids generally contain higher P and lower potassium (K) in relation to the level of N needed by the crop (Figure 7). Federal and state requirements for biosolids generally require application at the agronomic rate for N. This is because excess N is considered to present the highest risk of impacting water quality through leaching of nitrate to groundwater. Therefore, when biosolids are applied to meet the crop's nitrogen needs, too little K and too much P are usually provided to the crop.


P_2O_5 Loadings When Materials Used to Satisfy Corn* Nitrogen Needs

*125 bushels per acre corn grain with net PAN need of 84 lb N per acre

Figure 9: Phosphate loadings when materials are applied at rates to meet corn N needs. When organic fertilizers (including manures and biosolids) are applied to meet the crop's N needs, P is usually applied at rates that greatly exceed the crop's P need. Source: *Brandt, 2004*

Animal manures can also be unbalanced in their fertilizer values (Figure 9). Thus, when biosolids and manures are land applied to provide the N needs of the crop, excess P is added to the soil. Therefore, repeated applications of manures and biosolids to one site to meet the crop's entire N need is unsustainable. To prevent P buildup in the soil, biosolids can be applied at a rate to meet the crop's P needs, with the addition of supplemental N and K in the form of commercial fertilizers. Understanding that the biosolids application rate based on the P need of the crop is very low and may be difficult to accomplish (limitations of spreading equipment), another more suitable method is to land apply on a 3 to 5-year cycle based on the N application rate. The applications can be better managed and additional fertilizer applications are not necessary. Also, farmers are accustomed to having the N need of the crop satisfied from biosolids applications. Soil P levels may continue to increase slightly over time using this method, but at a slower and more acceptable rate.

Implementing a Nutrient Management Plan

A nutrient management plan is designed to optimize nutrient use for crop production and reduce water quality impacts in a scientifically sound and cost-effective manner. A comprehensive nutrient management strategy involves application of a science, technology and management -based framework to assess and reduce nutrient losses to waters of the U.S while optimizing crop yield and quality.

Farmers involved in nutrient management programs have demonstrated that voluntary management practices are reducing the loss of N fertilizer from fields. Their goal is to better manage nutrients to make them available for plant growth rather than to drain beyond the plant root zone and into shallow groundwater and surface waters. The application of comprehensive nutrient management planning processes to biosolids management has started in many jurisdictions and discussion with state personnel indicate these plans will be an essential part of future land-based biosolids management efforts.

A nutrient management plan is intended to address optimum utilization of nutrients for plant growth. Both voluntary and regulatory issues must be addressed. Nutrient management planning is good practice and phosphorus management specifically is required of some operations under provisions of the NRCS 590 program. A nutrient management plan addresses the rate of nutrient application, the timing of the application event relative to crop growth, the placement of those nutrients relative to the plant root zone, and the form of the nutrient relative to plant need. A phosphorus plan is intended to minimize phosphorus loss through runoff. Implementing a nutrient plan is an essential element of a biosolids management program.

A nutrient management plan optimizes application rates based on crop yield. All sites do not have identical capacity to produce crops. The nutrient management plan is intended to use scientifically sound

Copyright © 2014 Water Environment Federation. All rights reserved.

practice to justify nutrient loading based on the needs of specific crops, host soil resources, and climate. Nutrient loadings are based on the crop harvested and harvest records provide sound justification for the rate of nutrient addition. Nutrient management plans force wise use of resources and this will become increasingly critical as available stores of nutrients decline over time.

Assistance in nutrient management planning is available through the land grant university system and many state departments of agriculture, environment, or conservation. Individuals involved in biosolids management should contact local cooperative extension service offices to determine specific nutrient management needs in a specific area.

Proper Storage of Biosolids

Proper biosolids storage must also be considered when developing an effective biosolids land application program; if stored improperly, biosolids have a much greater potential to produce runoff that contains high concentrations of P and other nutrients. Four (4) variables affect the execution of successful P management when storing biosolids in the field.

1. *Water Content of Biosolids*: Liquid and some semi-sold material require well-constructed storage facilities that will prevent the movement runoff containing high P concentrations out of the confined storage area.
2. *Length of storage period*: Longer storage periods increase the potential for exposure to wet weather and potential for P to move out of the storage area and into surrounding waterways.
3. *Volume of stored material*: Management requirements in terms of site design, operation and the potential for water quality impacts may increase with the volume of material stored.
4. *Climate and weather conditions*: Wet conditions generally increase management requirements as compared to storage during dry or cold conditions.

When storing biosolids, it is important to minimize the exposure to precipitation and other sources of water. Various practices can be used to achieve this including site selection that avoids run-on, flooding, or high water tables that can intercept stored biosolids or installing upslope diversions to channel runoff away from a field stockpile or constructed storage facility (Figure 10). Containment of biosolids in enclosed structures or tanks is also a method for biosolids protection from water contact.

Any significant precipitation or upslope runoff that comes in contact with stored biosolids may contribute to a discharge of nutrients. Whether this water accumulates on or near the biosolids, runs off or leaches through the soil, it has the potential to transport contaminants to water resources. Practices to address this issue include:

- Proper shaping of field stockpiles to shed water and avoid puddles of water, or infiltration of water through a stockpile and subsequent loss through runoff or leaching.
- Construction of enclosed storage facilities or tanks.
- Construction of lagoons/pads with impervious earthen, concrete, or geotextile liners.
- Removal of accumulated water to sites where liquid may be applied.
- Providing buffers between storage areas and waterways.

For permanent long-term storage facilities, an impermeable liner is recommended to minimize potential for leaching. For all constructed storage facilities, site soils and water table investigations are essential to ensure stable foundations. Soil settling and shifting can result in leakage through cracks. High water tables may float concrete pads or rupture the watertight seals of lagoons.

Accumulated water forms a separate layer on top of liquid or semisolid biosolids. Water that has contacted the stored biosolids can also form puddles at the storage site. Seeping or runoff of this water to surface or ground water resources can be minimized by the following:

- For open storage facilities
  - Use sumps or gravity flow to direct accumulated water to on-site filter strips or treatment ponds.
  - Mix accumulated water with biosolids or removal

Figure 10: A well-managed biosolids storage area at a southcentral Pennsylvania Farm. Biosolids are completely covered with impervious tarps to avoid run-on and contained in a well-defined area, minimizing the potential for run-off containing high levels of P.

Copyright © 2014 Water Environment Federation. All rights reserved.

    - to land application site.
    - Decant and transport water accumulations off site to treatment facilities.
    - Apply to the land through irrigation systems making sure that runoff is not an issue.
- For constructed facilities
    - Roof to keep precipitation off of the biosolids
    - Pads should have adequate slope to prevent ponding and appropriate flow management

Practices to minimize erosion/surface losses

Unlike nitrogen (N), which is readily transported via leaching through soil pores, most P is tightly adsorbed to soil particles and, in general, does not leach readily through the soil profile. The primary mode of P transportation is via erosion and sediment movement from the soil surface. Therefore, employing farming practices that will minimize soil loss on agricultural fields where biosolids are applied is critical for reduced P movement into waterways.

Figure 11: No-till planting of corn on a terraced field near Plymouth, Iowa. No-till planting reduces soil disturbance, preventing wind and water from eroding the soil and removing P and other nutrients. Source: *http://www.livinghistoryfarm.org/*

Best management practices to reduce soil and biosolids movement include:

- injection of biosolids and/or immediate incorporation into the soil,
- reduced or no tillage,
- contour tillage,
- leaving plant residue in place after harvest, and
- planting cover crops.

While the primary method of P movement is via soil erosion, if P sources (biosolids, manure, commercial fertilizer) are applied immediately preceding a precipitation event or on frozen and/or snow-covered ground, P can also be transported via stormwater runoff. To minimize P movement via stormwater runoff and reduce the likelihood of water quality impacts from applied P, many states have implemented policies to restrict biosolids application:

- during winter months,
- during or just before precipitation events,
- on snow-covered or frozen ground,
- on steep slopes,
- in wetlands, or
- on exposed ledges or areas with shallow bedrock.

It is important for application program personnel to be aware of all regulations regarding weather and site conditions related to land application of biosolids.

Maintain robust and adequately-sized vegetated buffers

One of the most effective ways to reduce transport of sediment-bound P from agricultural and other settings is through maintenance of healthy vegetated buffers. While the federal Part 503 regulations and many state regulations require setbacks from surface waters for biosolids land application (the minimum is 10 meters), what matters most is that the nature of the setback area. The best vegetated buffers include a diversity of thickly-growing forbs, herbaceous plants, shrubs, and even trees. The width of the buffer needed will vary by state and from site to site, but should be at least 10 meters according to the federal regulations. Vegetated buffers provide many benefits (U.S. Dept. of Agriculture, 2014).

Regardless of the best management practices selected, working with each farmer to discover what options are best suited to his/her farm is critical to a successful biosolids management program. Work with farmers and nutrient management and conservation advisors to develop a feasible soil and erosion plan that will minimize the potential for loss of P.

Applying other residuals to reduce P solubility

Conventional best management practices reduce the potential for P movement into the environment – especially the movement of sediment-bound P. Recent research has demonstrated an additional way to reduce P availability – the addition of water treatment residuals (WTR) to soil amendments or soils.

Many drinking water treatment facilities mix non-toxic aluminum-based and iron-based chemicals into the water as part of the water cleaning process to destabilize and remove suspended solids. After these coagulants have bound with a variety of trace contaminants in the water, they are removed by settling, taking the contaminants with them. These water treatment residuals (WTR), sometimes called "alum sludge" or "ferric sludge," are managed in a variety of ways, including via discharge to a wastewater treatment facility, landfill disposal, or land application. WTRs are composed predominantly of the suspended solids removed from the water source and the precipitates formed by the added Al or Fe coagulant ; they also contain a variety of trace amounts of metals, suspended solids, organic chemicals, and biological particles.

Mixing biosolids with iron- or aluminum-rich byproducts, such as WTR, will reduce the environmental availability of P when the biosolids are land applied (Elliott et al, 2002). WTR can also be mixed directly into soils to increase adsorption of P, reducing P availability. Such practices are especially helpful in reducing the potential impacts of dissolved P, including when WTR are used in a buffer strip (Wagner et al., 2008). In a field study, Carpenter (2013) showed that, while application of alum residuals lowered the measured soil available P, soil fertility, corn crop yield, and tissue quality were not adversely affected.

Copyright © 2014 Water Environment Federation. All rights reserved.

As a result, WTRs are increasingly recognized as useful tools to reduce phosphorus impacts to surface waters, especially in areas where excess P is already impairing the health of lakes and streams. The use of this technology is still limited, and because the volumes of WTR available are smaller than the potential need, their use will likely have to be strategic: for example in field edges and buffer areas close to surface waters, where they can provide a final defense against P movement.

Another Best Practice: Getting P Out of Biosolids at the WRRF

WRRFs face many competing pressures. The management of P is becoming one of the most challenging. In many places, USEPA and states are ratcheting down permit limits on nutrient discharges, requiring costly advanced nutrient removal systems. The P removed ends up in increased concentrations in the biosolids. In states requiring nutrient management, P indices, and other restrictions on P applications, this means more thoughtful planning is needed for biosolids applications to soils.

This P challenge has put managers of WRRFs with biosolids land application programs in an awkward position. They maintain that extremely low permit limits for P discharges are not cost effective. It has become a matter of there being just too much phosphorus in some regions, and people arguing back and forth as to how best to control it. Soil scientists have mapped where excessive P occurs in the U. S., and it is predictably in those areas where cows, pigs, and other livestock are concentrated. In general, feeds grown in the Midwest are shipped to finishing operations in certain areas and states, where more manure is generated than needed for the available cropland. In a parallel fashion, crops for human consumption are shipped to urban areas where excess nutrients collect in wastewater. Rebalancing the cycling of P requires capturing P in a concentrated form from livestock finishing areas and urban areas and returning it to the vast areas in the Midwest and parts of California where it is needed to replace the P that left with the crop.

One way WRRFs can play a critically important role in addressing this problem is to remove P in the treatment process. P is definitely a resource, and if WRRFs are going to live up to their name, recovering P in a concentrated form should become a priority. Already, there are several facilities around North America that are removing P – or planning to (Chicago being the largest) – through use of advanced nutrient harvesting technologies. Initially, the application of these technologies was driven by the need to reduce the costly problem of accretion of struvite (magnesium ammonium phosphate) and related minerals on WRRF processing equipment, mostly at facilities with anaerobic digestion.

These relatively new nutrient-harvesting technologies include Ostara, Multiform Harvest, Crystalactor by DHV, and Paques. As of 2014, Ostara has the most installations worldwide, with several installations in North America. Multiform Harvest has a very similar technology and process; however they do not have as many installations. The Paque Phospaq system is generally applied to recover phosphorus from effluent water; they claim phosphorus removal efficiencies of 70-95% (Paques, 2013).

The use of these kinds of technologies produces a concentrated mineral material (e.g. struvite, apatite). The benefits are:

- the biosolids from a WRRF with this kind of technology may have lower concentrations of P and may re-focus attention in the wastewater community about the need to generate an appropriately balanced fertilizer to meet crop needs, and
- the concentrated form of P removed in the process can be efficiently transported to locations and uses where additional P is actually needed.

If WRRFs can efficiently remove P from biosolids, then biosolids can be applied more sustainably. And the concentrated P fertilizer can be recycled, reducing demand for mined phosphate.

But because of the critical worldwide need to recycle P and reduce the demand for mined phosphate, harvesting of P at WRRFs (and from animal manures) is inevitable. Already, in Europe, additional technologies are being developed, and countries are advancing policies requiring recovery of P. For example, Sweden is working toward a goal of recovering 60% of the P in wastewater by 2015 and putting most of it back on arable land (Evans, 2014).

Applying biosolids to soils is already an important part of the recycling of phosphorus and the reduction of demand for mined phosphate. Fertilizer legislation and regulations should not overly restrict the continuation of this recycling program. Biosolids and other organic residuals that are recycling P and other nutrients must be treated differently than chemical fertilizers, because they involve recycling of local resources, rather than importation of an energy-intensive limited natural resource.

But, as discussed above, WRRFs and biosolids managers can take measures now to reduce the potential for biosolids-borne P to impact surface waters.

Copyright © 2014 Water Environment Federation. All rights reserved.

References

Ajiboye B, O.O. Akinremi, G.J. Racz. 2004. Laboratory Characterization of Phosphorus in Fresh and Oven-Dried Organic Amendments. *Journal of Environmental Quality*. 33:1062-1069.

Beegle, D.B. 2012. *SOILS 402: Soil Nutrient Behavior and Management*. The Pennsylvania State University.

Brandt, R.C. 2003. Land application of biosolids under phosphorus-based nutrient management. Ph.D. Dissertation. The Pennsylvania State University. 215 p.

Brandt, R.C. 2013. Biosolids-P Management: P Index Standardization & Emerging No-Till Land Application Technologies. Mid Atlantic Biosolids Association Symposium. July 16-17.

Brandt, R.C., H.A. Elliott, and G.A. O'Connor. 2004. Water-Extractable Phosphorus in Biosolids: Implications for Land-Based Recycling. *Water Environment Research*. 76(2):121-129.

Carpenter, A. 2013. Water Treatment Residuals: Use as a Soil Amendment. Presentation to the North East Residuals & Biosolids Conference, October 30. http://www.nebiosolids.org/uploads/pdf/NE%20Conf.%202013/Carpenter-WaterTreatmentResidualsAsSoilAmendment-30Oct13.pdf

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications.* 8:559-568.

Chaney, R. 2013. Influence of Phosphorus Forms in Residuals on Plant Uptake and Potential for Environmental Releases. Mid-Atlantic Biosolids Association. http://www.mabiosolids.org/uploads/MABA%20Annual%202013/Chaney-Phosphorus%20Mgmt%20and%20Use%20of%20biosolids%20in%20remediation%20%5BCompatibility%20Mode%5D.pdf

Chaney, R. and E. Codling. 2005. Bio-based Plant Nutrient products: Heavy Metals Considerations. In Proc. Workshop Bio-Based Plant Nutrient Products. pp. 22-36. In: *Biobased Plant Nutrient Products: Quality Assurance, Marketing and Regulations*. R. Reynelles (ed.) Seattle, WA, Oct. 31, 2004. USDACREES, Washington, DC.

Chaney, R., L. Kukier, U., and E. E. Codling. 2013. Biosolids Phosphate: Plant Available but not Water Soluble. Presentation to the Mid-Atlantic Biosolids Association, July 2013, Lancaster, PA.

Chartered Institution of Water and Environmental Management (CIWEM). 2012. Phosphorus: Wastewater's Role in Stewardship of a Vital Resource. Policy statement, August 2012. http://ciwem.org/policy-and-international/policy-position-statements/phosphorus-wastewaters-role-in-stewardship-of-a-vital-resource.aspx

Codling, E. 2013. The real dirt on biosolids. *Agricultural Research,* Jan. 2013, pp. 16-17, USDA Agricultural Research Service. http://www.ars.usda.gov/is/AR/archive/jan13/biosolids0113.pdf

Codling, E.E., R.L. Chaney and C.L. Mulchi. 2000. Use of Aluminum - and Iron-rich Residues to immobilize phosphorus in poultry litter and litter-amended soils. *Journal of Environmental Quality* 29:1924-1931.

Columbus Dispatch, The. 2013. Gypsum on fields may cut runoff of phosphorus. February 3, 2013. http://www.dispatch.com/content/stories/local/2013/02/03/gypsum-on-fields-may-cut-runoff-of-phosphorus.html

Columbus Dispatch, The. 2013. Scotts drops phosphorus from lawn fertilizer. May 10, 2013. http://www.dispatch.com/content/stories/business/2013/05/10/scotts-drops-phosphorus-from-lawn-fertilizer.html

Easton, Z.M. and A.M. Petrovic. 2004. Fertilizer source effect on ground and surface water quality in drainage from turfgrass. Journal of Environmental Quality 33(2): 645-655.

Elliott, H.A., G.A. O'Connor, P. Lu and S. Brinton. 2002. Influence of water treatment residuals on phosphorus solubility and leaching. *J. Environ. Qual*. 31:1362-1369.

Elliott, H.A., G.A. O'Connor and S. Brinton. 2002. Phosphorus leaching from biosolids-amended sandy soils. *J. Environ. Qual*. 31:681-689.

Elliott, H.A., R.C. Brandt, P.J.A. Kleinman, A.N. Sharpley, and D.B. Beegle. 2005. Estimating source coefficients for phosphorus source indices. *Journal of Environmental Quality.* 35:2195-2201.

Evans, T. 2014. Phosphates: Time to Act. *The Chemical Engineer.* February. 29 – 32.

Gascho, G.J., R.D. Wauchope, J.G. Davis, C.C. Truman, C.C. Dowler, J.E. Hook, H. R. Sumner, and A.W. Johnson. 1998. Nitrate-Nitrogen, Soluble, and Bioavailable Phosphorus Runoff from Simulated Rainfall After Fertilizer Application. *Soil Science Society of America Journal*. 62:1711-1718.

Gaudreau, J. E., D. M. Victor, R. H. White, T. L. Provin, and C. L. Munster. 2002. Response of turf and quality of water runoff to manure and fertilizer. J. Environ. Qual. 31(4): 1316-1322.

Gburek, W.J., A.N. Sharpley, L. Heathwaite, and G. Folmar. 2000. Phosphorus Management at the Watershed Scale: A Modification of the Phosphorus Index. *Journal of Environmental Quality*. 29:130-144.

Havlin, John L., Samuel L. Tisdale, Werner L. Nelson, James D. Beaton. 2004. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Seventh Edition. Pearson Prentice Hall, New Jersey.

Kukier, U.; R. L. Chaney; J. A. Ryan; W.L. Daniels; R. H. Dowdy; and T. C. Granato. 2010. Phytoavailability of cadmium in long-term biosolids-amended soils. *Journal of Environmental Quality.* 39: 519-530.

Maguire, R.O. and J.T. Sims. 2002. Measuring Agronomic and Environmental Soil Phosphorus Saturation and Predicting Phosphorus Leaching with Mehlich 3. *Soil Science Society of America Journal*. 66:2003-2039.

Maguire, R.O., J.T. Sims, and F.J. Cole. 2000. Phosphorus Fractionation in Biosolids-Amended Soils: Relationship to Soluble and Desorbable Phosphorus. *Soil Science Society of America Journal*. 64:2018-2024.

Maryland Dept. of Agriculture. 2013. Fact Sheet: Maryland's Lawn Fertilizer Law – What You Should Know. http://mda.maryland.gov/resource_conservation/Documents/fertilizerwebpage.pdf

Copyright © 2014 Water Environment Federation. All rights reserved.

Minerals Education Coalition. 2013. Phosphate rock. http://www.mineralseducationcoalition.org/minerals/phosphate-rock.

NEIWPCC. 2014. Regional Clean Water Guidelines for Fertilization of Urban Turf, Final Report to the New England and New York State Environmental Agency Commissioners. http://neiwpcc.org/turffertilizer/turf-docs/finalreport.pdf.

North East Biosolids and Residuals Association, 2012. Water treatment residuals. http://www.nebiosolids.org/index.php?page=water-treatment-residuals.

Paques. 2013. PHOSPAQ. http://en.paques.nl/pageid=199/PHOSPAQ%E2%84%A2.html

Parry, R. 1998. Agricultural phosphorus and water quality: A U.S. Environmental Protection Agency perspective. *Journal of Environmental Quality*. 27:258-261.

Penn State Univ. 2001. *Managing phosphorus for agriculture and the environment*. Fact sheet. College of Agricultural Sciences, Agricultural Research and Cooperative Extension.

Penn State Univ. 2007. *The Pennsylvania Phosphorus Index: Version 2*. College of Agricultural Sciences, Agricultural Research and Cooperative Extension. http://panutrientmgmt.cas.psu.edu/pdf/phosphorus_index_factsheet.pdf

Sawyer, J. E. 1999. Differentiating and Understanding the Mehlich 3, Bray, and Olsen Soil Phosphorus Tests. http://www.agronext.iastate.edu/soilfertility/presentations/mbotest.pdf

Sharpley, A. 1995. Fate and Transport of Nutrients: Phosphorus (Working Paper No. 8). Natural Resources Conservation Service (NRCS). U. S. Dept. of Agriculture. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/rca/?&cid=nrcs143_014203

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullings. 2003. Development of Phosphorus Indices for Nutrient Management Planning Strategies in the United States. *Journal of Soil and Water Conservation*. 58(3):137-151.

Soil Association (United Kingdom). 2010. A rock and a hard place: Peak phosphorus and the threat to food security.

Tabbara, H. 2003. Phosphorus loss to runoff water twenty-four hours after application of liquid swine manure or fertilizer. *Journal of Environmental Quality*. 32:1044–1052.

U.S. Dept. of Agriculture, Natural Resources Conservation Service. 2014. Conservation buffers. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/newsroom/features/?&cid=nrcs143_023568

U.S. Environmental Protection Agency, Department of Agriculture. 2000. Guide to Field Storage of Biosolids. EPA 832-B-00-007. Washington, DC.

U.S. Environmental Protection Agency. 2009. National Water Quality Inventory: Report to Congress. EPA 841-R-08-001. Washington, DC.

Vadas, P.A., P.J. A. Kleinman, and A.N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface-applied manures. *Journal of Environmental Quality.* 33:749-756.

Wagner, D., H. Elliott, R. Brandt, and D. Jaiswal. 2008. Managing biosolids runoff using buffer strips enhanced with drinking water treatment residuals. *Journal of Environmental Quality.* 37(4):1567-74.

Additional Resources

- National Biosolids Partnership
- Water Environment Federation
- Enabling the Future: Advancing Resource Recovery from Biosolids, WEF, 2013.
- "Solids Process Design and Management" (Chapter 21: Sidestreams from Solids Treatment Processes), WEF Press, 2012.
- "What every operator should know about biological phosphorus removal," *WE&T* (Operator Essentials), July 2013, p. 48-50.
- Leaders Innovation Forum for Technology (LIFT), Phosphorus Recovery, WEF/WERF.
- Nitrogen and Phosphorus Pollution Data Access Tool (NPDAT), US EPA.
- Advances in the State of Biosolids Management Practice Fact Sheet, National Biosolids Partnership, 2012.

For further Biosolids information, please see http://www.biosolids.org.

CONTACT:

Water Environment Federation
601 Wythe Street
Alexandria, VA 22314
703-684-2400
biosolids@wef.org

Copyright © 2014 Water Environment Federation. All rights reserved.