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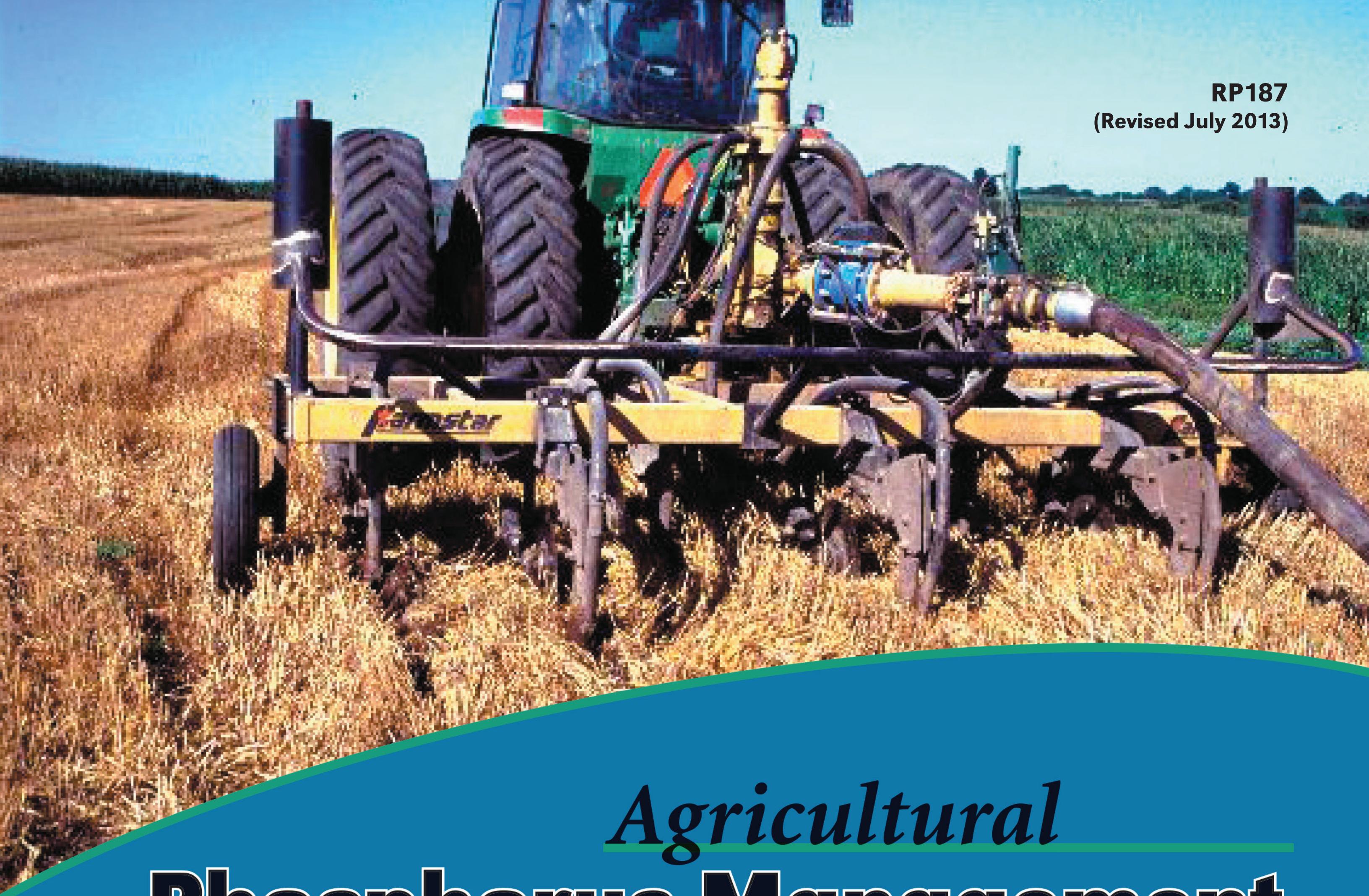

Agricultural Phosphorus Management and Water Quality Protection in the Midwest

HEARTLAND
Regional Water Coordination Initiative

EPA Region VII

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Introduction

Phosphorus (P) is an essential nutrient for growth of crops and aquatic vegetation and often needs to be applied to land for optimal crop growth. Land application of P as animal manure, biosolids (sewage sludge), and mineral fertilizer can increase the risk of P pollution of freshwater.

The movement of P from agricultural land to surface and groundwater is a complex process involving multiple pathways. Phosphorus moves into surface freshwaters dissolved in runoff water and attached to particulate matter eroded from the land. Recently applied P is particularly prone to losses and is affected by factors such as the form of P applied, the time since, and the placement. The factors contributing to P loss from agricultural land to surface water are commonly grouped as source (site and management) factors and transport factors (*Table 1*).

Table 1. Source and transport factors that contribute to the potential for P loss from agricultural lands to surface waters

Site and management factors	Transport factors
Soil P levels	Erosion from rainfall, snowmelt, and irrigation events
P application practices including time	Surface runoff rate and method of application
Associated field management practices	Subsurface drainage such as tillage and use of cover crops
	Percolation and underground movement of P to seepage areas
	Distance from P source to concentrated water flow or a water body
	Direct atmospheric deposition

This publication is a resource that nutrient management planners can use to understand the risk of P delivery to surface waters, assessment of this risk, and P management options for reducing this risk. It is targeted to U.S. EPA Region 7, which includes Iowa, Kansas, Missouri, and Nebraska.

Abbreviations: CAFO — concentrated animal feeding operation recognized by the state as meeting specified size and other requirements; NRCS — Natural Resources Conservation Service of the United States Department of Agriculture; U.S. EPA — the United States Environmental Protection Agency.

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Phosphorus Contamination of Surface Freshwaters

Phosphorus is often the limiting nutrient to the growth of vegetation in surface freshwater bodies. In these water bodies, increasing P concentration will increase growth of aquatic vegetation. Excessive growth of aquatic vegetation leads to depletion of oxygen, reduction of light transmission and water clarity, and production of algal toxins. These water quality changes can hurt fish populations, reduce water quality for recreation, and impart undesirable odors and tastes resulting in increased cost of treating water for domestic use. The progressive increase in nutrient concentration in water bodies that results in deterioration of water quality through overstimulation of aquatic vegetation is called eutrophication.

Eutrophication is a naturally occurring process that is often accelerated with intensification of agriculture or other land uses that result in increased flow of nutrients to water bodies. Changes that take centuries in natural systems can take just decades with the high rates of P loss associated with some intensive agricultural systems. Accelerated eutrophication is one of the most obvious and persistent surface freshwater quality problems in the United States. Over 65 percent of rivers and streams and 80 percent of lakes and reservoirs in the four-state area are rated as impaired (*National Water Quality Inventory Report to Congress, 2012 Reporting Cycle)*. Agriculture, broadly defined, is among the top sources of impairment of streams, lakes, and reservoirs in the four states.

The U.S. EPA has mapped 85 ecological regions of the United States based on characteristics of geology, physiography, vegetation, land use, climate, wildlife, soils, and hydrology (Level III Ecoregions of the Continental United States, U.S. EPA, December, 2011). The characteristics affect terrestrial and aquatic ecosystem quality and integrity. The Western Corn Belt Plains ecoregion covers most of Iowa, eastern Nebraska, and parts of Kansas and Missouri. Additional large ecoregions in the four-state area include the Central Great Plains, Nebraska Sand Hills, Central Irregular Plains, and the Ozark Highlands. Scientific and technical advisors to the U.S. EPA and state water agencies developed suggested ranges in total P limits or critical P concentrations, ranging from 10 to 76 parts per billion (ppb) in streams and from 8 to 50 ppb in lakes and reservoirs. Lower values are indicated for surface waters in the Ozark Highlands ecoregion, a region with low naturally occurring phosphorus; higher values are indicated for surface waters in the Corn Belt and Plains ecoregions, including most of Iowa and eastern and central Nebraska, regions with naturally high levels of phosphorus. Phosphorus and other pollutant limits or criteria to maintain the chemical, physical, and biological integrity, and designated beneficial uses, of surface water resources may ultimately be specified in state water quality standards. In 2012, the U.S. EPA approved Nebraska criteria for nutrients in lakes and reservoirs.

Four forms of P are commonly considered in discussions of freshwater quality (see box). A fifth form is in living organisms or biomass. Conversion of particulate P to a bioavailable P form is

Forms of Phosphorus in Runoff, Lakes, and Streams

Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters: revised Edition (Kovar and Pierzynski,(eds.) 2009, defines seven pools of P in water. Four of these are commonly used to describe P in runoff, streams, and lakes in work on water quality.

1. **Total P** (TP) is the total of all forms of P in the water sample.

2. **Total dissolved P** (TDP), often called dissolved P, is defined as P that passes through a 0.45-micron filter. Total dissolved P is primarily orthophosphate dissolved in the water but also may include some dissolved organic P. In some cases, only the orthophosphate component of total dissolved P is reported and is called dissolved orthophosphate (DP).

3. **Particulate P** (PP) is also known as sediment P; it is the difference between total P and total dissolved P. It is defined as P attached to sediment and nonsoluble organic matter.

4. **Bioavailable P** (BAP) is also known as algal available P; it is defined as the portion of total P that is available to algae. It includes all of total dissolved P and a portion of particulate P. Bioavailable P is estimated by extracting P from the water sample with a caustic chemical solution or by a P sink such as iron oxide impregnated filter paper or anion exchange resin.

Bioavailable P is typically considered the most important form of P affecting water quality. Particulate P is less available in aquatic systems in the short term, but becomes much more available over time.

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affected by several factors. Bioavailable P is expected to increase when there is an increase in the concentration of particulate P compared to bioavailable P. Some algae produce phosphatase, which reacts with organic particulate P to release inorganic P as dissolved P. Vertical cycling of water, due to seasonal temperature differences with depth of the water and the depletion of oxygen in the bottom waters, causes resuspension of particulate P, some of which is converted to bioavailable P. Bottom feeding fish such as carp, wind and waves in shallow lakes, and motorboat traffic cause much resuspension of particulate P, driving the reaction to release bioavailable P. Therefore, in the short term, bioavailable P fractions are of greatest concern. In the long term, however, we need to be concerned about the relatively large amount of particulate P entering surface freshwaters.

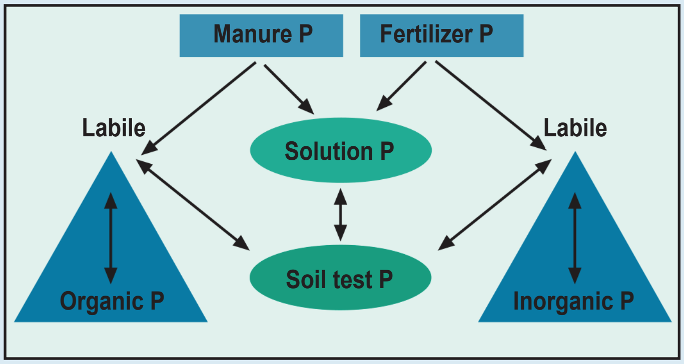

Figure 1. The primary soil P pools (Modified from Sharpley and Sheffield, **Livestock and Poultry Stewardship Curriculum***)*

The Role of Phosphorus on Agricultural Land

Soils typically contain 300 to 1000 ppm of total P. Soil systems are similar to water systems in that only a small portion of the total P is easily available to plants. The soil P system is commonly described as having three pools of P (*Figure 1*). A small fraction of soil P is dissolved in the soil solution in the orthophosphate form, the form that is taken up by plants. As the plant depletes orthophosphate in the soil solution, dissolved P is replenished from the second major soil P pool called labile P. Labile P is P that is held by relatively weak bonds to soil particles and organic matter. The third soil P pool, non-labile or stable P, is held strongly to soil particles in the form of iron and aluminum phosphates in acid soils, calcium phosphates in calcareous soils, and in highly recalcitrant bonds to organic matter in all soils. Stable P is considered unavailable to plants and is released at a very slow rate to the labile and soluble P pools.

Most P fertilizers are composed of water soluble P compounds and some manure P is water soluble. Application of fertilizer or manure P causes an initial dramatic increase in soluble P in the soil at the point of contact. Chemical equilibrium is rapidly reestablished as much of the added P enters the labile P pool. Over time some of the P in the labile pool is converted into more stable organic and mineral forms. The immediate effect of P fertilization and manure P applications is to increase the capacity of the labile P pool to replenish solution P and total soil P. The net long-term effect depends on soil properties, P removal by crops, and P loss by other mechanisms.

Key resources for agronomic P management in the four-state region include:

Soluble soil P is typically less than 1 percent of total soil P and is readily available to plants.

Labile soil P is typically less than 5 percent of total soil P and is less tightly bonded than stable P.

Stable P is often more than 95 percent of total soil P. It includes tightly bonded P in secondary and primary minerals and in organic forms.

Iowa: *A General Guide for Crop Nutrient and Limestone Recommendations in Iowa.* Iowa State University Extension Publications Pm-1688.
http://www.extension.iastate.edu/Publications/PM1688.pdf

Kansas: *Soil Test Interpretations and Recommendations.* Kansas State University Extension Publication MF2586.
http://www.agronomy.ksu.edu/soiltesting/doc1813.ashx

Missouri: *Phosphorus in Missouri Soils.* University of Missouri Extension Publication G9180.
http://extension.missouri.edu/p/G9180

Nebraska: *Nutrient Management for Agronomic Crops in Nebraska.* University of Nebraska–Lincoln Extension EC155.
http://ianrpubs.unl.edu/epublic/live/ec155/build/ec155.pdf

NebGuides on fertilizer use. *extension.unl.edu/publications/*

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Manure as an Unbalanced Fertilizer

With manure, as compared to fertilizers, the producer has little control over the proportion of nutrients applied to the field. Many manure sources tend to oversupply P compared to N (*Figure 2*). Where soil test P is low, the excess P is valuable for raising P levels. Where soil test P is already highly available, there is no agronomic benefit from the excess P.

In addition to the nutrients applied, manure application often results in increased yield compared to use of fertilizer alone, possibly due to improved soil physical, chemical, and microbial properties. The liming effect of some manures can be significant; the equivalent of 60 to 70 lb of agricultural lime per ton has been measured for typical feedlot manure. Runoff and erosion with heavy rainfall or snowmelt events are often less due to improved water infiltration with some manures applied; this may mean more water available to the crop and less erosion as illustrated in *Figure 3*.

Risks of manure P moving to surface waters often are associated with patterns of P distribution at large and small scales. For example, large amounts of P are mined in Florida and transferred as fertilizer to agricultural lands or as supplements to animal rations in the Midwest. The grain or forage crops are harvested and transported to concentrated animal feeding operations. Most of the P consumed by animals is excreted. If enough cropland area is available for manure application near the animal feeding operation, the manure P can be used with agronomic and economic efficiency, and environmental safety. Often, however, the available cropland is insufficient to apply the manure according to crop P needs and manure P is not used efficiently with potential for degrading water quality.

The manure P produced in most counties of the four-state region does not exceed the P that needs to be applied to maintain optimal crop performance (*Figure 4*). One exception is a group of five counties in southwest Missouri that generates 25 percent of the manure P in the state but has less than 1 percent of the corn production. A similar situation of intense livestock feeding with little cropland for manure application exists in southwest Kansas. Because of the bulky nature of manure, however, transport costs to deliver manure to distant fields are high. The high transport costs often result in overapplication of manure to fields near the animal feeding operation.

Manure Phosphorus

Approximately 187 million tons of manure, based on an average water content of 50 percent, are produced annually by confined animals in the United States. This is approximately equal to a single heap that is 1/2 mile wide at the base and 3/4 mile high. Livestock excreted P is about 1.9 million tons per year with 45 percent from confined operations. Nutrients in this manure are sufficient to meet 25 percent of the P, as well as 45 percent of the potassium (K), required for U.S. crops.

Manure is a bulky P source and P content varies widely among manure types. Some manures may have 80 to 100 lb P_2O_5 per ton (poultry, for example), whereas others may contain 10 lb P_2O_5 per ton or less. Most manure P is in inorganic forms (50-95 percent), such as calcium phosphates and dissolved orthophosphate. The proportion of manure P soluble in water varies greatly depending on the animal species, age, and diet, and can vary from trace amounts to more than 80 percent of the total P. Water soluble manure P is not a good indicator of P available to a crop because labile inorganic and organic P forms become readily available for crops or algae shortly after being in contact with soil or runoff. Estimates of manure P that becomes available to the first crop after application range from 60 to 100 percent in the North Central Region (J. Peters et al., 2004. Unpublished. NCR-13 Regional Soil Testing Committee). In recent years, use of phytase to increase the digestibility of phytate P in swine and poultry rations has increased dramatically and is becoming the norm in large feeding operations. This practice can reduce the

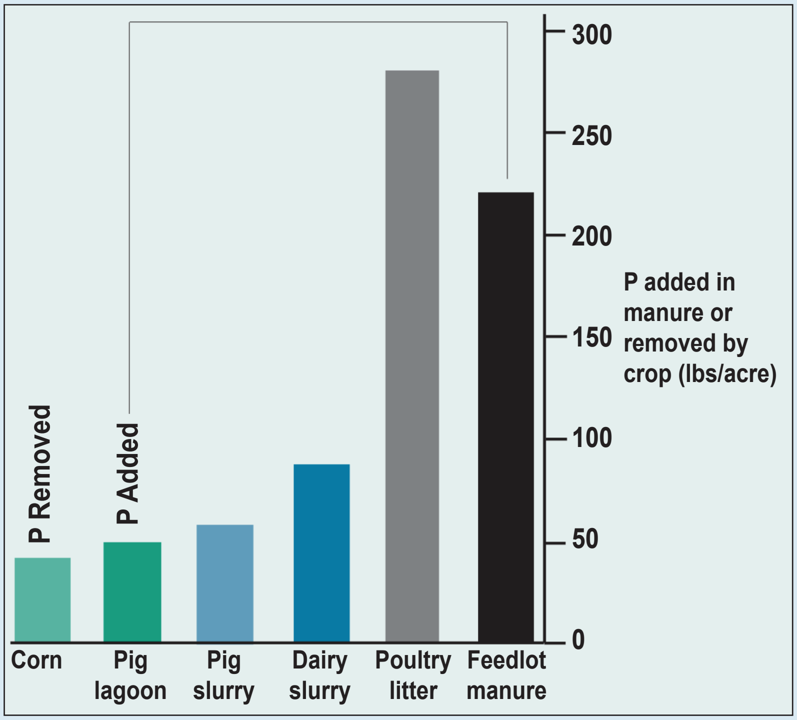

Figure 2. When manure is applied to meet crop nitrogen needs, the amount of phosphorus added can greatly exceed phosphorus removed by the crop. This information assumes nitrogen-based surface manure application with a corn yield goal of 150 bushels per acre. When feeding distillers grains, P added with feedlot manure is more than indicated here. (Modified from Sharpley and Sheffield, Livestock and Poultry Stewardship Curriculum)

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total P in manure 25 to 35 percent when mineral supplementation is reduced accordingly. A reduction of P in manure increases the N-P ratio of manure to one more similar to that removed by the crop (*Figure 2*). Recent investigations do not confirm earlier reports suggesting that phytase use increases significantly the proportion of soluble P in manures.

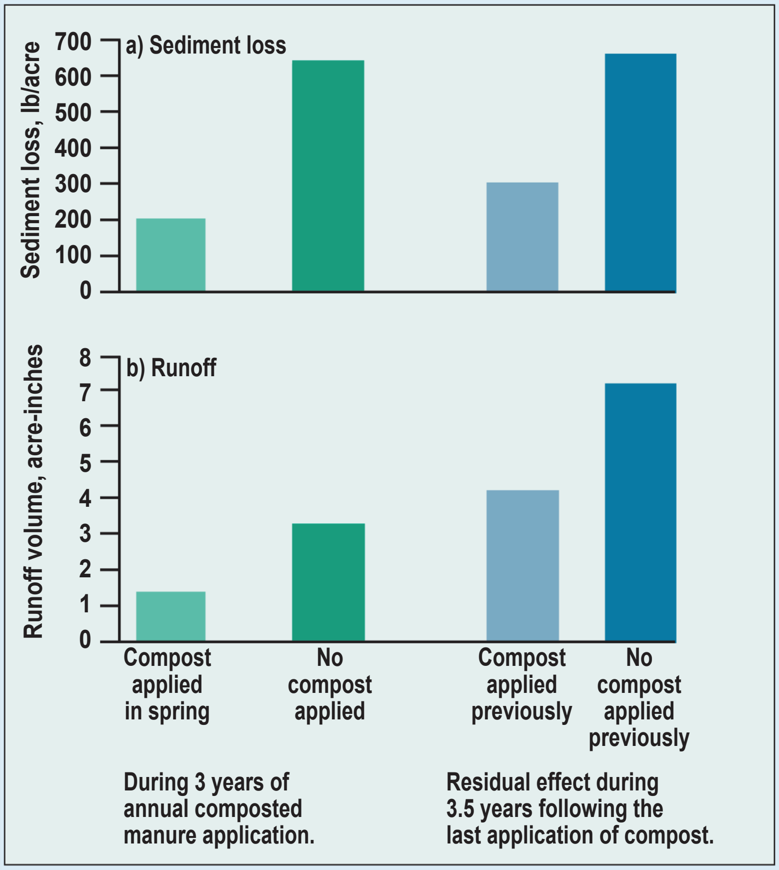

Figure 3. Composted manure application resulted in less loss of sediment (a) and less runoff (b) during three years of annual application, and during three and one-half years following application.

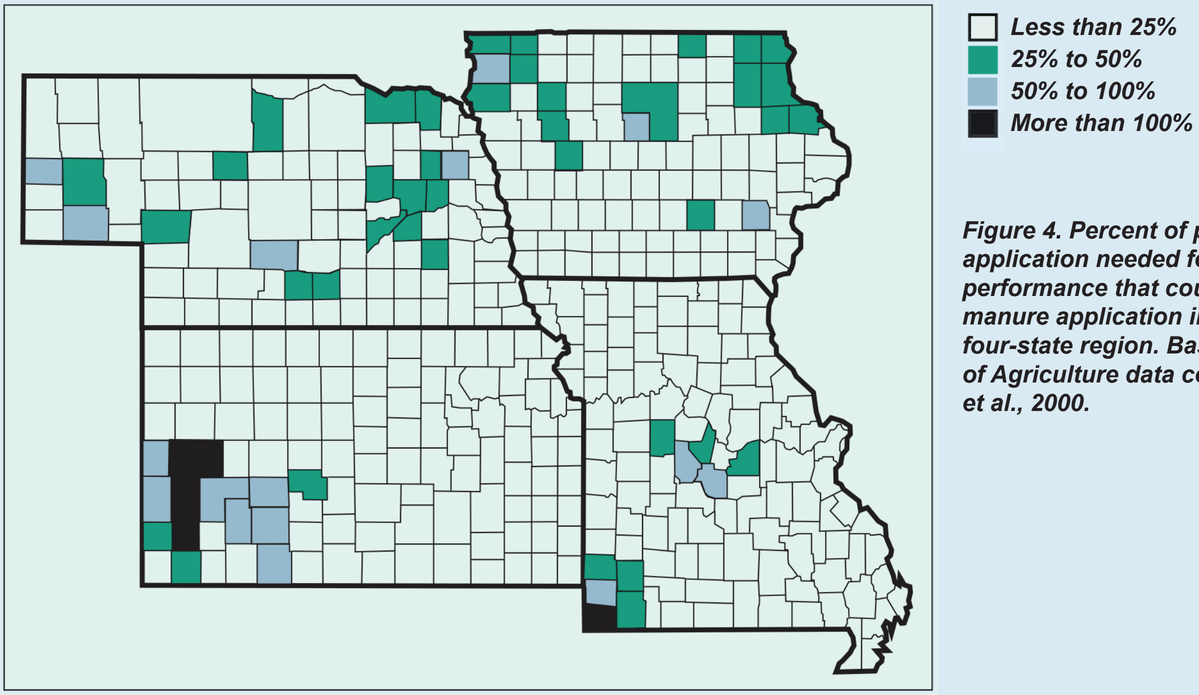

Figure 4. Percent of phosphorus application needed for optimal crop performance that could be met with manure application in counties in the four-state region. Based on 1997 Census of Agriculture data compiled by Kellogg et al., 2000.

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Source Factors Contributing to Phosphorus Delivery to Surface Waters

Source factors that affect P delivery to surface waters include soil P level and management practices (*Table 1*), such as the time and method of P application. Tillage practice and cropping system are often considered as source factors.

Soil Phosphorus Level

The potential for dissolved, bioavailable, and particulate P loss increases as soil P increases. This relationship holds for surface runoff, subsurface drainage, and erosion. Soil P may be determined by agronomic soil tests such as Bray-P1, Olsen, and Mehlich-3 colorimetric or ICP (inductively coupled plasma) versions, and by environmental soil P tests that measure water dissolved P or presumed bioavailable P (such as the iron oxide impregnated filter paper test). The results of the agronomic and environmental tests for soil P are generally well correlated. These soil tests can be used in assessment of the risk of P delivery to surface waters, provided the soil sample accurately reflects the conditions of the mixing zone that contribute to dissolved P in runoff. All states in the region currently use agronomic tests for P loss assessments, eliminating the cost of collecting and processing additional samples for environmental purposes.

Table 2. Stratification of Bray-P1 in a soil where manure was regularly applied and incorporated with a disk. Bray-P1 in the soil that is most exposed to runoff and erosion is much higher than indicated by a 0- to 8-inch sample (C. Wortmann and D. Walters, University of Nebraska–Lincoln).

Depth	Bray-P1	Total P
0-2”	380	1288
2-4”	154	754
4-8”	37	506
0-8”	143	742

Most studies have found that concentrations of dissolved, bioavailable, and particulate P in runoff increase linearly as soil P level increases. In some cases, P concentration in runoff may increase more rapidly with increases in soil P at excessively high levels as compared to lower soil P levels. In an Iowa study of subsurface drainage at three locations, P concentration in the water did not increase much until topsoil P (6-inch depth) exceeded 50 ppm by the Olsen test and 80 ppm by the Bray-P1 test (*Figure 5*). Another consideration is that the total P concentration in sediment is higher than in the eroded soil; this P enrichment occurs due to removal of organic material and fine soil particles that are higher in P than the average for the soil.

Interpretation of agronomic soil tests is generally based on a sampling depth of 0-6 or 0-8 inches. The limited solubility of P in the soil and rapid assimilation of added P into the labile and stable P pools limits the mobility of P in soils. Phosphorus tends to accumulate on the soil surface unless it is incorporated, resulting in high P levels in the mixing zone of soil and runoff water, especially for no-till and forage fields. This affects soil test results (*Table 2*) and has implications for P loss in runoff. Tillage reduces soil P stratification, but only slightly with many tillage implements. Some research suggests that a shallower sampling depth improves prediction of dissolved P loss with surface runoff from stratified no-till and pasture fields. Soil test P, however, for samples of 0-2 inches often better accounts for variation in runoff P compared with samples of 0 to 6 or 8 inches (*Figure 6*). Most P indexes in the region are calibrated for the sampling depth recommended for agronomic purposes to avoid additional soil testing. The Nebraska P Index calls for use of the 0-2 inch soil depth for fields with no

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tillage or conservation tillage and have surface application of P; alternatively, the soil test P for 0- to 8-inch sample depth is multiplied by 2.5 to account for the likely stratification of P in such fields.

Spatial variability in soil P levels across the field needs to be considered in assessing risk. Grazing animals tend to deposit more manure near feeding areas, shaded areas, water sources, and fences and gates, resulting in relatively high soil P levels in these areas. High concentrations of P in patches of manure throughout a pasture, or due to uneven manure application on cropland, can strongly affect soil test results. Sites of old farmsteads often have high soil P levels as well.

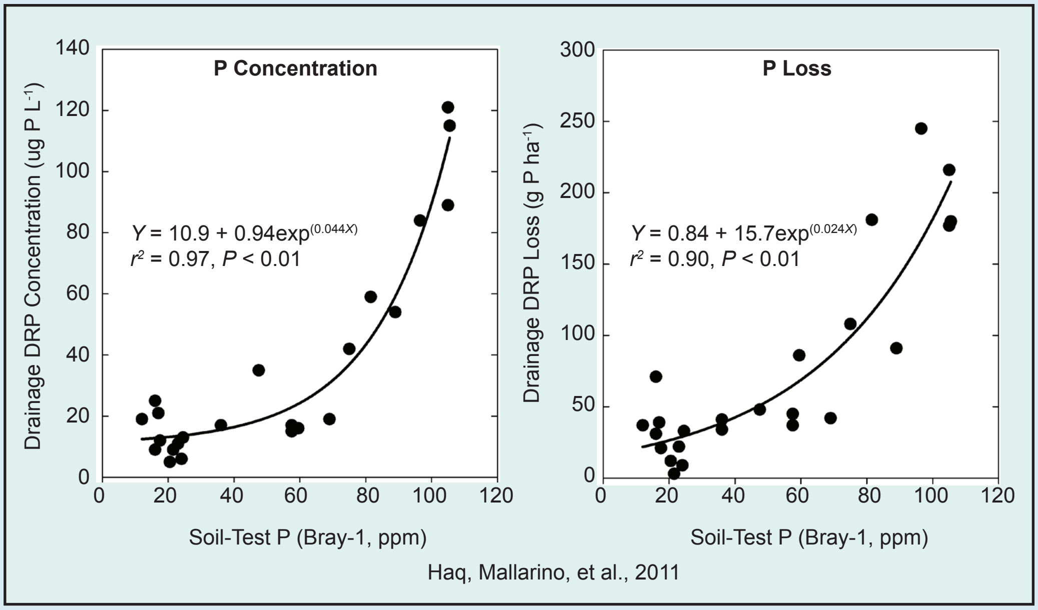

Figure 5. Phosphorus loss in tile drainage as affected by soil test Bray-P1 (Haq, Mallarino, et al., 2011).

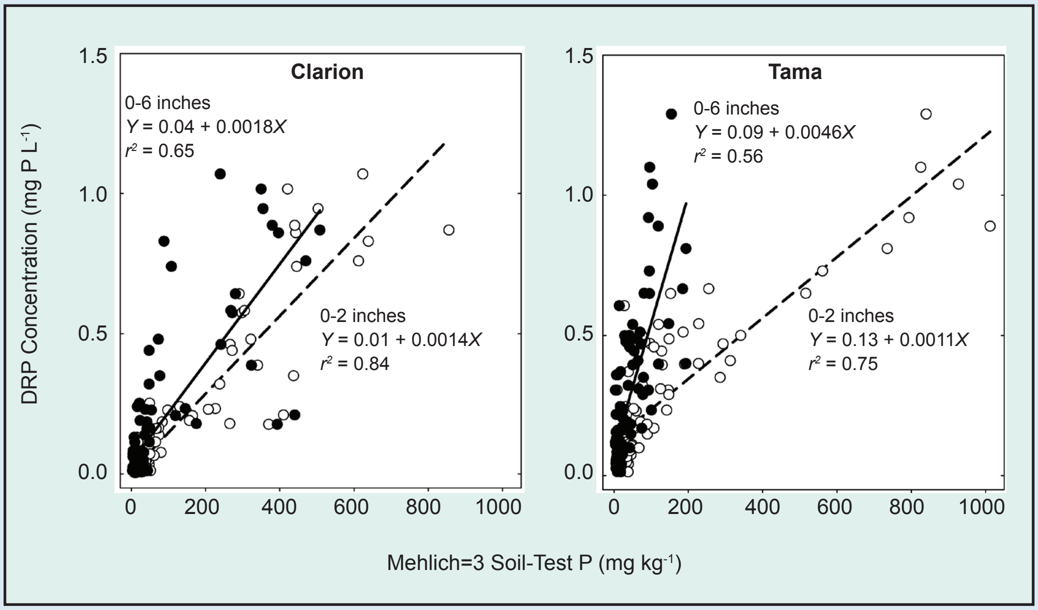

Figure 6. Runoff phosphorus loss is more closely related to soil test P of the 0-2 compared with the 0-6 inch depth (Allen and Mallarino, 2009).

Phosphorus Application

Rate of P application. Water passing over the soil surface and interacting with recently applied manure or fertilizer P supports high concentrations of P in runoff, much of it as dissolved P (*Figure 7*). The concentration of P in the runoff shortly after application typically increases linearly as the rate of P application increases. This has implications for manure management (see box, page 11).

Time of P application. Time can dramatically reduce the effect of recently applied P on runoff P concentrations. Iowa research showed that total and dissolved P concentrations were over 60 percent less when a runoff event occurred 10 days after, as compared to immediately after surface application of liquid swine manure (*Figure 7*). In another field rainfall simulation study with 100 lb P_2O_5/acre applied, runoff P was further reduced with time after application by periodic wetting of the soil until the tenth day when the runoff event was simulated for both fertilizer and manure applications (*Figure 8*). Runoff P for poultry manure was low compared with other P sources and the effect of delayed runoff was proportionally smaller. As added P reacts with the soil, it enters the labile soil P pool and is less prone to losses in runoff. Risk of P runoff can be substantially reduced by applying P when runoff events are unlikely for one to three weeks after P application. Probability of runoff in this region is typically

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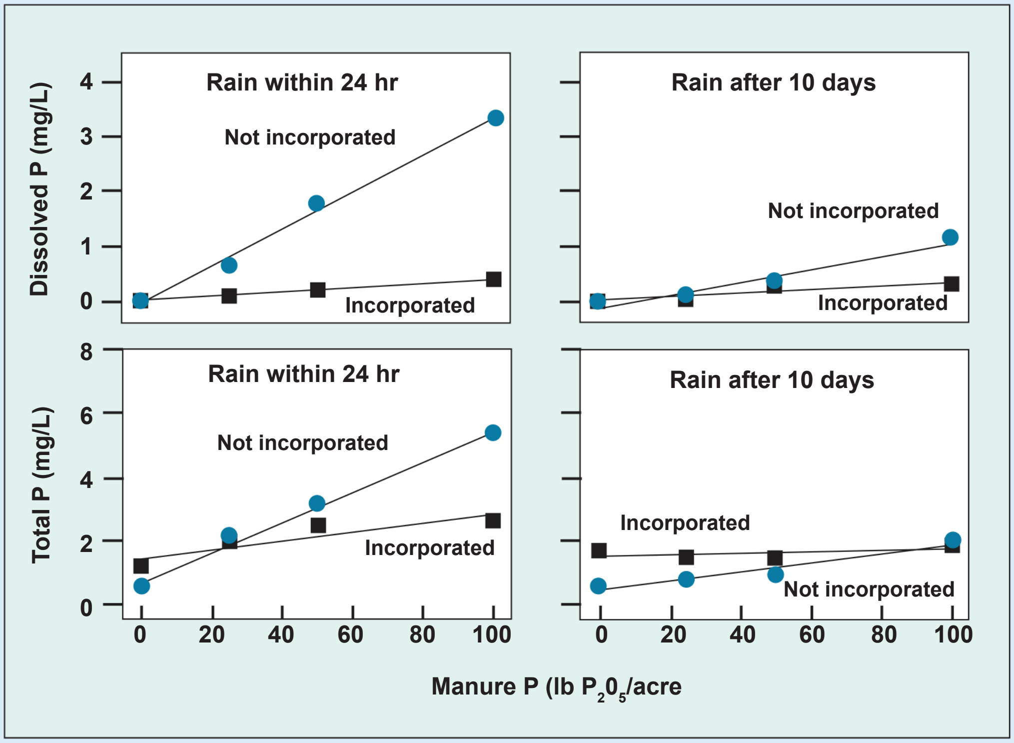

Figure 7. Phosphorus concentration in runoff was less with incorporation compared with surface application of liquid swine manure when runoff occurred shortly after application in this Iowa study. When the runoff event occurred 10 days after application, with no rainfall in the meantime, phosphorus loss was greatly reduced and there was no benefit from incorporation (B. Allen, A. Mallarino, and J. Baker, Iowa State University).

greatest in the spring, in some cases due to snowmelt events, but more commonly due to spring rainfall on already moist soil.

Research has shown beneficial effects of manure P compared to fertilizer P on P losses from runoff events soon after application (*Figure 8*). Manure P typically is less soluble in water than fertilizer P, and this may result in less dissolved P in runoff occurring immediately after surface application without incorporation into the soil. Also, manure application often results in reduced erosion and runoff from a field (*Figure 3a*). Reductions in sediment and runoff volume can exceed 2.5 percent per ton of surface-applied manure (dry matter basis) per acre. The effect of manure on runoff and erosion can extend for at least three years after manure application (*Figure 3b*).

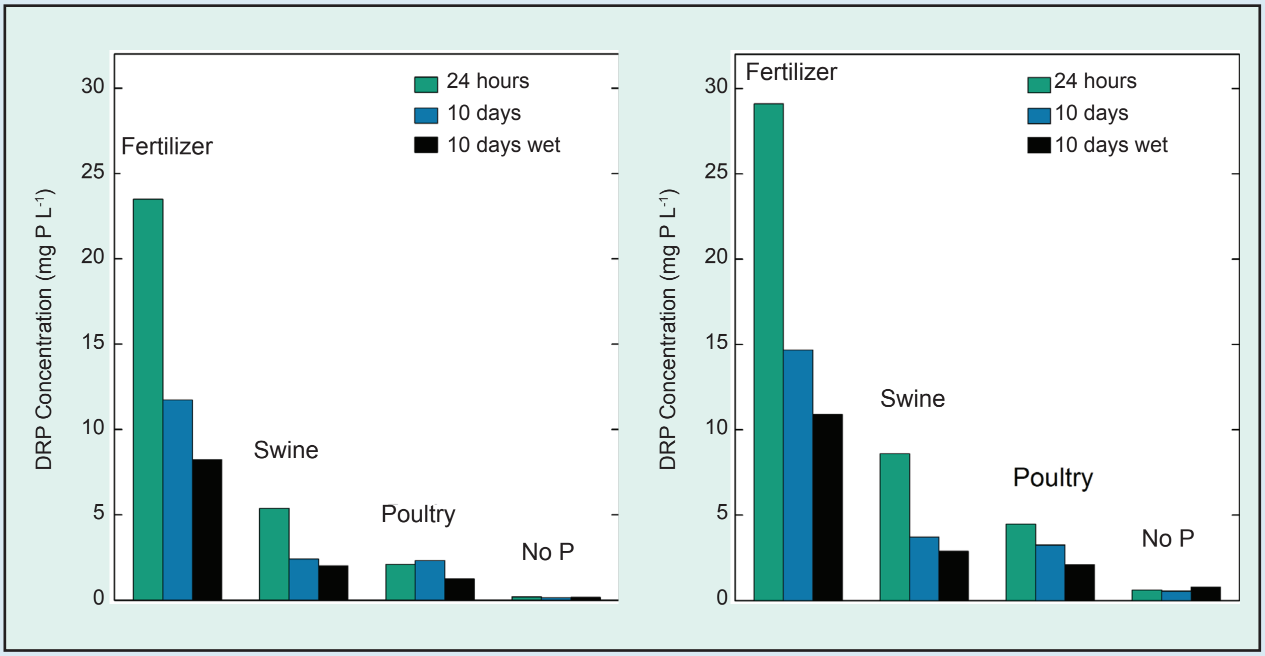

Figure 8. The risk of P runoff declines dramatically with time after application, especially if there is a non-runoff rainfall event in the meantime.

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Do lower P application rates benefit water quality?

Reducing the rate of manure application often will reduce the concentration of P in runoff. Does that reduction benefit water quality?

In practice, reduced P application rates translate into manure being applied on more acres. For example, halving the application rate may result in the need to apply manure to twice the land area of a watershed.

In this case, reduced rates in some areas may, or may not, improve water quality because the total P applied to the watershed may not change. Regional research is showing that short-term P loss with runoff may increase linearly (*Figure 7*) or exponentially with increasing P application rates. Also, research shows that soil P usually increases linearly with an increased P application rate. Therefore, the actual impact of P application transfer within a watershed on total P reaching surface waters is uncertain.

A similar question arises about how to enforce P limits on manure application. Manure P application on land with high P runoff risk is often limited to P removal by the crop. Is it better to limit P applications to the annual need of the crop, or should a farmer be allowed to apply two or more years of P in a single nitrogen-based application and then refrain from additional application until subsequent crops have removed the excess P?

There is little evidence that applying the same amount of P in infrequent applications at higher rates, e.g., once in four years, results in more long-term potential for P runoff loss than annual applications with proportionally lower application rates. Infrequent application may allow better timing of application and more careful application so risk of runoff may be less with infrequent applications at higher P rates. Also, infrequent N-based applications benefit farmers because they can meet the full N need of the crop in that year and eliminate the costs of supplemental N application for that crop.

Method of P application. Runoff P loss may or may not be reduced with incorporation or injection of manure or fertilizer P. Generally, however, dissolved P in runoff, and maybe other P types as well, is higher with surface application if the runoff event occurs shortly after application (*Figure 7*). However, the increased risk with surface application decreases during the days and weeks following application. Ongoing Iowa and Missouri research suggests that the reduction in P loss by a delayed runoff event shown in *Figure 7* for liquid manure is less pronounced when fertilizer or dry manure is applied, and the soil is dry, and no rainfall occurs before the runoff event.

The greater concern with surface application of P is the increase in soil P level at the soil surface (in the soil-runoff water mixing zone) that results in a long-term contribution to risk of runoff P loss. Incorporation of applied P, deep-band placement of fertilizer P, or injection of slurry manure reduces the rate of P build-up at the soil surface. However, the increased soil erosion risk associated with the incorporation or injection of manure or fertilizer needs to be considered. On highly erodible land, the P rate and the degree of soil and crop residue disturbance by application or tillage equipment largely determines the option of least risk.

Incorporating manure or fertilizer P may affect runoff P loss.

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Phosphorus application to grazing lands. A greater proportion of the total P lost from pastures, as compared to cropland, is dissolved P. The amount of P that can potentially be lost from pastures is related not only to soil P level and P application, but also to the amount of ground cover, treading damage from animals, and the deposition of manure on the soil surface.

Most nutrient losses in runoff associated with livestock grazing occur when high animal densities result in overgrazing, which leaves compacted, bare soil prone to low infiltration of water and high runoff. Seasonal effects may be pronounced. Surface runoff and the risk of P loss tend to be greatest during late spring when infiltration rates are slow due to high antecedent soil water content.

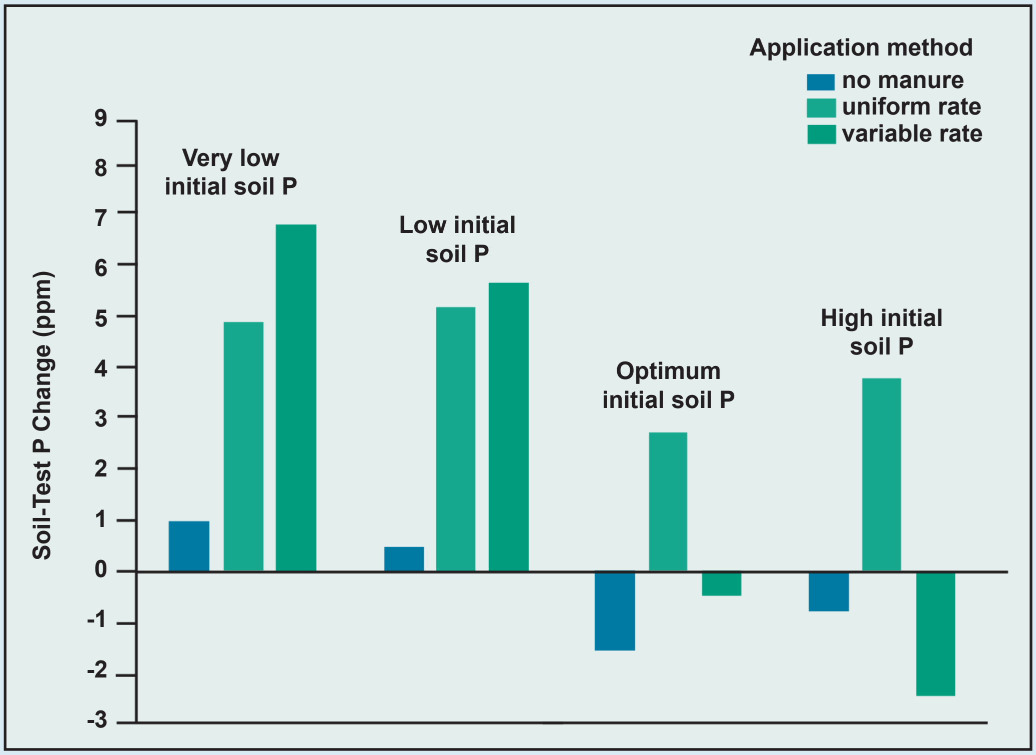

Figure 9. Effect of uniform application and soil-test phosphorus (STP) based variable-rate application of liquid swine manure on STP change within a field for various initial STP interpretation classes. Variable rate application resulted in a greater increase in STP where STP was very low and low as compared to uniform application. Variable rate application resulted in a decrease in STP where STP was at optimum and high levels (D. Wittry and A. Mallarino, Iowa State University).

Variable rate P application. Dense soil sampling from many fields has shown very large within-field spatial variability of soil test P. Precision agriculture technologies available to producers or custom applicators facilitate application of fertilizer and manure at rates adequate for different parts of a field. Iowa research has shown that grid or zone soil sampling methods combined with variable rate application based on soil test P often does not increase crop yield compared with traditional methods. However, the research shows that application according to spatial variability minimizes P application to high-testing areas and reduces soil test P variability within fields (*Figure 9*). Moreover, variable rate P application can be practically implemented on the basis of P index ratings for field zones, not just based on soil test P. Variable rate application of fertilizer P is common, as is variable rate application of manure by some custom applicators.

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Cover Crops, Tillage, and Other Site Management Practices

The risk of runoff P loss is affected by ground cover as illustrated by a case in Oklahoma with an erosion rate of 3 tons per acre per year; use of cover crops resulted in a 70 to 85 percent reduction in total P lost (*Figure 10*). Reduced tillage is expected to reduce total P loss, but not necessarily dissolved P, especially if reduced tillage results in high soil P at the soil surface.

Deep plowing, in the case of excessively high P concentration at the soil surface, may be a sound practice to reduce runoff P loss if it can be accomplished without a significant increase in erosion. Dissolved reactive and total P in runoff were reduced by 80 percent and 45 percent, respectively, in eastern Nebraska by moldboard plowing to an 8-inch 20-foot depth.

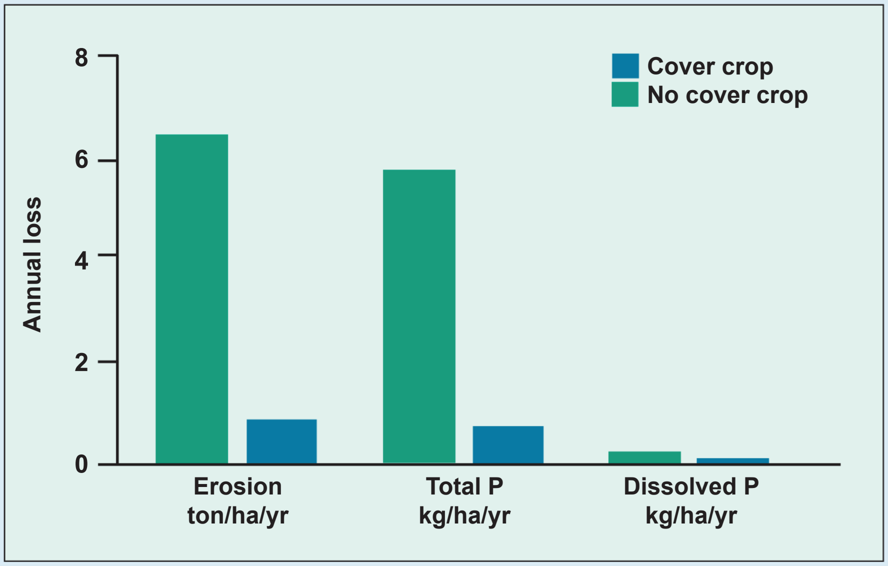

Figure 10. Adding a cover crop to the cropping system greatly reduced erosion loss and total phosphorus loss in Oklahoma. (From Sharpley and Sheffield, Livestock and Poultry Environmental Stewardship Curriculum)

Transport Factors Contributing to Phosphorus Loss to Surface Waters

Erosion, runoff, subsurface drainage, distance to water body or concentrated water flow, and stream bank/bed cutting are the major factors for P transport to surface waters (*Table 1*). Atmospheric deposition of P in surface waters may be significant but is not addressed here.

Erosion

Erosion can cause significant P loss even with moderate soil P levels.

Erosion is the primary contributor to P loss on many fields, particularly tilled fields. Controlling erosion is the most effective way to reduce total P loss on these fields. Most of the P associated with erosion is particulate P. Erosion can cause significant P loss even with agronomically moderate soil P levels. As discussed above, much of the particulate P entering a water body is not immediately available to aquatic vegetation, but a large proportion may become available over time. Therefore, the amount of total P entering waters is of medium- and long-term concern.

Several processes are involved in water erosion. The raindrop splash effect, sheet erosion, rill erosion, and gully erosion are briefly discussed.

Raindrop splash effect. The raindrop splash effect (*Figure 11*) is very important to disruption of soil aggregates as well as movement of sediment downslope as a contribution to sheet erosion. Energy from falling raindrops causes "detachment" of particulate inorganic and organic P, and the splash effect causes particles to move downhill.

Sheet erosion. Sheet erosion, although often not noticed, typically is the main erosive force. Sheet flow transports detached particulate P as a function of soil colloid size and the erosive capacity of the flowing water. As sheet flow

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Sheet flow is reduced by ground cover, resulting in more sedimentation and re-adsorption of P.

mixes with soil at the very surface, it is affecting the soil that is typically highest in P concentration. Sedimentation, adsorption, and resuspension of P occur with sheet erosion. Sheet flow is reduced by ground cover with vegetation and crop residues (*Figure 11*), resulting in more sedimentation and re-adsorption of P.

Rill erosion. Rill erosion results from the concentration of water flow associated with sheet erosion. It primarily transports surface soil that is relatively high in soil P as compared to deeper soil.

Gully erosion. Gully erosion results from further concentration of sheet and rill flow of runoff water. Gully erosion cuts deep and removes the surface soil as well as deeper soil that may still have substantial amounts of total P but relatively less solution and labile P as compared to the surface soil. Gully erosion needs to be prevented as it is difficult to check once started. In many cases, the flow from gullies is dispersed before it reaches the surface water body, offering an opportunity to effectively use vegetative buffer strips to slow the rate of flow for increased sedimentation and P adsorption. Vegetative barriers will be less effective in trapping contaminants if the flow is concentrated in small areas when it enters and passes through the buffer strips.

Surface Runoff

Runoff is the transport factor that leads to erosion, but in the assessment of risk and the planning for reduced P loss, it is convenient to separate P loss from runoff and from erosion. Soil P conditions within the top 1-inch of soil are most important to runoff where water mixes with soil to cause desorption or dissolution of P from soil, fertilizer, or manure to increase bioavailable P in runoff. Runoff becomes more important relative to erosion with well-managed no-tillage and grassland systems where erosion is well controlled but runoff is significant.

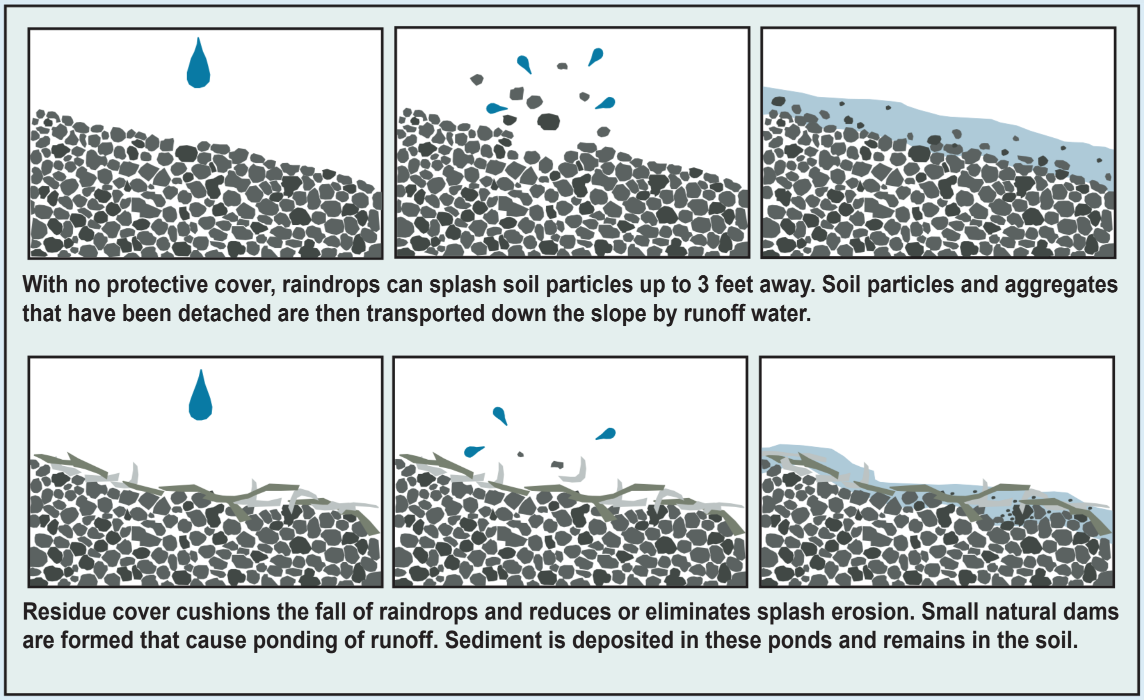

Figure 11. The raindrop splash effect is a major process in erosion as fine soil particles are released from weak soil aggregates and carried in the splash and subsequent sheet flow. Ground cover with crop residues or vegetation and improved soil aggregation reduce the raindrop splash effect. (Modified from NCRCS-USDA Photo Gallery)

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Subsurface Drainage

Risk of P delivery is greater the closer the field is to the water body.

Subsurface drainage can be a transport mechanism where installed systems have conduits near the soil surface, especially where soils have little capacity to retain P. Under natural subsurface drainage systems, transport of P to surface waters can be expected to be greatest with: 1) high soil P levels; 2) sandy soil, due to more leaching of P; 3) limited soil depth above layers that restrict downward water movement; and 4) short distance to seepage of the water to the surface. Studies of subsurface drainage in Iowa have found significant downward movement of P in the top 2 feet of the soil profile, but much retention of P in the subsoil as the water moves laterally to the subsurface drains.

Distance from the Field to Concentrated Flow or to the Water Body

The risk of P entering surface waters increases as distance to concentrated water flow and/or the water body decreases. A great proportion of overland flow in a field occurs within 100 feet of a channel, the area where field runoff accumulates. In addition, reductions in P concentration in runoff flow occur over distance due to sediment deposition, re-adsorption of P, and dilution. Current U.S. EPA regulations for CAFOs prevent manure application within 100 feet of a direct conduit to surface waters if the land is cultivated; the setback is 30 feet if the setback area is in perennial vegetation. The importance of distance has not been well quantified but logically the rate of decrease in runoff P risk increases with distance, probably until about 300 feet, beyond which distance may not be a significant consideration.

Assessment of the Risk for Agricultural Phosphorus Delivery to Surface Waters Risk Assessment Options

In 1999, NRCS issued a national policy requiring an assessment of P loss from every field as part of the nutrient management process. In 2003, U.S. EPA released revised permit requirements for CAFOs including P loss assessments on all land controlled by a CAFO and receiving manure. The national guidelines allow a choice of up to three methods for P assessment:

1. Agronomic P limit, a soil test P level needed for optimum crop production.
2. Threshold P limit, a soil test P level based on water concerns.
3. P index, a P loss assessment tool that integrates multiple factors.

The P assessment tools are used to determine a rating of potential P loss from the field. That rating determines the P management strategies required for that field.

Agronomic P limit. With this approach, fields that have soil test P levels much above the optimum level for crop production should not receive additional manure application. The agronomic P limit assessment is the most restrictive method identifying the largest number of fields as unsuitable for

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manure application or requiring P-based manure applications. This approach, however, would maximize the efficiency of manure as a nutrient source. Producers in Missouri have this approach as an option for assessment of P runoff risk.

Threshold P limit. This approach sets a soil test P limit above the agronomic P limit, creating the opportunity for application of P as manure on fields where P is agronomically adequate. The justification for a higher "environmental" soil P limit is that the potential for P loss is higher above some soil test levels where P is more easily desorbed from soil and more P is released into water passing over or through the soil. Iowa research suggests a soil test P break point for P loss with tile drainage. The existence and location of such a break point is a matter of debate. Much of the research investigating the effect of soil test P on P concentrations in runoff has found a linear response although there are some examples with apparent break points. The greatest strength of the threshold P limit is its simplicity. The greatest weakness is its failure to account for the potential for P transport to surface waters with the expectation that it will underrate the potential for P delivery to surface waters in some cases of low soil P, and overrate the potential in some cases of high soil P. Kansas uses a threshold limit in the regulation of manure P application.

A P index is a tool for identifying fields with a high probability of P loss.

The P Index. The use of P indexes in P management was introduced in the early 1990s and P indexes are now commonly used in regulation of P application. A P index is intended to be a relatively simple tool for identifying fields with a high probability of P loss, and to evaluate the effect of alternative management practices.

The P index approach addresses some of the complexity of the P loss process and can more accurately assess risk of P loss than the threshold P limit. Most P indexes are constructed so that the P transport potential modifies the P source potential to reflect the amount of P reaching the water body. Multiplicative functions are increasingly used where the potential of P source factors is multiplied by the potential for P transport from the field, thereby accounting for the interaction of source and transport factors.

More recent computer-based P indexes access and process much data to integrate the different processes controlling P delivery from fields. In addition to soil erosion potential, soil runoff class, soil P level, and P application, the P index may include distance to water body, tillage, vegetation or grazing management, and site hydrology (for example, slope gradient and length, flooding frequency, drainage class, subsurface drainage, etc.).

Risk assessment using a P index is increasingly used as a basis for planning and regulation of P management to protect water quality. Study of the various factor scores, or partial index values, that contribute to the final risk rating can often reveal the source or transport mechanisms most responsible for the P loss at a site. This information can be used to diagnose the cause of the P loss and to identify solutions to the problem. Therefore, the P index becomes a flexible and effective management tool.

P Indexes in U.S. EPA Region 7

Each state has a P index. These P indexes generally fall into two categories. The simplified model approach is used by Iowa, Missouri, and Nebraska; all inputs are continuous variables that can be measured and entered into the index. A tabular factor driven approach is used in Kansas. Estimation of sediment loss in sheet and rill erosion using RUSLE2 is common, but the Nebraska P Index has a built-in calculator calibrated against RUSLE2 for estimation of sheet and rill erosion.

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Iowa P Index — *www.ia.nrcs.usda.gov/technical/Phosphorus/phosphorusstandard.html*

The Iowa P Index uses an Excel® computer spreadsheet to access and integrate information on soil units, landscape forms, runoff curves, and precipitation to estimate and integrate volume of water runoff, sediment delivery ratio, and sediment trap efficiency of soil conservation practices. The user supplies estimates of sediment loss, soil test P level, and the distance from the center of the field to the nearest perennial or intermittent stream. The spreadsheet processes this information to estimate P delivered within each of the three transport components: erosion (sediment-bound P loss), runoff (dissolved P loss), and subsurface drainage (dissolved P loss through tiles or coarse subsoil). The outputs from these components are summed to get an overall approximation of biologically available P delivered. The resulting number (expressed in lb P/acre/year) is placed into one of five risk classes (very low to very high). The P index ratings can be calculated for an entire field or for different management zones within a field, based on soil type, soil P level, or landscape differences. The Bray-P1, Olsen, and colorimetric or ICP versions of the Mehlich-3 soil P tests can be used for index calculations, and a 6-inch sampling depth is assumed.

The Iowa P index reflects the concept that erosion from cropland is a major source of P loads to surface waters and that a large proportion of the particulate P can be made bioavailable to aquatic vegetation over time in the shallow glacial-derived lakes or artificial reservoirs predominant in Iowa. Therefore, the index weighs particulate P loss heavily when the erosion risk is high. Partly due to this long-term approach and emphasis on cropland, the current version of the index does not differentiate based on solubility of commonly used P sources even though these may be of short-term significance in a water body for surface application without injection or incorporation into the soil.

Kansas P Index — *oznet.ksu.edu/waterquality/P-Index.xls*

The Kansas P Index uses the multiplicative approach to integrate source with transport factors. Source factors include soil test P and P applications from fertilizers and manures, including rate, method, and timing. The transport factors include soil erosion, furrow or sprinkler irrigation erosion, soil runoff class, and distance from the edge of field to surface water.

The potential for runoff at a given location varies greatly during the year because of variations in soil water conditions. This is particularly pronounced in the Great Plains Region. Probability of runoff is less in the winter because of low rainfall, and during late summer because of high evapotranspiration demands. Soil water tends to be higher in the spring and early fall because of reduced evapotranspiration demands and more precipitation, which increases the probability of runoff. To account for these differences, a lower risk is assigned to surface broadcast P applications made in July, August, and November through February as compared to September, October, and March through June. The Kansas P index uses five interpretation categories.

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Missouri P Index — *www.nmplanner.missouri.edu/tools/pindex.asp*

The Missouri P Index uses a multiplicative model to estimate sediment and dissolved P loss in runoff. Particulate P load is estimated using the soil erosion rate and the concentration of particulate P, which is estimated using soil test P. Soluble P losses are approximated using soil test P to estimate the concentration of soluble P in runoff and a curve number approach to estimate the volume of runoff. Index values are dominated by the impact of erosion, particularly on tilled row crop fields. The resulting values are partitioned into a four-level rating system. The rating system is more restrictive in 51 counties of the Clearwater region dominated by forage-based agriculture than in the other 64 counties of Missouri.

The P index is a strategic planning tool to identify fields with high risk of P loss as part of developing a five-year nutrient management plan. Potential losses of P from rainfall events soon after an application are viewed as very important but not appropriate for a long-term planning tool. Consequently, P application is not a factor in this P index.

The P index is in a spreadsheet format and is to be updated to incorporate tools of RUSLE2, such as for calculating sediment delivery ratio.

Nebraska P Index — *http://water.unl.edu/web/manure/software#pindex*

The Nebraska 2012 P Index is a multiplicative model in an easy-to-use spreadsheet format. It was developed in consideration of the Iowa P Index with most underlying functions adapted for Nebraska conditions. In comparison with the Iowa P Index:

- it does not consider tile drainage,
- it has an irrigation component,
- it has a second option for estimating ephemeral gully erosion,
- it calculates estimates of sheet and rill erosion,
- it has a manure credit component considering the soil conditioning effect of manure application that improves water infiltration and reduces soil susceptibility to erosion, and
- it has enhanced capacity for record storage.

The P index source factors include soil test P, and the rate, method, and time of applying manure and fertilizer P, and other in-field management practices. The transport factors are runoff, erosion, and distance from point of application to concentrated water flow. The distance effect varies according to the dominant land form. The PI rating is the total of P losses associated with runoff and erosion. Interpretation is based on four classes of risk.

Interpretation of the P Loss Risk Ratings

Phosphorus index scores are classed into four or five categories of risk of P entering surface waters. Interpretation of risk levels varies slightly in P indexes used across the region. The risk levels and interpretations may be similar to the following.

1. **Very low.** Minimal risk of P delivery to surface water.
2. **Low.** Current practices keep water quality impairment due to agricultural P pollution low. Manure can be applied at rates sufficient to meet crop N needs unless the combined effect of all practices suggests increased risk of P loss.

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3. **Medium.** Delivery of agricultural P may cause some water quality impairment, and consideration should be given to alternative conservation and P management practices. Manure or fertilizer P application should not exceed crop P removal. The manure application rate can be sufficient to meet a crop's N need for that year, but total P applied in one or more applications made in a four-year period should not exceed crop removal during that four-year period.

4. **High.** Phosphorus loss from the field causes much water quality impairment. Remedial action, such as alternative conservation measures or P management practices, is required. Manure or fertilizer P should not be applied until the P index score is reduced to *medium*.

5. **Very high.** Impairment of water quality is extreme and remedial action is urgently required. Manure and fertilizer P should not be applied. Improved soil conservation measures or other practices to reduce the risk of P loss should be implemented.

Management Practices to Reduce Phosphorus Delivery to Fresh Surface Waters

Most P entering surface waters generally comes from only a small part of the total land area of the watershed such as an individual field. These areas of high P loss typically have high levels of both source and transport factors. The most cost-effective approach to reducing delivery of agricultural P to surface waters may be identification of these high risk areas followed by a targeted application of practices to reduce P loss.

Reducing the Effect of P Source Factors

Several management practices may be considered for reducing source factor contribution to the risk of agricultural P delivery to surface freshwater bodies.

- Avoid soil test P buildup to excessive levels due to over-application of P.
- Zone fields for fertilizer or manure application when P loss risk varies within a field.
- Use phytase enzyme and minimize ration P supplements for monogastric livestock to reduce P concentration in manure.
- Apply P when runoff events are unlikely for one to three weeks after P application.
- Avoid excessive rates of P application; however, application of a high rate once in several years may not be of greater risk than applying the same amount in annual applications if all other factors are the same (see box, page 10). Similarly, applying a high rate of P in one field does not necessarily imply increased risk than if the same total amount of P were applied to several areas within a field, assuming similar field conditions and application practices.
- Avoid excessive overgrazing and compaction of grazing lands before P application.
- Maintain ground cover with crop residues or vegetation prior to and for several weeks after P application.

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The following practices may be useful if they can be done without increasing the risk of erosion.

- Inject or incorporate manure where feasible.
- In cases of extremely high levels of soil P at the surface, but low P in deeper soil, conduct a one-time deep plow tillage to bury or dilute the high P soil.
- Harvest more biomass to remove more soil P for earlier depletion of excessive soil P levels.

Reducing the Effect of P Transport Factors

Several management practices may be considered for reduced transport factor contribution to the risk of agricultural P delivery to surface freshwater bodies.

Terracing erodible land may reduce total P loss by 90 percent.

- Maintain ground cover, such as with reduced or no tillage or with cover crops, and enhance soil aggregate stability to reduce "detachment" of soil particles due to the raindrop splash effect (*Figure 11*). Manure use may improve soil aggregate stability.
- Use physical barriers such as terraces to control sheet erosion and to prevent rill and gully erosion. Terraces significantly reduce peak rates of runoff, thereby reducing erosive capacity. Terracing erodible land may reduce erosion losses by as much as 90 percent, with similar effects on total P loss. In some cases, dissolved P concentration in the runoff may be increased.
- Use vegetative barriers to intercept or slow water flow associated with sheet erosion to reduce erosive capacity and increase sedimentation and P adsorption. Filter strips, buffer areas, terraces, and vegetated wetlands may be useful to reduce P in runoff. Vegetated riparian buffer strips can be very effective in reducing total P loading to surface waters; however, most studies show buffers are only moderately effective in reducing dissolved P in runoff as soluble P retention is most dependent on infiltration. Buffer strip effectiveness is reduced if excess sedimentation builds a low berm on the field edge, resulting in concentrated flow through a low point in the buffer.

Use tile outlet terraces to reduce gully erosion.

- Avoid overgrazing in riparian areas. In one study, stream banks along continuously grazed pastures were eroding along 40 percent of the channel length. Streams are considered healthy if less than 20 percent of the channel length has eroding banks.
- Use grassed waterways or tile outlet terraces to prevent gully erosion in fields. Grassed waterways may be, but typically are not, effective in reducing P in runoff unless they are designed with gradual slopes for significant reduction in peak runoff rates to allow sedimentation and P adsorption to occur. There is, however, little field data addressing the retention of P by grassed waterways.
- Construct wetlands at the bottom of slopes or at tile outlets for sedimentation of particulate P and adsorption of dissolved P, as well as P uptake by plants.
- Maintain buffer areas, filter strips, and wetlands. Under heavy, long-term P loading, these can become P-saturated and lose effectiveness. Long-term effectiveness in reducing P delivery will require management to maintain vegetative vigor and to export excess nutrients. Burning grass stands causes N loss to the atmosphere, and enhances nutrient uptake and growth the following season, while haying waterways can remove nutrients. Likewise, woody species should be maintained in vigorous, rapidly growing condition by occasional harvesting or thinning of the stand.

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Cost and Effectiveness of Phosphorus Management Practices

The effectiveness of management practices in reducing runoff P loss has been estimated considering farm data, expert opinion, and the results of numerous field, laboratory, and computer modeling studies on the effect of crop management practices (and land application of livestock waste). The estimated typical cost and effectiveness values (2003 values) of these practices are presented for situations of conventional tillage, no-till, and land application of manure (*Table 3*). The effectiveness of a practice in reducing runoff P is expressed as the percent reduction relative to the expected runoff P of a situation with the same crop produced on land having greater than 1 percent slope, upland clay or clay loam soils, and broadcast application of P fertilizer before planting without incorporation. The base scenario for manure application has broadcast application and no incorporation of livestock waste during the summer to tilled fields rather than the fertilizer P application. The estimates are considered median values for cost and effectiveness, realizing that the actual values may be much different for some situations.

Table 3. The estimated typical cost and effectiveness of practices for reducing P loss in runoff with three crop production systems: conventional tillage (CT), no-till (NT), and manure use (MU). (Adapted from Kansas State University Publication MF-2572).

Best management practice	Production systems	Cost/Acre $	Dissolved P	Total P
			% reduction in P runoff	
Pre-plant incorporate P into the top 2 inches of soil before the first runoff event	CT, MU	7.15	60/70	20/20
Subsurface application of P fertilizer	CT, NT, MU	3.50	60/70/70	30/50/20
Crop rotation	ALL	0.00	25	25
Establish vegetative buffer strips	ALL	a/	25	50
Conservation tillage farming (>30% residue cover following planting)	CT, MU	0.00	0	35
No-till farming	NT, MU	0.00	0	40
Contour farming (without terraces)	ALL	6.80	20	30
Terraces with tile outlets	ALL	b/	10	30
Terraces with grass waterways (with contour farming)	ALL	c/	30	30
Soil sampling and testing	ALL	1.00	0 - 25	0 - 25
Sound fertilizer recommendations	ALL	0.00	0 - 25	0 - 25
Test livestock waste for nutrient value	MU	1.00	0 - 30	0 - 30

a/Establishment cost of $100 per acre of buffer area plus an annual cost equal to the average per acre land rental rate for the acreage within the vegetative buffer strip.

b/One-time installation cost of $40 per acre plus an annual cost of $13.60 per acre.

c/One-time installation cost of $30 per acre plus an annual cost of $13.60 per acre (all crop acres in the field).

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Table 4. The effect of swine slurry manure application strategies on land, time, and cost required for manure application, and the value of manure (land and application time from Lory et al., 2004, 2012 cost and value estimates based on Massey, 1996 and Massey, 2003)

Application Limit	**Land/au acres**	**Application time minutes/AU**	**Cost $/1000 Gallons**	**Value $/1000 gallons**
N-based	**0.32**	**10.6**	**$16.04**	**$32.44**
Annual P	**1.19**	**15.0**	**$27.97**	**$54.90**
4-yr P	**1.09**	**13.1**	**$18.06**	**$55.14**

N-based: manure applied on basis to meet the annual N need of the 150 bu/ac corn; annual P: manure applied annually to match annual P removal of 150 bu/ac corn; and four-year P: manure applied once in four years to match P removal during that period (150 bu/ac corn fb 50 bu/ac soybean).

The percent reduction in runoff P from adopting a listed practice is the effectiveness obtained from adoption of a single practice. There may be an advantage in adopting two or more practices, but the effect may not be fully additive. For example, the adoption of subsurface application of P (60 percent reduction in dissolved P loss) and crop rotations (25 percent reduction in dissolved P loss) may have a cumulative effect, but the total benefit may be less than an 85 percent reduction in dissolved P loss. It may be closer to 70 percent (60% + (100% - 60%)*25%). The estimated cost of a practice is the expected loss in producer profitability associated with adoption. Alternatively, it can be treated as the payment-to- producer required to fully compensate for the costs.

Alternative Manure Application Strategies

Land application based on a P-standard (e.g., crop removal of P in one year or over several years, such as for a four-year period) will often increase land, expenses, and time needed for application as compared to manure application based on a crop N need basis (*Table 4*). Many farmers choose to apply slurry manure to meet crop N need because of land and time constraints. Application on a P-standard, however, increases the value of the manure because excess nutrients associated with an N need-based application are not valued. When most nutrients are valued (as may occur with a P-standard application), the increased value of manure may exceed the added cost of P-standard application. This is illustrated with information obtained from 17 swine slurry facilities in five states (*Table 4*). It is assumed that fields closest to the livestock facility will receive manure before distant fields. Because the N:P ratio in this swine lagoon effluent closely matches the N:P crop removal of many cropping systems, adopting a P-standard has little impact on land used, application time, and cost of application, and the supplied nutrients are of greater value to the crop producer.

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