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Agricultural Phosphorus and Eutrophication

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Abstract

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Inputs of phosphorus (P) are essential for profitable crop and livestock agriculture. However, P export in watershed runoff can accelerate the eutrophication of receiving fresh waters. The rapid growth and intensification of crop and livestock farming in many areas has created regional imbalances in P inputs in feed and fertilizer and P output in farm produce. In many of these areas, soil P has built up to levels in excess of crop needs and now has the potential to enrich surface runoff with P.

The overall goal of our efforts to reduce P losses from agriculture to water should be to increase P use-efficiency, balance P inputs in feed and fertilizer into a watershed with P output in crop and animal produce, and manage the level of P in the soil. Reducing P loss in agricultural runoff may be brought about by source and transport control strategies. This includes refining feed rations, using feed additives to increase P absorption by animals, moving manure from surplus to deficit areas, finding alternative uses for manure, and targeting conservation practices, such as reduced tillage, buffer strips, and cover crops, to critical areas of P export from a watershed. In these critical areas, high P soils coincide with parts of the landscape where surface runoff and erosion potential are high.

Keywords: eutrophication, fertilizer, phosphorus, P input, P output, runoff

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Introduction

Eutrophication

Phosphorus (P) is an essential element for plant and animal growth and its input has long been recognized as necessary to maintain profitable crop and animal production. Phosphorus inputs can also increase the biological productivity of surface waters by accelerating eutrophication. Eutrophication is the natural aging of lakes or streams brought on by nutrient enrichment. This process can be greatly accelerated by human activities that increase nutrient loading rates to water.

Eutrophication has been identified as the main cause of impaired surface water quality (U.S. Environmental Protection Agency 1996). Eutrophication restricts water use for fisheries, recreation, industry, and drinking because of increased growth of undesirable algae and aquatic weeds and the oxygen shortages caused by their death and decomposition. Associated periodic surface blooms of cyanobacteria (blue-green algae) occur in drinking water supplies and may pose a serious health hazard to animals and humans. Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern United States, and Chesapeake Bay tributaries in particular, have been linked to excess nutrients in affected waters. Neurological damage in people exposed to the highly toxic, volatile chemical produced by these algae has dramatically increased public awareness of eutrophication and the need for solutions (Burkholder and Glasgow 1997).

Eutrophication of most fresh water around the world is accelerated by P inputs (Schindler 1977, Sharpley et al. 1994). Although nitrogen (N) and carbon (C) are also essential to the growth of aquatic biota, most attention has focused on P inputs because of the difficulty in controlling the exchange of N and C between the atmosphere and water and the fixation of atmospheric N by some blue-green algae. Therefore, P is often the limiting element, and its control is of prime importance in reducing the accelerated eutrophication of fresh waters. When salinity increases, as in estuaries, N generally becomes the element controlling aquatic productivity. However, in Delaware's inland bays (coastal estuaries), nitrate-N leaching has elevated N concentrations to the point where P is now the limiting factor in eutrophication.

Figure 1. Watersheds with a high potential for soil and water degradation from manure P (Adapted from Kellogg and Lander 1999).

Lake water concentrations of P above 0.02 ppm generally accelerate eutrophication. These values are an order of magnitude lower than P concentrations in soil solution critical for plant growth (0.2 to 0.3 ppm), emphasizing the disparity between critical lake and soil P concentrations and the importance of controlling P losses to limit eutrophication.

Agricultural Production

Confined animal operations are now a major source of agricultural income in several states. Animal manure can be a valuable resource for improving soil structure and increasing vegetative cover, thereby reducing surface runoff and erosion potential. However, the rapid growth and intensification of crop and animal farming in many areas has created regional and local imbalances in P inputs and outputs. On average, only 30 percent of the fertilizer and feed P input to farming systems is output in crops and animal produce. Therefore, when averaged over the total usable agricultural land area in the United States, an annual P surplus of 30 lb/acre exists (National Research Council 1993). This has led to P applications in excess of crop removal, soil P accumulations, and an increased risk of P loss in runoff (Kellogg and Lander 1999) (fig. 1).

Before World War II, farming communities tended to be self-sufficient in that enough feed was produced locally and recycled to meet animal requirements. After World War II, increased fertilizer use in crop production fragmented farming systems, creating specialized crop and animal operations that efficiently coexist in different regions within and among countries. Since farmers did not need to rely on manures as nutrient sources (the primary source until fertilizer production and distribution became less expensive), they could spatially separate grain and animal production. Today, less than a third of the grain produced is fed on farms where it is grown (Lanyon 2000) resulting in a major one-way transfer of P from grain-producing to animal-producing areas.

The potential for P surplus at the farm scale can increase when farming systems change from cropping to intensive animal production, since P inputs become dominated by feed rather than fertilizer. With a greater reliance on imported feeds, only 27 percent of the P in purchased feed for a 74,000-layer operation on a 30-acre farm in Pennsylvania could be accounted for in farm outputs (table 1). This nutrient budget clearly shows that the largest input of

Table 1. Farming system and P balance

P	Farming system: Crop*	Dairy†	Poultry‡	Hogs§
Input	- - - - - - lb P/acre/yr - - - - - -			
Fertilizer	20	10	0	0
Feed	0	20	1,375	95
Output	–18	–13	– 365	-60
Balance	+2	+17	+1,010	+35

SOURCE: Lanyon and Thompson (1996) and Bacon et al. (1990).

* 75-acre cash crop farm growing corn and alfalfa.

† 100-acre dairy farm with 65 dairy holsteins averaging 14,500 lb milk/cow/yr, 5 dry cows, and 35 heifers. Crops were corn for silage and grain, alfalfa, and rye for forage.

‡ 30-acre poultry farm with 74,000 layers; output includes 335 lb P/acre/yr in eggs, 20 lb P/acre/yr sold in crops (corn and alfalfa), and 10 lb P/acre/yr manure exported from the farm.

§ 75-acre farm with 1,280 hogs, output includes 40 lb P/acre/yr manure exported from the farm.

nutrients to a poultry farm and, therefore, the primary source of any on-farm nutrient excess, is in animal feed. Annual P surpluses of 80 to 110 lb/acre/yr were estimated by Sims (1997) for a typical poultry grain farm in Delaware. This scenario is consistent with other concentrated animal production operations, including dairy and hogs.

Phosphorus accumulation on farms has built up soil P to levels that often exceed crop needs. Today, there are serious concerns that agricultural runoff (surface and subsurface) and erosion from high P soils may be major contributing factors to surface water eutrophication. Agricultural runoff is all water draining from an area (field or watershed) including surface runoff, subsurface flow, leaching, and tile drainage processes. Phosphorus loss in agricultural runoff is not of economic importance to farmers because it generally amounts to only 1 or 2 percent of the P applied. However, P loss can lead to significant off-site economic impacts, which in some cases occur many miles from P sources. By the time these water-quality impacts are manifest, remedial strategies are difficult and expensive to implement; they cross political and regional boundaries; and because of P loading, improvement in water quality will take a long time.

Nitrogen-based management has been practiced and advocated by farm advisers for many years. Farmers are only now becoming aware of P issues. Many are confused and feel that science has misled them or let them down by not emphasizing the P management issues. Therefore, the research community must do a better job of transferring and translating its findings to the agricultural community as a whole. For example, we must be able to show where P is coming from, how much P in soil and water is too much, and how and where these inputs and losses can be reduced in order to develop agricultural resource management systems that sustain production, environmental quality, and farming communities.

In this publication, P is in its elemental form, rather than as P_2O_5, which is commonly used in fertilizer analysis. The conversion factor from P to P_2O_5 is 2.29. When discussing plant available forms of soil P, as determined by soil testing laboratories, we will refer to them as “soil test P” (ppm or mg/kg) and identify in each case the specific method of analysis used. Based on a 6-inch soil depth containing 2 million pounds of soil, the conversion factor for ppm to lb P/acre is 2. For more detailed information on the methods used for soil P testing, how they were developed, and why they vary among regions see Fixen and Grove (1990), Pierzynski (2000), Sharpley et al. (1994, 1996), and Sims (1998).

Soil Phosphorus

Soil P exists in organic and inorganic forms, but these are not discrete entities with indistinct forms occurring (fig. 2). Organic P consists of undecomposed residues, microbes, and organic matter in the soil. Inorganic P is usually associated with Al, Fe, and Ca (aluminum, iron, and calcium, respectively) compounds of varying solubility and availability to plants. Phosphorus has to be added to most soils so that there are adequate levels for opti-

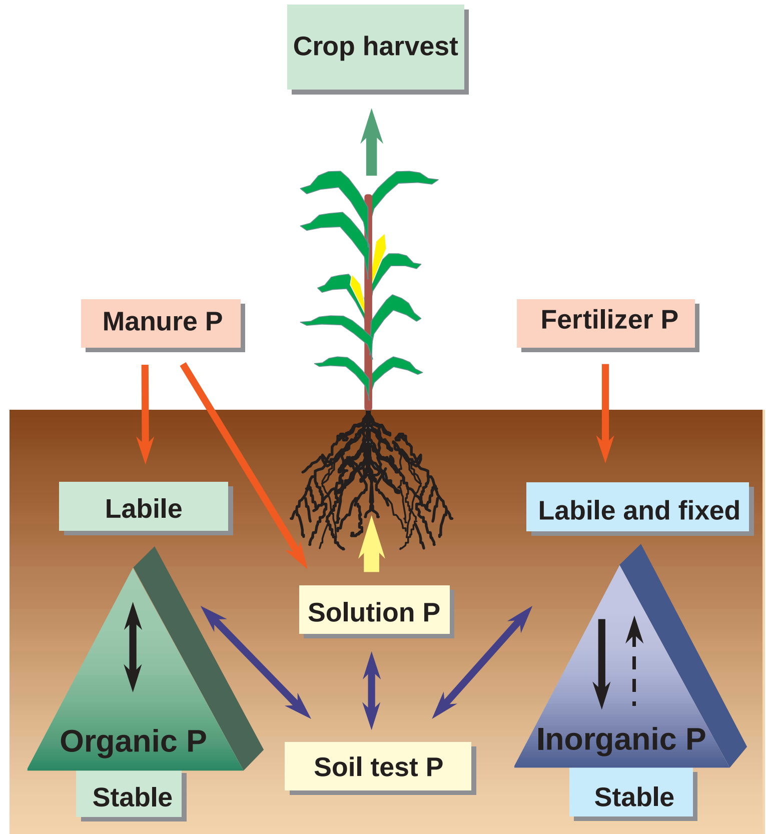

Figure 2. The phosphorus cycle in soil

mum crop growth and yield. However, P can be rapidly fixed in relatively insoluble forms and therefore be unavailable to plants, depending on soil pH and type (Al, Fe, and Ca content). Converting stable forms of soil P to labile or available forms usually occurs too slowly to meet crop P requirements (fig. 2). As a result, soil P tests were developed to determine the amount of plant-available P in soil and from this how much P as fertilizer or manure should be added to meet desired crop yield goals.

In most soils, the P content of surface horizons is greater than that of the subsoil because of sorption of added P, greater biological activity, cycling of P from roots to aboveground plant biomass, and more organic material in surface layers (fig. 3). In reduced tillage systems, fertilizers and manures are

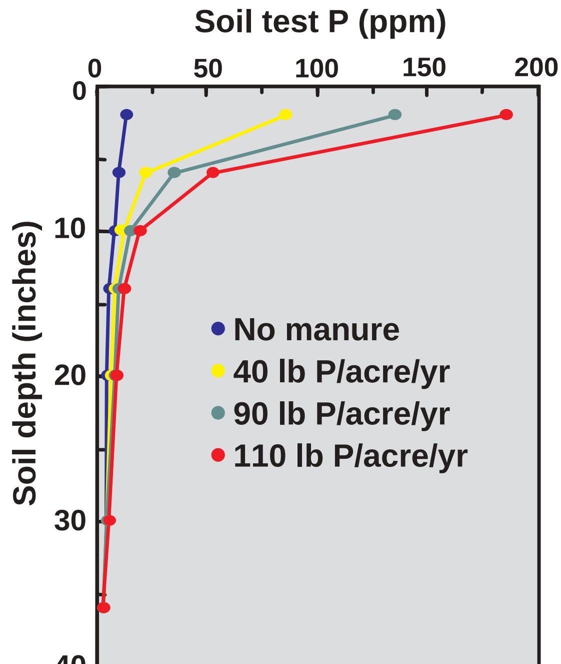

Figure 3. Soil test P (as Mehlich–3 P) accumulates at the surface with repeated application of P for 10 years. Note that typical fertilizer P applications for a corn crop in Oklahoma with a medium soil test P (20 to 40 ppm Mehlich–3 P) is about 20 lb P/acre. (Adapted from Sharpley et al. 1984.)

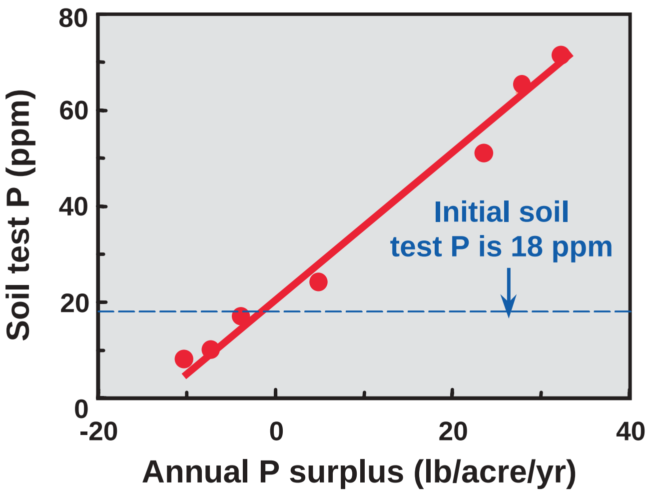

Figure 4. Increase in soil test P from applying more P than a crop needs each year (as Bray–I P). A negative surplus indicates crop and soil removal. (Adapted from a 25-year study by Barber 1979.)

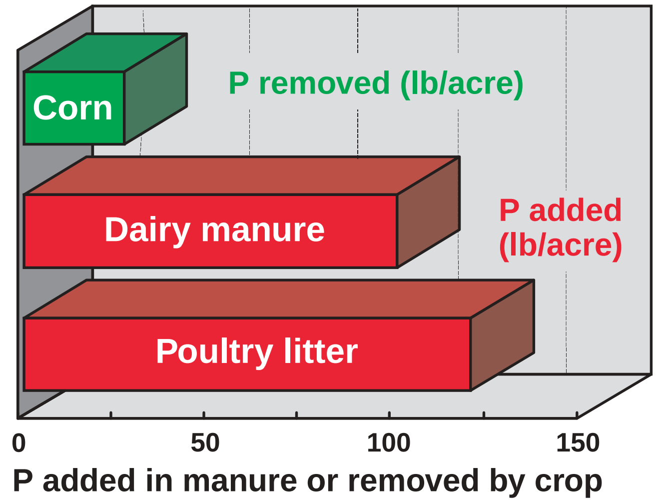

Figure 5. Applying manure to meet crop N needs (about 200 lb available N/acre) adds much more P than corn crop needs.

not incorporated or they are incorporated only to shallow depths, thereby exacerbating P buildup in the top 2 to 5 inches of soil. In some situations, P can easily move through the soil, as we will discuss later.

Continual long-term application of fertilizer or manure at levels exceeding crop needs will increase soil P levels (fig. 4). In many areas of intensive, confined animal production, manures are normally applied at rates designed to meet crop N requirements but to avoid groundwater quality problems created by leaching of excess N. This often results in a buildup of soil test P above amounts sufficient for optimal crop yields. As illustrated in figure 5, the amount of P added in

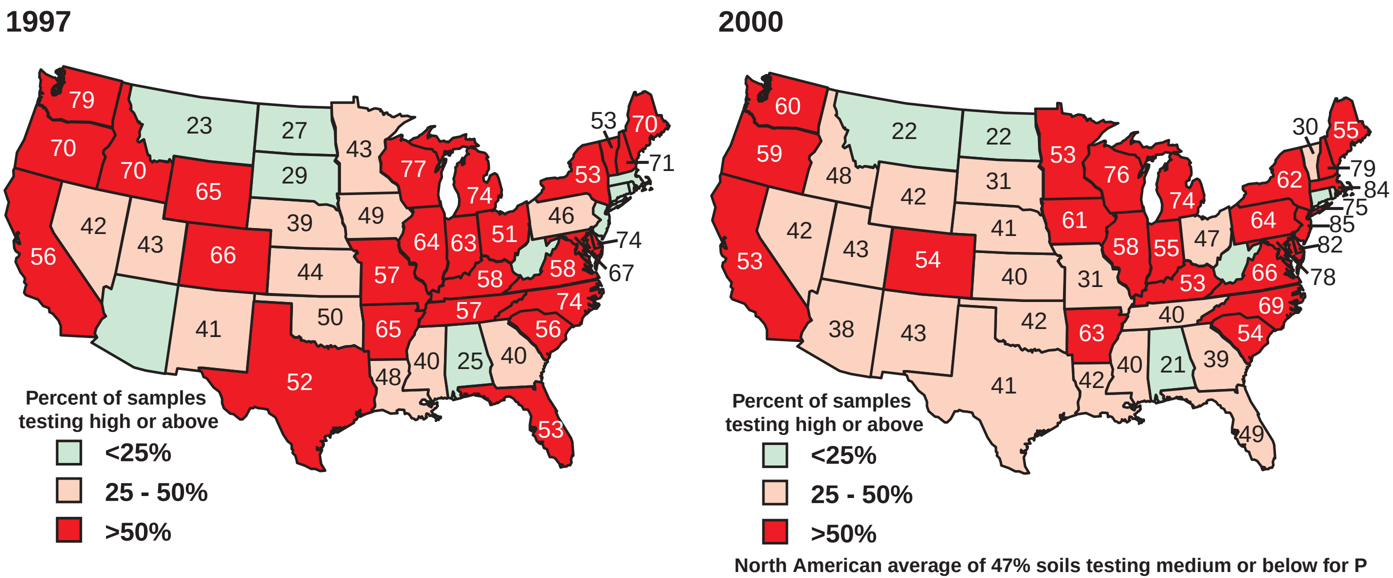

Figure 6. A survey of agricultural soils analyzed by state soil test laboratories in 1997 and 2000 shows a regional buildup of soil test P near P-sensitive waters (Fixen 1998, Fixen and Roberts 2000).

average applications of dairy manure (8 to 10 tons/acre and 0.5 percent P) and poultry litter (4 tons/acre and 1.5 percent P) are considerably greater than what is removed in harvested crops; the result is an accumulation of soil P.

In 2000, several state soil test laboratories reported that the majority of agricultural soils analyzed had soil test P levels in the high or above categories, which require little or no P fertilization. It is clear from figure 6 that high soil P levels are a regional problem, because the majority of agricultural soils in several states still test medium or low. For example, most Great Plains soils still require P for optimum crop yields. Unfortunately, problems associated with high soil P are aggravated by the fact that many of these agricultural soils are located in states with sensitive water bodies, such as the Great Lakes, Lake Champlain, the Chesapeake and Delaware Bays, Lake Okeechobee, the Everglades, and other fresh water bodies (fig. 6).

Distinct areas of general P deficit and surplus exist within states and regions. For example, soil test summaries for Delaware reveal the magnitude and localization of high soil test P levels that can occur in areas dominated by intensive animal production (fig. 7). From 1992 to 1996 in Sussex County, Delaware, with its high concentration of poultry operations, 87 percent of

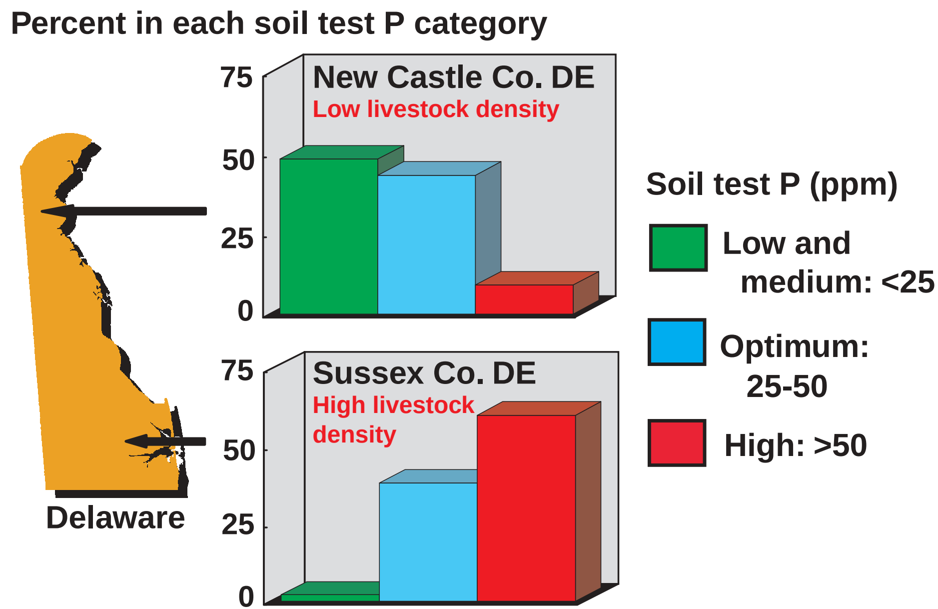

Figure 7. Elevated soil test P levels (as Mehlich–1 P) are usually localized in areas of confined animal operations.

fields tested had optimum (25 to 50 ppm) or excessive soil test P (>50 ppm), as determined by Mehlich–1; whereas, in New Castle County, with only limited animal production, 72 percent of fields tested were rated as low (<13 ppm) or medium (13 to 25 ppm).

Though rapidly built up by applications of P, available soil P decreases slowly once further applications are stopped. Therefore, the determination of how long soil test P will remain above crop sufficiency levels is of economic and environmental importance to farmers who must integrate manure P into sustainable nutrient management systems. For example, if a field has a high potential to enrich agricultural runoff with P because of excessive soil P, how long will it be before crop uptake will lower soil P levels so that manure can be applied again without increasing the potential for P loss? McCollum (1991) estimated that without further P additions, 16 to 18 years of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production would be needed to deplete soil test P (Mehlich–3 P) (Mehlich 1984) in a Portsmouth fine sandy loam from 100 ppm to the agronomic threshold level of 20 ppm.

The Loss of Phosphorus in Agricultural Runoff

The term "agricultural runoff" encompasses two processes that occur in the field—surface runoff and subsurface flow. In reality these can be vague terms for describing very dynamic processes. For example, surface or overland flow can infiltrate into a soil during movement down a slope, move laterally as interflow, and reappear as surface flow. In this publication, agricultural runoff refers to the total loss of water from a watershed by all surface and subsurface pathways.

Forms and Processes

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms (fig. 8). Sediment P includes P associated with soil particles and organic material eroded during flow events and constitutes about 80 percent of P transported in surface runoff from most cultivated land (Sharpley et al. 1992). Surface runoff from grass, forest, or noncultivated soils carries little sediment and is, therefore, generally dominated by dissolved P (about 80 percent of P loss). This dissolved form comes from the release of P from soil and plant material (fig. 8). This release occurs when rainfall or irrigation water interacts with a thin layer of surface soil (1 to 2 inches) and plant material before leaving the field as surface runoff (Sharpley 1985). Most dissolved P is immediately

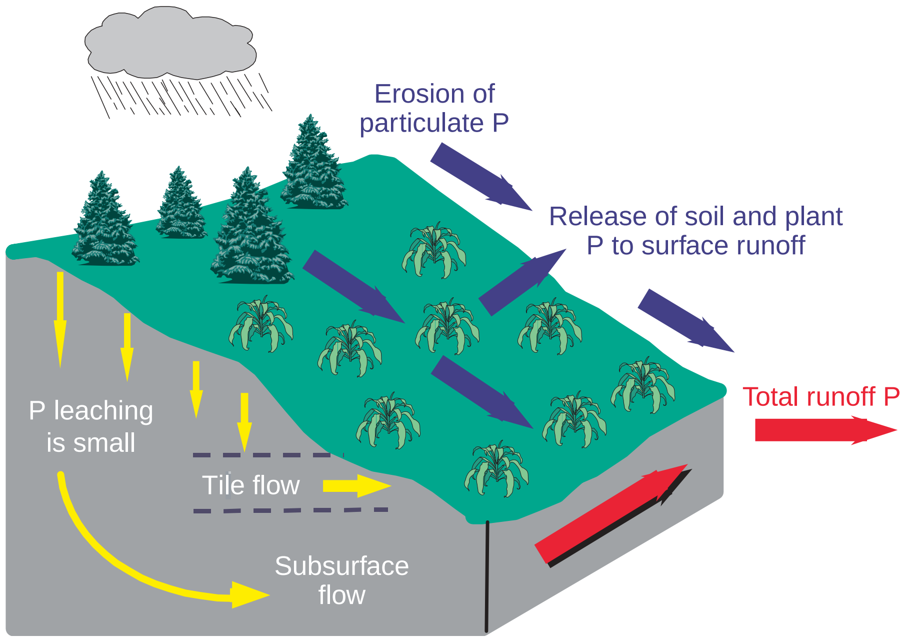

Figure 8. Phosphorus can be released from soil and plant material to surface and subsurface runoff water or lost by erosion.

available for biological uptake. Sediment P is not readily available, but it can be a long-term source of P for aquatic biota (Ekholm 1994, Sharpley 1993).

In most watersheds, P export occurs mainly in surface runoff, rather than subsurface flow. However, in some regions, notably the Coastal Plains and Florida, as well as fields with subsurface drains, P can be transported in drainage waters. Generally, the concentration of P in water percolating through the soil profile is low because of P fixation by P-deficient subsoils. Exceptions occur in sandy, acid organic, or peaty soils with low P fixation or holding capacities and in soils where the preferential flow of water can occur rapidly through macropores and earthworm holes (Bengston et al. 1992, Sharpley and Syers 1979, Sims et al. 1998).

Irrigation, especially furrow irrigation, can significantly increase the potential for soil and water contact and therefore can increase P loss by both surface runoff and erosion in return flows. Furrow irrigation exposes unprotected surface soil to the erosive effect of water movement. The process of irrigation also has the potential to greatly increase the land area that can serve as a potential source for P movement, a fact that is especially important in the western United States.

The Dependence of Agricultural Runoff P on Soil P

Many studies report that the loss of dissolved P in surface runoff depends on the P content of surface soil (fig. 9). In a review of several studies, Sharpley et al. (1996) found that the relationship between surface runoff P and soil P varies with management. Relationship slopes were flatter for grass (4.1 to 7.0, mean 6.0) than for cultivated land (8.3 to 12.5, mean 10.5), but the slopes were too variable to allow

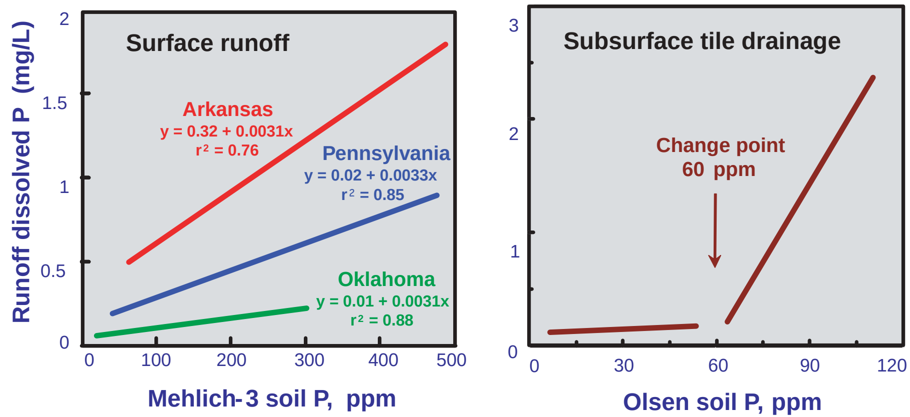

Figure 9. Effect of soil P on the dissolved P concentration of surface runoff from several pasture watersheds (adapted from Sharpley et al. 2001) and subsurface tile drainage from Broadbalk fields. (Adapted from Heckrath et al. 1995.)

use of a single or average relationship to recommend P amendments based on water-quality criteria. Clearly, several soil and land management factors influence the relationship between dissolved P in surface runoff and soil P.

All in all, the loss of P in subsurface flow, as well as surface runoff, is linked to soil P concentration. Heckrath et al. (1995) found that soil test P (Olsen P) greater than 60 ppm in the plow layer of a silt loam caused the dissolved P concentration in tile drainage water to increase dramatically (0.15 to 2.75 mg/L) (fig. 9). They postulated that this level (60 ppm), which is well above that needed by major crops for optimum yield, is a critical point above which the potential for P movement through the soil profile greatly increases (Ministry of Agriculture, Food and Fisheries 1994). Similar studies suggest that this change point can vary threefold as a function of site hydrology, relative drainage volumes, and soil P release characteristics (Sharpley and Syers 1979).

These and similar studies compared agricultural runoff P to soil P using traditional soil test methods that estimate plant availability of soil P. While these studies show promise in describing the relationship between the level of soil P and surface runoff P, they are limited for several reasons. First, soil test extraction methods were developed to estimate the plant availability of soil P and may not accurately reflect soil P release to surface or subsurface runoff water. Second, although dissolved P is an important water-quality variable, it represents only the dissolved portion of P readily available for aquatic plant growth. It does not reflect fixed soil P that can become available with changing chemistry in anaerobic conditions.

The final concern is with sampling depth. It is generally recommended that soil samples be collected to plow depth, usually 6 to 8 inches for routine evaluation of soil fertility. However, it is the surface inch or two in direct contact with runoff that is important when using soil testing to estimate P loss. Consequently, different sampling procedures may be necessary when using a soil test to estimate the potential for P loss. To overcome these concerns, approaches are being developed that provide a more theoretically sound estimate, than traditional agronomic chemical extractants do, of the amount of P in soil that can be released to runoff water and the amount of algal-available P in runoff (Pierzynski 2000, Sharpley 1993).

An approach, developed in the Netherlands by Breeuwsma and Silva (1992) to assess P leaching potential, is to determine soil P saturation (percent saturation = available P/maximum P fixation). This approach is based on the fact that, as P saturation or the amount of fixed P increases, more P is released from soil to surface runoff or leaching water. This method is used to limit the loss of P in surface and ground waters. A critical P saturation of 25 percent has been established for Dutch soils as the threshold value above which the potential for P movement in surface and ground waters becomes unacceptable.

Remediation

The overall goal to reduce P loss from agriculture to water should increase the efficiency of P use by balancing P inputs in feed and fertilizer into a watershed with P outputs in crop and animal produce and managing the level of P in the soil. Reducing P loss in agricultural runoff may be brought about by source and transport control strategies. The transport of P from agricultural land in surface runoff and erosion has been reduced; however, much less attention has been directed toward source management.

When looking at management to minimize the environmental impact of P, there are several important factors that must be considered. To cause an environmental problem, there must be a source of P (that is, high soil levels, manure or fertilizer applications, etc.) and it must be transported to a sensitive location (that is, for leaching, runoff, erosion, etc.). Problems occur where these two come together. A high P source with little opportunity for transport may not constitute an environmental threat. Likewise, a situation where there is a high potential for transport but no source of P to move is also of little threat. Management should focus on the areas where these two conditions intersect. These areas are called “critical source areas” (fig. 10).

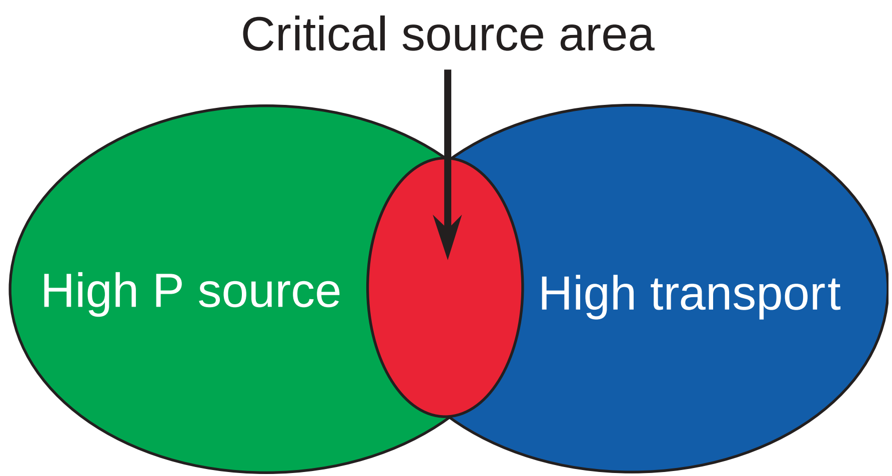

Figure 10. Critical source areas for P loss from a watershed occur where areas of high soil P and transport potential coincide.

Source Management

Reducing off-farm inputs of P in feed

Manipulation of dietary P intake by animals may help balance farm P input and output in animal operations because feed inputs are often the major cause of P surplus (table 1). Morse et al. (1992) recorded a 17-percent reduction in P excretion when the daily P intake of dairy cows was reduced from 82 to 60 g/day. The U.S. National Research Council (2001) recommends dietary P levels for animal production and dairy cows that range between 0.32 and 0.38 percent P, depending on milk yields (table 2). Dietary P in excess of these recommendations can be decreased without harming production or animal health. In fact, Wu et al. (2001) found essentially all P fed in excess of 0.32 percent was excreted by high-producing dairy cows (table 2).

Table 2. Dairy cattle feed recommendations, milk production, fecal P excretion, and losses of P in surface runoff after land application of manure

Dietary P level	Milk production[1]	P excreted[1]	Runoff dissolved P[2]	
%	kg/day	g P/day	ppm	g/ha
0.31	42.4	43	0.30	7
0.39	38.7	66	N.D.[3]	N.D.
0.47	39.4	88	2.84	79

SOURCE: Adapted from Wu et al. (2001).

SOURCE: Adapted from Ebeling et al. (2002). The high P diet in this study was 0.49% P.

N.D. No data available from this study.

The potential effect of overfeeding P to dairy cows and land when applying manure on runoff P was demonstrated by Ebeling et al. (2002). When cows had 0.31 and 0.47 percent P in their diets and the manure (0.48 and 1.28 percent P, respectively) was applied to silt loams covered with corn residues in Wisconsin, runoff P increased dramatically from 7 to 79 g/ha (table 2).

Clearly, amounts of excreted P can be reduced by carefully matching dietary P inputs to animal requirements. As P requirements can change during an animal's life cycle, including lactation in dairy cows for example, further gains in decreasing P excretion may be made by periodically changing dietary P levels.

It is common to supplement poultry and hog feed with mineral forms of P because of the low digestibility of phytin, the major P compound in grain. This supplementation contributes to P enrichment of manures and litters. Enzyme additives for animal feed are being tested to increase the efficiency of P uptake from grain during digestion. Development of such enzymes that would be cost-effective in terms of animal weight gain may reduce the P content of manure. One method is to use phytase, an enzyme that enhances the efficiency of P recovery from phytin in grains fed to poultry and hogs. Another promising method is to develop grain varieties that are lower in phytin.

A third method is to increase the quantity of P in corn that is available to animals by reducing the amount of phytate produced by corn. This would decrease phytate-P, which contributes as much as 85 percent of P in corn grain, and increase inorganic P concentrations in grain. Ertl et al. (1998) manipulated the genes controlling phytate formation in corn and showed that the use of low-phytate corn in poultry feed can increase the availability of P and other phytate-bound minerals and proteins and reduce P excretion.

Soil P management and estimating threshold levels for environmental risk assessment

The long-term use of commercial fertilizers has increased the P status of many agricultural soils to optimum or excessive levels. The goal of P fertilization was to remove soil P supply as a limitation to agricultural productivity; however, for many years actions taken to achieve this goal did not consider the environmental consequences of P loss from soil to water. The constraint on P buildup in soils from commercial fertilizer use was usually economic, with most farmers recognizing that soil tests for P accurately indicated when to stop applying fertilizer P. Some "insurance" fertilization has always occurred, particularly in high-value crops, such as vegetables, tobacco, and sugarcane. However, the use of commercial fertilizers alone would not be expected to grossly overfertilize soils because farmers would cease applying fertilizer P when it became unprofitable. Today's dilemma is caused by the realization that soils considered optimum in soil test P (or perhaps only slightly overfertilized) from a crop produc-

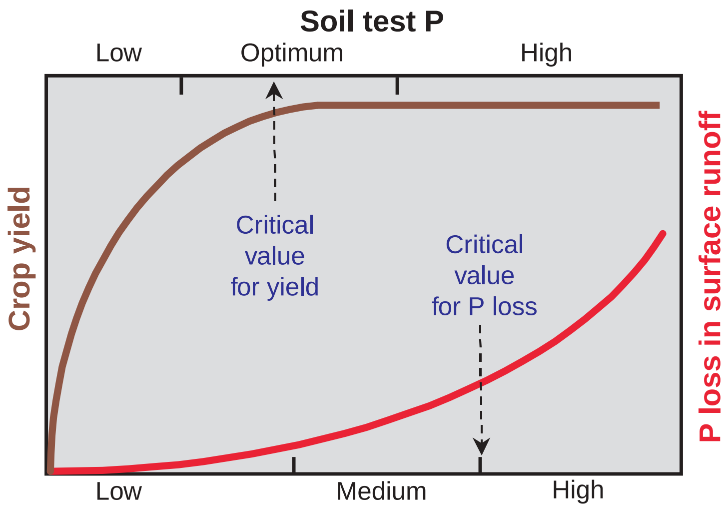

Figure 11. As soil P increases, so does crop yield and the potential for P loss in surface runoff. The interval between the critical soil P value for yield and runoff P will be important for P management.

tion perspective may still provide environmentally significant quantities of soluble and sediment P in surface runoff and erosion.

Environmental concern has forced many states to consider developing recommendations for P applications and watershed management based on the potential for P loss in agricultural runoff. A major difficulty is the identification of a threshold soil test P level to estimate when soil P becomes high enough to result in unacceptable P enrichment of agricultural runoff. Table 3 gives examples from several states, along with agronomic threshold concentrations for comparison.

Environmental threshold levels range from less than 2 times (Maine and Michigan) to 4 times (Pennsylvania and Texas) the agronomic thresholds.

Soil test results for environmental purposes must be interpreted carefully. The comments given on soil test reports—low, medium, optimum, high, and so forth—were established based on the expected response of a crop to P. However, one cannot assume a direct relationship between the soil test calibration for crop response to P and runoff enrichment potential. In other words, one cannot accurately project that a soil test level above an expected crop response level exceeds crop needs and is therefore potentially polluting. What will be crucial in terms of managing P based in part on soil test levels will be the interval between the critical or threshold soil P value for crop yield and runoff P (fig. 11).

Table 3. Threshold soil test P values and P management recommendations

State	Threshold values, ppm		Soil test P method	Management recommendations to protect water quality
	Agronomic	Environmental		
Arkansas	50	150	Mehlich-3	*Above 150 ppm P:* add no P, provide buffers next to streams, overseed pastures with legumes to aid P removal, and provide constant soil cover to minimize erosion.
Colorado	15*	20	Olsen	*Above 20 ppm P:* use P index.
Delaware	50	150	Mehlich-3	*Above 150 ppm P:* develop P-based nutrient management plan (for example, P addition not to exceed crop removal) or use P index.
Idaho	40	40	Olsen	*Above 40 ppm P:* addition not to exceed crop removal and plan required to decrease soil test P to < 40 ppm and minimize transport potential.
Kansas	50	200	Mehlich-3	*Above 200 ppm P:* no P addition regardless of P index rating.
Maine	20	20	Morgan	*Row crops > 20 ppm soil P:* addition not to exceed crop removal for highly erodible soils or soil in P sensitive watershed. *Sod crop:* P addition not to exceed crop removal if soil test P is > 5 times crop removal.
Maryland	25	75	Mehlich-1	*Use P index > 75 ppm P:* soils with high index must reduce or eliminate P additions.

Table 3. Threshold soil test P values and P management recommendations (continued)

State	Threshold values, ppm		Soil test P method	Management recommendations to protect water quality
	Agronomic	Environmental		
Michigan	40	75 and 150	Bray-1	*75 to 150 ppm P:* P addition not to exceed crop removal. *Above 150 ppm P:* apply no P until soil text P is < 150 ppm P.
Ohio	40	150	Bray-1	*Above 40 ppm P:* no fertilizer P addition. *Above 150 ppm P:* apply no P until soil test P is < 150 ppm P.
Oklahoma	30	130 and 200	Mehlich-3	*Non-nutrient limited watershed 130 to 200 ppm P* - half P rate and adopt measures to decrease runoff and erosion; *> 200 ppm P* - P addition not to exceed crop removal. *Nutrient limited watershed 60 to 130 ppm P* - half P rate; *> 130 ppm P* - add no P. *Slope – 8 to 15%* halve P rate: > *15%* add no P.
Pennsylvania	50	200	Mehlich-3	*Above 200 ppm P and < 150 ft from stream:* use P index.
Texas	44	200	Texas A&M	*Above 200 ppm P:* addition not to exceed crop removal.
Wisconsin	30	100	Bray-1	*50 to 100 ppm P:* P addition not to exceed crop removal. *Above 100 ppm P:* P additions must be < crop removal or use P index to determine if P additions are restricted.
In Your Area				

SOURCE: Adapted from Lory and Scharf 2000, Sharpley et al. 1996.
*AB-DTPA is ammonium bicarbonate – diethylelenetriaminepentaacetic acid (Pierzynski 2000).

There is reluctance on the part of most soil testing programs to establish upper threshold limits for soil test P. Reasons range from the fact that soil tests were not originally designed or calibrated for environmental purposes to an unjustified reliance upon soil test P alone by environmental regulatory agencies. Refusing to participate in the debate on the appropriateness of critical limits for soil test P is extremely shortsighted and may force others with less expertise to set the limits that are so important to the soil testing and agricultural community. A foresighted stance acknowledges that agronomically based soil tests can play a role in environmental management of soil P but are only a first step in a more comprehensive approach. This awareness will enhance the credibility of soil testing programs and improve the contribution they make to the agricultural community.

Manure management

Farm advisers and resource planners are recommending that P content of manure and soil be determined by soil test laboratories before land application of manure. This is important because without such determinations, farmers and their advisers tend to underestimate the nutritive value of manure. Soil test results can also demonstrate the positive and negative long-term effects of manure use and the time required to build up or deplete soil nutrients. For instance, soil tests can help a farmer identify the soils in need of P fertilization, those where moderate manure applications may be made, and fields where no manure applications need to be made for crop yield response.

Commercially available manure amendments, such as slaked lime or alum, can reduce ammonia (NH_3) volatilization, leading to improved animal health and weight gains; reduce the solubility of P in poultry litter by several orders of magnitude; and decrease dissolved P, metal, and hormone concentrations in surface runoff (Moore and Miller 1994, Moore et al. 1995, Nichols et al. 1997). Also, the dissolved P concentration (11 mg/L) of surface runoff from fescue treated with alum-amended litter was much lower than that from fescue treated with unamended litter (83 mg/L) (Shreve et al. 1995). Perhaps the most important benefit of manure amendments for air and water quality would be an increase in the N:P ratio of manure via reduced N loss because of NH_3 volatilization. An increased N:P ratio of manure would more closely match crop N and P requirements.

A mechanism should be established to facilitate movement of manures from surplus to deficit areas. At the moment, manures are rarely transported more than 10 miles from where they are produced. However, mandatory transport of manure from farms with surplus nutrients to neighboring farms where nutrients are needed faces several significant obstacles. First, it must be shown that manure-rich farms are unsuitable for manure application based on soil properties, crop nutrient requirements, hydrology, actual P movement, and sensitive water bodies. Then, it must be shown that the recipient farms are more suitable for manure application. The greatest success with redistribution of manure nutrients is likely to occur when the general goals of nutrient management set by a national (or state) government are supported by consumers, local governments, the farm community, and the animal industry. This may initially require incentives to facilitate subsequent transport of manures from one area to another. Again, this may be a short-term alternative if N-based management is used to apply the transported manures. If this happens, soil P in areas receiving manures may become excessive in 3 to 5 years.

Innovative methods are being used by some farmers to transport manure. For example, grain or feed trucks and railcars are transporting dry manure back to the grain source area instead of returning empty (Collins et al. 1988). In Delaware, a local poultry trade organization has established a manure bank network that puts manure-needy farmers in contact with manure-rich poultry growers. Even so, large-scale transportation of manure from producing to non-manure-producing areas is not occurring.

Composting, another potential tool, may also be considered a management tool to improve manure distribution. Although it tends to increase the P concentration of manures, composting reduces the volume of manures and therefore transportation costs. Additional markets are also available for composted materials. As the value of clean water and the cost of sustainable manure management is realized, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost-effective, and create expanding markets.

Transport Management

Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour farming tillage, cover crops, and impoundments (settling basins). Basically, these practices reduce the impact of rainfall on the soil surface, reduce runoff volume and velocity, reduce sediment transport, and increase soil resistance to erosion. None of these measures, however, should be relied on as the sole or primary practice to reduce P losses in agricultural runoff.

Most of these practices are generally more efficient at reducing sediment P than dissolved P. Several researchers report little decrease in lake productivity with reduced P inputs following implementation of conservation measures (Gray and Kirkland 1986, Knuuttila et al. 1994, McDowell et al. 2002). Many times, the impact of remedial measures used to help improve poor water quality will be slow because lake and stream sediments can be a long-term source of P in waters even after inputs from agriculture are reduced. Therefore, immediate action may be needed to reduce future problems.

Targeting Remediation

Threshold soil P levels are being proposed to guide P management recommendations. In most cases, agencies that seek these levels hope to uniformly apply a threshold value to areas and states under their domain. However, it is too simplistic to use threshold soil P levels as the sole criterion to guide P management and P applications. For example, adjacent fields having similar soil test P levels but differing susceptibilities to surface runoff and erosion, due to contrasting topography and management, should not have similar P management recommendations. Also, it has been shown that in some agricultural watersheds, 90 percent of annual algal-available P export from watersheds comes from only 10 percent of the land area during a few relatively large storms (Pionke et al. 1997). For example, more than 75 percent of annual water discharge from watersheds in Ohio (Edwards and Owens 1991) and Oklahoma (Smith et al. 1991) occurred during one or two severe storms. These events contributed over 90 percent of annual total P export (0.2 and 5.6 lb/acre/yr in Ohio and Oklahoma, respectively). Therefore, threshold soil P values will have little meaning unless they are used in conjunction with an estimate of a site's potential for surface runoff and erosion.

A sounder approach advocated by researchers and an increasing number of advisers is to link areas of surface runoff and high soil P content in a watershed (fig. 12).

Soil test P >100 ppm

Areas most vulnerable to P loss

Area of high transport potential

Integrated P and N management

Figure 12. Identifying P loss vulnerability (high soil test P and transport potential) to more effectively target measures to reduce P export in surface runoff from watersheds.

Preventing P loss is now taking on the added dimension of defining, targeting, and remediating source areas of P where high soil P levels coincide with high surface runoff and erosion potentials. This approach addresses P management at multifield or watershed scales. Furthermore, a comprehensive P management strategy must address down-gradient water-quality impacts, such as the proximity of P-sensitive waters. Conventionally applied remediations may not produce the desired results and may prove to be an inefficient and costly approach to the problem if this source-area perspective to target application of P fertility, surface runoff, and erosion control technology is not used.

The concept of a simple P index has been developed by a group of research scientists with diverse expertise as a screening tool for use by field staffs, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in surface runoff (Lemunyon and Gilbert 1993). The index accounts for and ranks transport and source factors controlling P loss in surface and subsurface runoff, delineating sites where the risk of P movement is expected to be higher than that of others (table 4).

Site vulnerability to P loss in surface runoff is assessed by selecting rating values for a variety of source and transport factors. Source factors of the P index are based on soil test P and fertilizer and manure rate, method, and timing of application. The correction factor of 0.2 for soil test P is based on field data that showed a five-fold greater concentration of dissolved P in surface runoff with an increase in mineral fertilizer or manure, compared to an equivalent increase in Mehlich-3 P (Sharpley and Tunney 2000).

To calculate transport potential for each site, erosion, surface runoff, leaching potential, and connectivity values were first summed. A relative transport potential was determined by dividing this summed value by 22, which is the value corresponding to *high* transport potential (erosion is 7, surface runoff is 8, leaching potential is 0, and connectivity is 8). This normalization process assumes that when a site's full transport potential is realized, the transport factor is 1 or greater. Transport factors less than 1 represent a fraction of the maximum potential.

A P index value, representing cumulative site vulnerability to P loss, is obtained by multiplying the summed transport and source

Table 4. The P indexing approach using Pennsylvania's index version from July 2001

Transport Factors						**Your field**
Erosion	Soil loss *(ton/A/yr)*					
Runoff potential	0 Very low	2 Low	4 Medium	6 High	8 Very high	
Sub-surface drainage	0 None		1 Some		2* Patterned	
Contributing distance	0 > 500 ft	2 500 to 350 ft	4 350 to 250 ft	6 250 to 150 ft	8 < 150 ft	
Transport sum = Erosion + Runoff potential + Sub-surface drainage + Contributing distance						
Modified connectivity	0.7 Riparian buffer- applies to distance < 150 ft.		1.0 Grassed waterway or none		1.1 Direct connection-applies to distance > 150 ft.	
Transport factor = Modified connectivity x (Transport sum/22)						
Phosphorus index value = 2 x Source factor x Transport factor						

*As an example, indices for other states can be found on the National Phosphorus Research Project's home page at http://pswmru.arsup.psu.edu/
†Or rapid permeability soil near a stream.

(cont.)–

Table 4. The P indexing approach using Pennsylvania's index version from July 2001 (cont.)

Source Factors						Your field
Soil test	Soil test P (ppm P)					
	Soil test rating = 0.20 Soil test P (ppm P)*					
Fertilizer P rate	Fertilizer P (lb P_2O_5/acre)					
Fertilizer application method	0.2 Placed or injected 2" or more deep	0.4 Incorporated < 1 week	0.6 Incorporated > 1 week or not incorporated April – October	0.8 Incorporated > 1 week or not incorporated Nov. – March	1.0 Surface applied to frozen or snow-covered soil	
	Fertilizer rating = Rate x Method					
Manure P rate	Manure P (lb P_2O_5/acre)					
Manure application method	0.2 Placed or injected 2" or more deep	0.4 Incorporated < 1 week	0.6 Incorporated > 1 week or not incorporated April – October	0.8 Incorporated > 1 week or not incorporated Nov. – March	1.0 Surface applied to frozen or snow-covered soil	
Manure P availability	0.5 Treated manure/Biosolids	0.8 Dairy	1.0 Poultry/Swine			
	Manure rating = Rate x Method x Availability					

factors. Index values are normalized so that the break between *high* and *very high* categories is 100. In most indices, this simply requires multiplying the index value by 2. The P index value for a site can then be used to categorize the site's vulnerability to P loss (table 5).

The index is a tool for field personnel to identify agricultural areas or management practices that have the greatest potential to accelerate eutrophication. It can be used to identify management options available to land users and will allow them flexibility in developing remedial strategies. The first step is to determine the P index for soils adjacent to sensitive waters and prioritize the efforts needed to reduce P losses. Then, management options appropriate for soils with different P index ratings can be implemented. General recommenda-

Table 5. General interpretation of the P index

P index	Rating	General interpretation
< 60	Low	**Low** potential for P loss. If current farming practices are maintained, there is a low risk of adverse impacts on surface waters.
60 to 80	Medium	**Medium** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the risk of P loss.
80 to 100	High	**High** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and P management plans are needed to minimize the risk of P loss.
> 100	Very high	**Very high** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss.

↖ Your Field ↗

tions are given in table 6; however, P management is very site specific and requires a well-planned, coordinated effort among farmers, extension agronomists, and soil conservation specialists.

Making Management Decisions

Farm N inputs can usually be more easily balanced with plant uptake than P inputs can, particularly where confined animal operations exist. In the past, separate strategies for either N or P were developed and implemented at farm or watershed scales. Because N and P have different chemistry and flow pathways through soils and watersheds, these narrowly targeted strategies often conflict and lead to compromised water quality. For example, manure application based on crop N requirements to minimize nitrate leaching to groundwater often results in excess soil P and enhances potential P losses in surface runoff. In contrast, reducing surface runoff losses of P via conservation tillage can increase water infiltration into the soil profile and enhance nitrate leaching.

For P, a primary strategy is to minimize surface runoff and particulate transport. In most cases, decreasing P loss by plant cover, crop residues, tillage and planting along contours, and buffer zones also decreases nitrate loss. Some exceptions are practices that promote water infiltration, which tend to increase leaching, and tillage practices that do not incorporate P fertilizers and manures into the soil. No-till is commonly recommended as a conservation measure for cropland that is eroding. Conversion to no-till is followed by loss of soil and total N and P in surface runoff and increased nitrate leaching and algal-available P transport (Sharpley and Smith 1994).

Nitrogen losses can occur from any location in a watershed, so remedial strategies for N can be applied to the whole watershed. Phosphorus losses usually occur from areas prone to surface runoff; therefore, the most effective P strategy would be to (1) avoid excessive soil P buildup in the whole watershed and thereby limit losses in subsurface flow and (2) use more stringent measures for the most vulnerable sites to minimize loss of P in surface runoff.

Development of sound remedial measures should consider these conflicting impacts of conservation practices on resultant water quality. Clearly, a technically sound framework must be developed that includes critical sources of N and P

Table 6. Management options to minimize nonpoint - source pollution of surface waters by soil P

Phosphorus index	Management options
< 60 (Low)	***Soil testing:*** Test soils for P at least every 3 years to monitor buildup or decline in soil P. ***Soil conservation:*** Follow good soil conservation practices. Consider effects of changes in tillage practices or land use on potential for increased transport of P from site. ***Nutrient management:*** Consider effects of any major changes in agricultural practices on P loss *before* implementing them on the farm. Examples include increasing the number of animal units on a farm or changing to crops with a high demand for fertilizer P.
60 to 80 (Medium)	***Soil testing:*** Test soils for P at least every 3 years to monitor buildup or decline in soil P. Conduct a more comprehensive soil testing program in areas identified by the P index as most sensitive to P loss by surface runoff, subsurface flow, and erosion. ***Soil conservation:*** Implement practices to reduce P loss by surface runoff, subsurface flow, and erosion in the most sensitive fields (that is, reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management). ***Nutrient management:*** Any changes in agricultural practices may affect P loss; carefully consider the sensitivity of fields to P loss before implementing any activity that will increase soil P. Avoid broadcast applications of P fertilizers and apply manures only to fields with low P index values.

(cont.)

Table 6. Management options to minimize nonpoint - source pollution of surface waters by soil P (cont.)

Phosphorus index	Management options
80 to 100 (High)	***Soil testing:*** A comprehensive soil testing program should be conducted on the entire farm to determine fields that are most suitable for further additions of P. For fields that are excessive in P, estimates of the time required to deplete soil P to optimum levels should be made for use in long-range planning. ***Soil conservation:*** Implement practices to reduce P loss by surface runoff, subsurface flow, and erosion in the most sensitive fields (that is, reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management). Consider using crops with high P removal capacities in fields with high P index values. ***Nutrient management:*** In most situations involving fertilizer P, only a small amount used in starter fertilizers is needed. Manure may be in excess on the farm and should only be applied to fields with lower P index values. A long-term P management plan should be considered.
> 100 (Very high)	***Soil testing:*** For fields that are excessive in P, estimate the time required to deplete soil P to optimum levels for use in long-range planning. Consider using new soil testing methods that provide more information on environmental impact of soil P. ***Soil conservation:*** Implement practices to reduce P loss by surface runoff, subsurface flow, and erosion in the most sensitive fields (that is, reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management). Consider using crops with high P removal capacities in fields with high P index values. ***Nutrient management:*** Fertilizer and manure P should not be applied for 3 years or more. A comprehensive, long-term P management plan must be developed and implemented for an entire crop rotation.

export from agricultural watersheds so that optimal strategies at farm and watershed scales can be implemented to best manage N and P.

Summary

The overall goal to reduce P losses from agriculture should be to balance off-farm inputs of P in feed and fertilizer with outputs in products and to manage soils in ways that retain crop nutrient resources. Source and transport control strategies can provide the basis for increasing P-use efficiency in agricultural systems.

Future advisory programs should reinforce the fact that all fields do not contribute equally to P export from watersheds. Most P export comes from only a small portion of the watershed as a result of relatively few storms. Although soil P content is important in determining the concentration of P in agricultural runoff, surface runoff and erosion potential often override soil levels in determining P export. If water or soil do not move from a field or below the root zone, then P will not move. Clearly, management systems will be most effective if targeted to the hydrologically active source areas in a watershed that operate during a few major storms.

Manure management recommendations will have to account for site vulnerability to surface runoff and erosion, as well as soil P content, because not all soils and fields have the same potential to transfer P to surface runoff and leaching. As a result, threshold soil P levels should be indexed against P transport potential, with lower values for P source areas than for areas not contributing to water export.

Phosphorus applications at recommended rates can reduce P loss in agricultural runoff via increased crop uptake and cover. It is of vital importance that management practices be implemented to minimize soil P buildup in excess of crop requirements, reduce surface runoff and erosion, and improve capability to identify fields that are major sources of P loss to surface waters.

Overall—

- management systems should balance P inputs and outputs at farm and watershed scales;
- source and transport controls should target and identify critical source areas of P export from watersheds; and
- farmers should link threshold soil P levels that guide manure applications with site vulnerability to P loss.

Consideration of all these factors will be needed to develop extension and demonstration projects that educate farmers, the animal industry, and the general public about what is actually involved in ensuring clean water. It is hoped this will help overcome the common misconception that diffuse or nonpoint sources are too difficult, costly, or variable to control or target substantial reductions (fig. 13).

Efforts to implement defensible remedial strategies that minimize P loss from agricultural land will require interdisciplinary research involving soil scientists, hydrologists, agronomists, limnologists, and animal scientists. Development of guidelines to implement such strategies will also require consideration of the socioeconomic and political impacts of any management changes on rural and urban communities and of the mechanisms by which change can be achieved in a diverse and dispersed community of land users.

Figure 13. Several *myths* about P still exist:

- Most management practices are permanent solutions. In most cases the only permanent solution to reducing P losses is balancing farm and watershed P inputs and outputs.

- Soils are infinite sinks for P. Research shows that soils cannot indefinitely fix applied P. Continued applications of P beyond crop requirements, a common scenario where organic wastes have been heavily used in agriculture, are a major cause of soil P saturation.

- Crop N requirements should drive manure management. Basing manure management on mature N and crop N needs can lead to undesirably high P applications due to the unfavorable N:P ratios of most manures and crop requirements.

- Phosphorus does not move through the soil. While most P losses occur with surface runoff, P may move through soils with combinations of low P-fixing capacities, with preferential flow (or subsurface drains), or high soil test P contents.

- Erosion control will stop P losses in runoff. Erosion control is not the sole answer; reduction of dissolved P loss in runoff can only be achieved by minimizing P loss at the source and implementing practices that reduce total P in runoff.

- By controlling point sources we can solve water quality problems. Although point source inputs have been reduced in many areas, nonpoint source inputs now contribute to a greater share of water quality problems.

- Phosphorus management strategies can be universally applied. All fields and water bodies are not created equal; management plans for P and best management practices must be tailored to site vulnerability to P loss and proximity of P-sensitive waters.

- We don't know enough about agricultural P. We know a lot about how P reacts with soil and is transferred to runoff, but we have not adequately disseminated this information to land users and state and Federal agencies.

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