Lesson 34

Agricultural Phosphorus Management: Protecting Production and Water Quality

By Andrew Sharpley, USDA-Agricultural Research Service

Financial Support

Funding for the development of this lesson was provided by USDA-CSREES and the U.S. EPA National Ag Assistance Center under a grant awarded to the University of Nebraska Cooperative Extension, University of Nebraska-Lincoln. The following organizations were also affiliated with this project: MidWest Plan Service and USDA-ARS.

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Intended Outcomes

The participants will

- Recognize the role of phosphorus (P) in controlling eutrophication.
- Identify what happens to P in soil when it is added via manure and fertilizer.
- Learn what practical farming measures can be used to minimize P loss.
- Target cost-beneficial best management practices, understand how water moves within a landscape, and learn where large sources of P exist.
- Review innovative products and measures being developed to help producers manage P.

Contents

Activities

Determine the risk associated with high soil P.

PROJECT STATEMENT

This educational program, Livestock and Poultry Environmental Stewardship, consists of lessons arranged into the following six modules:

- Introduction
- Animal Dietary Strategies
- Manure Storage and Treatment
- Land Application and Nutrient Management
- Outdoor Air Quality
- Related Issues

Introduction

Is manure an environmental risk or benefit?

Phosphorus (P), an essential nutrient for crop and animal production, can accelerate freshwater eutrophication, now one of the most common water quality impairments in many developed countries. Recent outbreaks of harmful algal blooms (for example, *cyanobacteria and Pfiesteria*) have increased society's awareness of eutrophication and the need for solutions, the concentration of specialized farming systems has led to a P transfer from grain- to animal-producing areas. This transfer has created regional surpluses in P inputs as fertilizer and feed, built up soil P levels in excess of crop needs, and increased the loss of P from land to water. Recent research has shown that this loss of P in both surface and subsurface flow from watersheds originated from only a small area of a watershed during a few storms. These areas are where high soil P or P application as fertilizer or manure coincide with areas of high runoff or erosion potential. The overall goal of efforts to reduce P loss to water should be to balance P inputs and outputs at farm and watershed levels, while managing soil and P in ways that maintain productivity. Management strategies that minimize P loss to water may involve optimizing P-use efficiency, refining animal feed rations, using feed additives to increase animal absorption of P, moving manure from surplus to deficit areas, and applying conservation practices, such as reduced tillage, buffer strips, and cover crops, to critical areas of P export from a watershed. As issues related to P management are discussed in this lesson, producers are encouraged to evaluate their own P-related risk on current land application sites. This can be done with the aid of the Environmental Stewardship Assessment (P Index, Appendix A) and Regulatory Compliance Assessment (Appendix B)

Phosphorus [is] an essential nutrient for crop and animal production…

Phosphorus and Water Quality Impairment

Since the late 1960s, point sources of water pollution have been reduced due to their ease of identification. In some areas, however, the relative contribution of agricultural nonpoint sources to remaining water quality impairment has increased. Besides soil and pesticide loss from agriculture, most water quality concerns center on nonpoint transport of the nutrients P and nitrogen (N), which are essential inputs for optimum crop and animal production.

Recent assessments of water quality status have identified eutrophication as one of the main causes of water quality "impairment" in the United States (U.S. Environmental Protection Agency 1996, U.S. Geological Survey 1999). 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 (Figure 34-1). While P and N contribute to eutrophication, P is the primary agent in freshwater eutrophication, because many algae are able to obtain N from the atmosphere (Carpenter et al. 1998, Schindler 1977). Thus, controlling eutrophication mainly requires reducing P inputs to surface waters.

…eutrophication [is] one of the main causes of water quality impairment in the United States…

Eutrophication restricts water use for fisheries, recreation, industry, and drinking, due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their death and decomposition (Table 34-1). Also, many drinking water supplies throughout the world experience periodic massive surface blooms of *cyanobacteria* (Kotak et al. 1993). These blooms

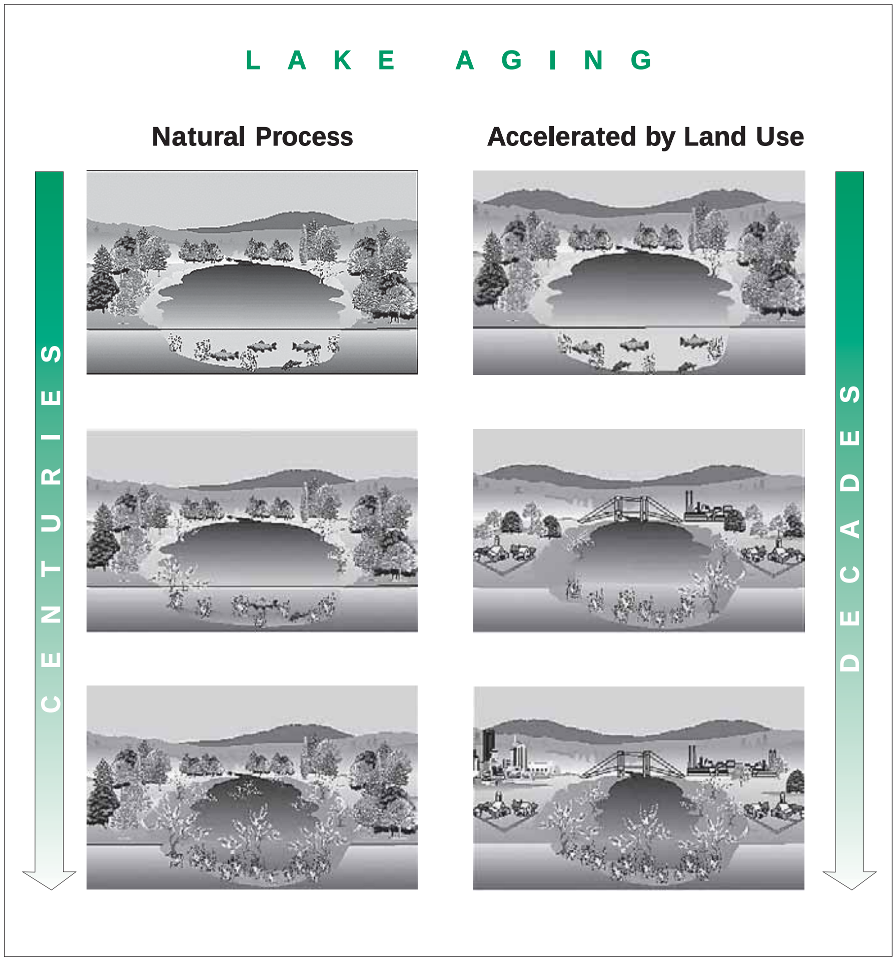

Figure 34-1. Effect of land use on accelerated eutrophication.

Table 34-1. Adverse effects of eutrophication on lakes and rivers.

- Increased biomass of phytoplankton
- Shifts in phytoplankton to bloom-forming species that may be toxic or inedible
- Increased biomass of benthic and epiphytic algae
- Changes in macrophyte species composition and biomass
- Decreases in water transparency
- Taste, odor, and water treatment problems
- Oxygen depletion
- Increased incidence of fish kills
- Loss of desirable fish species
- Reductions in harvestable fish and shellfish
- Decreases in aesthetic value of water body

Adapted from Smith 1998.

contribute to a wide range of water-related problems including summer fish kills, unpalatability of drinking water, and formation of trihalomethane during water chlorination (Kotak et al. 1994, Palmstrom et al. 1988). Consumption of cyanbacterial blooms or water-soluble neuro- and hepatoxins released when these blooms die can kill animals and may pose a serious health hazard to humans (Lawton and Codd 1991, Martin and Cooke 1994).

...P is the primary agent in freshwater eutrophication...

Because of these problems with drinking water treatment, some areas, such as New York State, have done a "U turn" in strategic planning for nutrient management and water quality impacts. It is now cheaper to treat the cause of eutrophication rather than its effects. In the early 1990s, New York City decided it would be more cost-effective to identify and remediate the sources of P in its water supply watersheds rather than build a new water treatment facility. Since then, a variety of programs were established to control nutrient loadings for point and nonpoint sources (NPSs) in the New York City watershed. Because their concern was freshwater quality, P was the main nutrient of consideration.

Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern United States may also be influenced by nutrient enrichment (Burkholder and Glasgow 1997). Although the direct cause of these outbreaks is unclear, the scientific consensus is that excessive nutrient loading helps create an environment rich in microbial prey and organic matter that *Pfiesteria* and menhaden (target fish) use as a food supply. In the long term, decreases in nutrient loading will reduce eutrophication and will likely lower the risk of toxic outbreaks of Pfiesteria-like dinoflagellates and other harmful algal blooms. This has dramatically increased public awareness of eutrophication and the need for solutions.

The sources of P and N to lakes and rivers consist of point sources, such as discharges from factories and sewage treatment plants, and NPSs, such as suburban lawns and agricultural lands. On a practical basis, point sources are readily identified and measured, while NPSs are diffuse and difficult to identify and measure. The main NPSs contributing to the P load of water bodies are summarized in Table 34-2. Runoff from uncultivated or pristine land is considered the natural background loading, which cannot be reduced. This source determines the natural trophic status of a lake or river and can be sufficient to cause eutrophication.

In this lesson, P is referred to in its elemental form rather than as P_2O_5, commonly used in fertilizer analysis. The conversion factor from P to P_2O_5 is 2.29. When plant-available forms of soil P (as determined by soil testing laboratories) are discussed, they will be referred to as soil test P (ppm or mg/kg) and in each case the specific method of analysis used will be identified. Based on a six-inch soil depth containing 2 million pounds of soil, the conversion factor from ppm to lbs P/acre is 2.0. For more detailed information on the methods used for soil P testing, how they were developed, and why they vary among regions, see the following articles: Fixen and Grove (1990), Sharpley et al. (1994 and 1996), and Sims (1998).

The Forms and Reactivity of P in Soil

Added P is rapidly fixed by Al, Fe, and Ca compounds in soil...

Soil P exists in inorganic and organic forms (Figure 34-2). Each form consists of a continuum of many P compounds, existing in equilibrium with each other and ranging from solution P (taken up by plants) to very stable or unavailable compounds (the most typical). In most soils, 50% to 75% of the P is inorganic.

Table 34-2. Nonpoint sources of phosphorus.

Terrestrial	
Runoff from pristine land[1]	• soil erosion • animal excreta • plant residues
Runoff from cultivated land[1]	• soil erosion • fertilizer loss • animal excreta • plant residues • sewage sludge
Runoff from urban land[1]	• soil erosion • septic tanks • domestic waste
Atmosphere (cultural[2]; natural[1])	• wet precipitation • dry precipitation
Aquatic	
Lake sediments[2]	• bottom sediments • resuspended sediments
Biological[1]	• fauna and flora

[1] Impossible to control.
[2] Difficult to control.

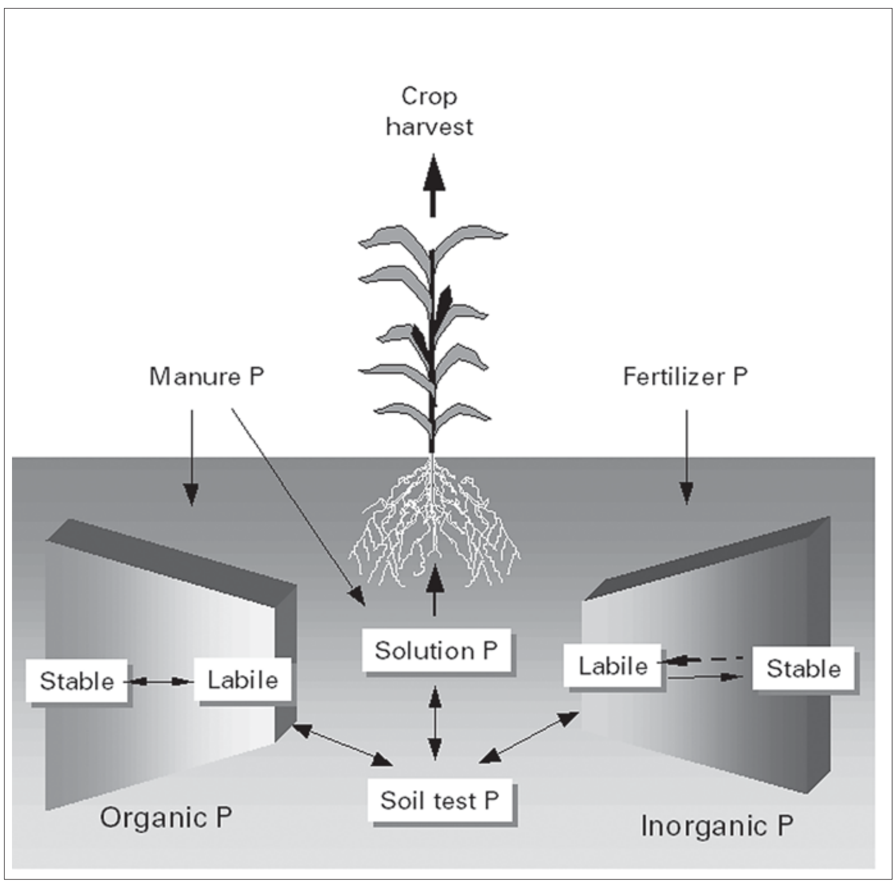

Figure 34-2. The P cycle in soil.

Inorganic P is usually associated with Al, Fe, and Ca compounds of varying solubility and availability to plants. Phosphorus has to be added to most soils so that there are adequate levels for optimum crop growth and yield. However, P can be rapidly fixed (also referred to as sorption) in forms unavailable to plants, depending on soil pH and type (Al, Fe, and Ca content). Conversion of unavailable to available forms of soil P usually occurs too slowly to meet crop P requirements (dashed line on Figure 34-2). 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. The estimated amount of plant-available soil P is subsequently referred to as soil test P.

Organic P compounds range from readily available undecomposed plant residues and microbes within the soil to stable compounds that have become part of soil organic matter. Biological processes in the soil, such as microbial activity, tend to control the mineralization and immobilization of organic P. Mineralization is the breakdown or conversion of readily available organic P to inorganic solution P. Although this occurs in most soils, it is usually too slow to provide enough P for crop growth. Immobilization is the formation of more stable organic P, which is resistant to breakdown.

In most soils, the P content of surface horizons is greater than subsoil (Figure 34-3). Except in special situations, added P tends to be fixed by the soil where it is applied, allowing for little movement down through the soil. In addition, P is cycled from roots to above ground parts of the plant and redeposited in crop residues on the soil surface. This builds up organic material and stimulates biological activity in surface layers. Further, in reduced tillage systems, fertilizers and manures are surface applied with little or no mechanical incorporation, exacerbating P buildup in the top 2 to 5 inches of soil.

Phosphorus content and availability varies with soil parent material, texture, pH, as well as with management factors such as the rate of P

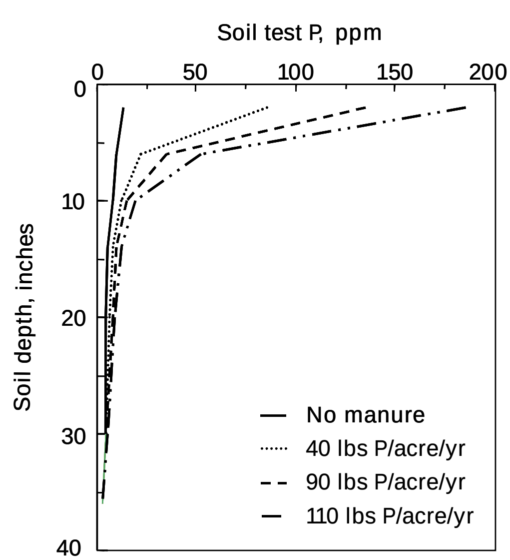

Figure 34-3. Soil test P (as Mehlich-3 P) accumulates at the surface with repeated application of P for 10 years. Note that typical fertilizer P applications for a corn crop in Oklahoma with a medium soil test P (20-40 ppm Mehlich-3 P) is about 20 lbs P/acre.

Adapted from Sharpley et al. 1984.

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...the rapid growth of the animal industry in certain areas of the United States ... [has created] regional and local imbalances in P inputs and outputs...

applications and tillage practice. Although P is relatively immobile in the soil, it is not non-mobile. It can move, especially where soils have become highly enriched with P.

Overall, soil pH is the main property controlling inorganic P forms, although Al, Fe, and Ca content determine the amounts of these forms (Figure 34-4). In acid soils, Al and Fe dominate fixation of P, while Ca compounds fix P in alkaline soils. As a result, P availability is greatest at soil pH between 6 and 7 (Figure 34-4). Immobilization of inorganic P by these processes renders a portion of the added P unavailable for plant uptake (Figure 34-5). Mehlich-3 soil P decreased with time after application of P to a clay and silt loam soil. At the same time, more inorganic P was fixed with Al and Fe (Figure 34-5). This illustrates why crop removal of inorganic P from soil is generally low. In the United States, an average 29% of P added in fertilizer and manure is removed by harvested crops, ranging from < 1% in Hawaii to 71% in Wyoming (National Research Council 1993). The low recovery reflects the predominance of high P-fixing soils in Hawaii.

The Evolution of Agriculture from P Sink to P Source

In many states, animal feeding operations (AFOs) are now the major source of agricultural income. However, the rapid growth of the animal industry in certain areas of the United States has been coupled with an intensification of operations. For example, during the last 10 years, cattle, pig, and poultry numbers have increased 10% to 30%, while the number of farms on which they were reared has decreased 40% to 70% (Gardner 1998).

This intensification has been driven by a greater demand for animal products and an improved profitability associated with economies of scale. Also, it has resulted in a major one-way transfer of P from grain-producing areas to animal-producing areas, creating regional and local imbalances in P inputs and outputs (Lanyon 2000, Sharpley et al. 1998, Sims 1997). On average, only 30% of the fertilizer and feed P input to farming systems is output in crops and animal produce.

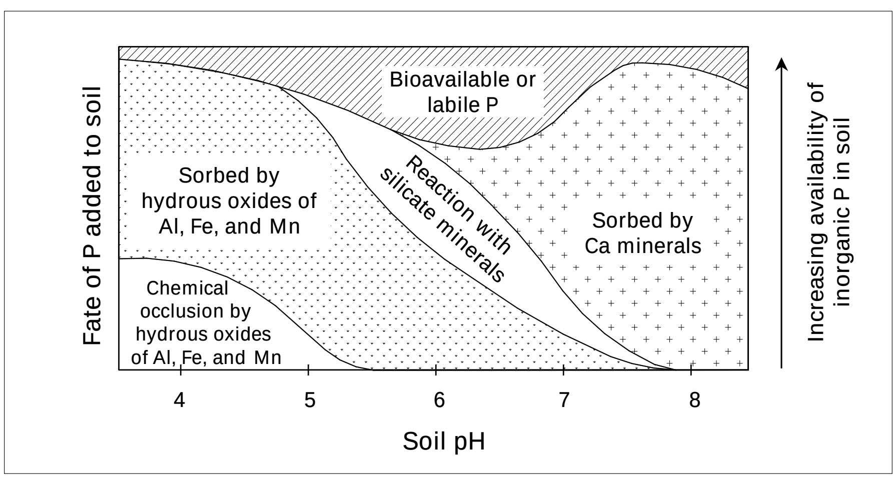

Figure 34-4. Approximate representation of the fate of P added to soil by sorption and occlusion in inorganic forms, as a function of soil pH.

Before World War II, farming communities tended to be self-sufficient; they produced enough feed locally to meet animal requirements and could recycle the manure nutrients effectively to meet crop needs. As a result, sustainable nutrient cycles tended to exist in relatively localized areas (Figure 34-6). After World War II, increased fertilizer use in crop production contributed to specialized farming systems, with crop and animal operations in different regions of the country (Figure 34-7). By 1995, over half of the corn grain produced in the Cornbelt was exported as animal feed. In fact, less than 30% of the corn grain produced on farms today is fed on the farms where it was grown.

The evolution of our agricultural systems is resulting in a major transfer of nutrients from grain-producing areas to animal-producing areas, and consequently, an accumulation of P in soils of those areas. For example, the potential for P and N surplus at the farm scale can be much greater in CAFOs than in cropping systems when nutrient inputs become dominated by feed rather than fertilizer (Table 34-3). With a greater reliance on imported feeds,

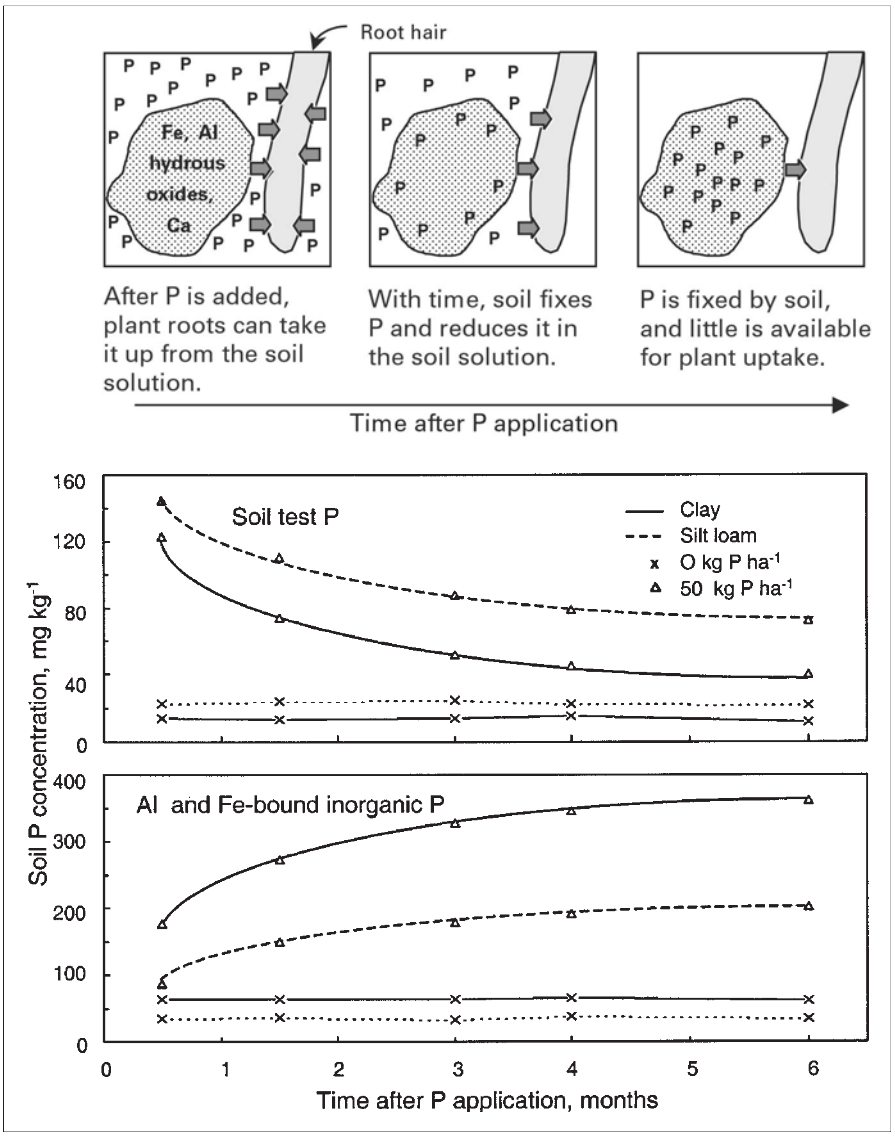

Figure 34-5. The change in soil test (Mehlich-3 P) and absorbed soil P (Al and Fe-bound) with time after P application.

Continual long-term application of fertilizer or manure at rates exceeding crop needs will increase soil P levels.

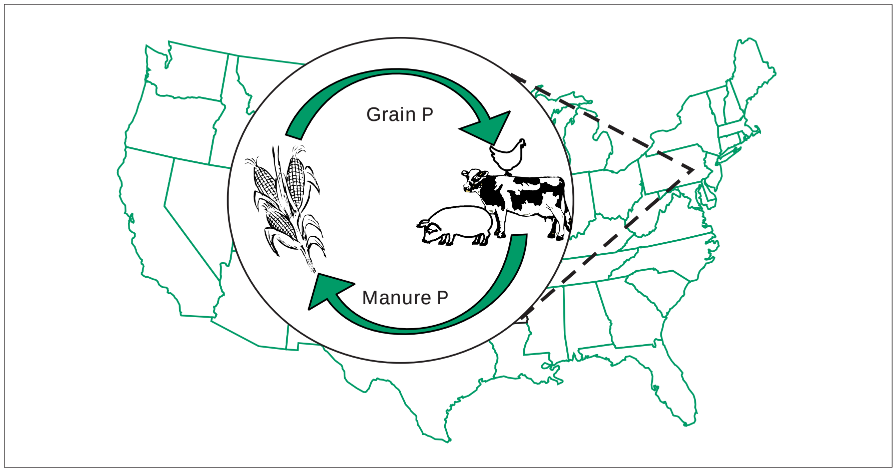

Figure 34-6. Before World War II, nutrient cycling was localized and sustainable within watersheds.

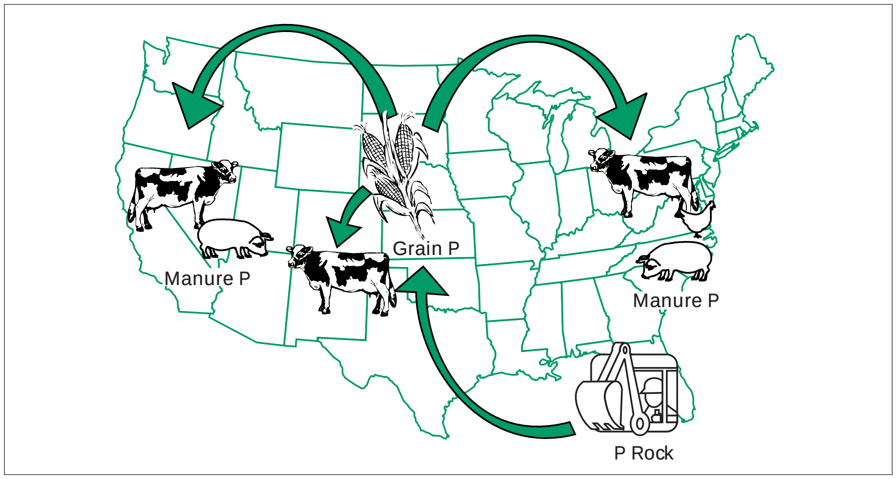

Figure 34-7. Since World War II, the nutrient cycle has been broken on a national level, with P tending to move from areas of grain production to areas of livestock production.

Table 34-3. Farming system and nutrient budget.

Farming System	Nutrient Input In: Feed	Nutrient Input In: Fertilizer	Output	Balance
	lbs/acre/yr			
Phosphorus budget				
Cash crop [1]	—	20	18	+2
Dairy [2]	28	10	13	+25
Hog [3]	95	—	60	+35
Poultry [4]	1,390	—	470	+920
Nitrogen budget				
Cash crop [1]	—	85	82	3
Dairy [2]	138	9	68	79
Hog [3]	350	9	230	129
Poultry [4]	5,200	—	2,940	2,260

[1] 75-hectare cash crop farm growing corn and alfalfa.
[2] 100-hectare farm with 65 dairy Holsteins averaging 14,550 lbs milk/cow/yr, 5 dry cows, and 35 heifers. Crops were corn for silage and grain, and alfalfa and rye for forage.
[3] 75-hectare farm with 1,280 hogs; output includes 40 lbs P and 132 lbs N/acre/yr manure exported from the farm.
[4] 30-hectare farm with 74,000 poultry layers; output includes 7 kg P and 80 lbs N/acre/yr manure exported from the farm.
Adapted from Lanyon and Thompson 1996 and Bacon et al. 1990.

only 30% of P and 55% of N in purchased feed for a 74,000-layer operation on a 30-acre farm in Pennsylvania could be accounted for in farm outputs (Table 34-3). These nutrient budgets clearly show that the largest input of nutrients to CAFOs, and thus the primary source of any on-farm nutrient excess, is in animal feed.

Continual long-term application of fertilizer or manure at rates exceeding crop needs will increase soil P levels. In many areas of intensive confined animal production, manures are normally applied at rates designed to meet crop N requirements 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 Figure 34-8 shows, the amounts of P added in "average" dairy manure (8-10 tons/acre and 0.5% P) and poultry litter (4 tons/acre and 1.5% P) applications are considerably greater than is removed in harvested corn for example. The result is an accumulation of soil P.

A 2000 survey of several state soil test laboratories revealed that high soil P levels are a regional phenomenon and that soils of high P content unfortunately tend to be located near sensitive bodies of water such as the Great Lakes, Lake Champlain, Chesapeake and Delaware Bays, Lake Okeechobee, the Everglades, and other freshwater bodies and estuaries (Figure 34-9). Most soils analyzed in these areas had soil test P levels in the high or very high categories, indicating that little or no supplemental P was required for the current crop and possibly for several future crops. Most soils in other regions of the country tested medium or low; most Great Plains soils, for example, still require P for optimum crop yields.

Within states and regions, distinct areas of general P deficit and surplus exist. For example, soil test summaries for Delaware indicate the magnitude and localization of high soil test P levels that can occur in areas dominated by intensive animal production (Figure 34-10). In Sussex County, Delaware, with a high concentration of poultry operations, 87% of fields tested in 1992 to 1996 had optimum (25-50 ppm) or excessive soil test P (> 50 ppm, as determined by Mehlich-1). In New Castle County, with only limited animal production, 72% of the fields tested were rated as low (< 13 ppm) or medium (13-25 ppm).

Though rapidly built up by P applications, the decline in available soil P is slow once further applications are stopped. Thus, the determination of how long soil test P will remain above crop sufficiency levels is of economic and

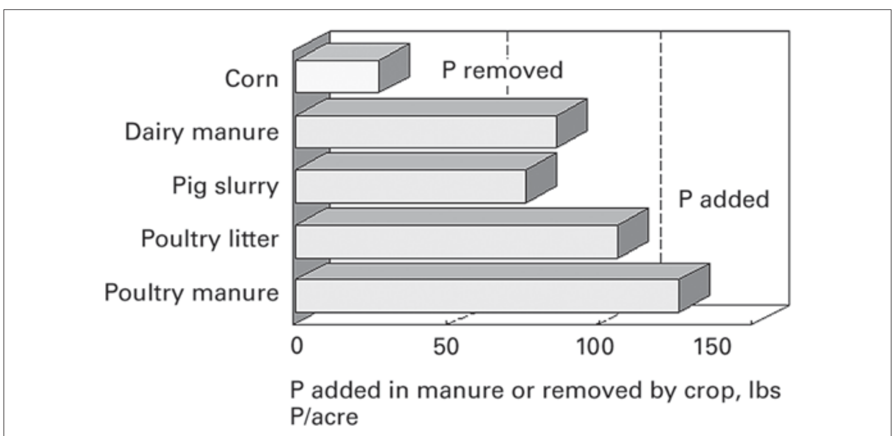

Figure 34-8. Applying manure to meet crop N needs (about 200 lbs available N/acre) will add much more P than corn uses annually.

Continual long-term application of fertilizer or manure at rates exceeding crop needs will increase soil P levels.

Though rapidly built up by P applications, the decline in available soil P is slow once further applications are stopped.

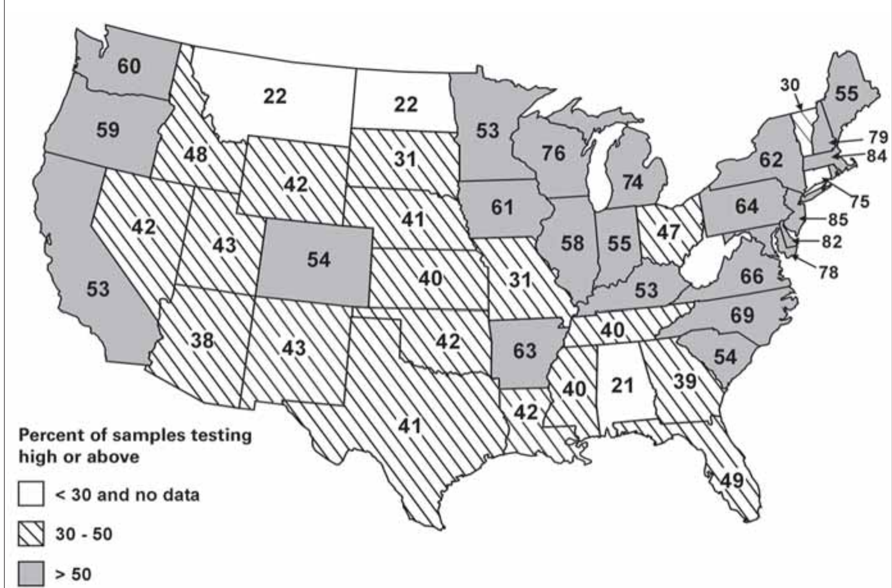

Figure 34-9. A survey of agricultural soils analyzed by state soil test labs in 2000 shows a regional buildup of soil test P near P-sensitive waters.
Adapted from Fixen and Roberts 2002..

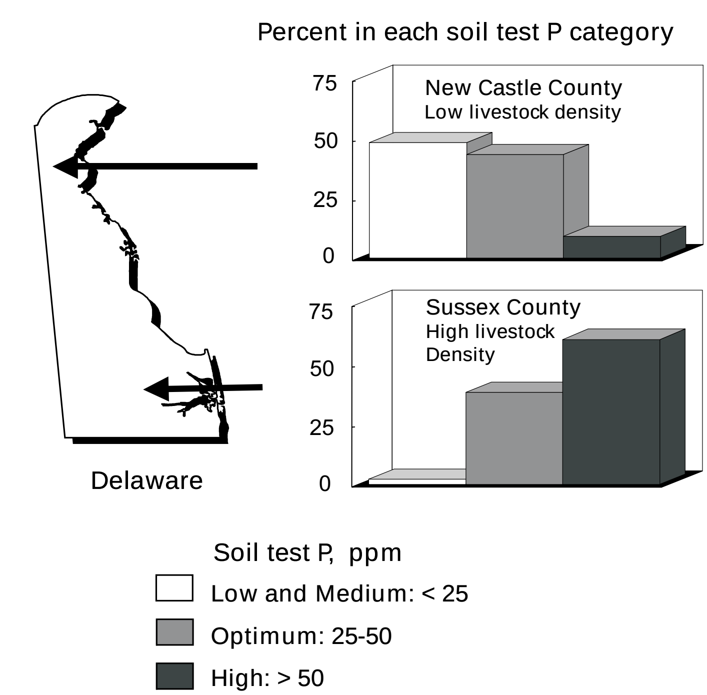

Figure 34-10. Elevated soil test P levels (as Mehlich-1 P) are usually localized in areas of confined animal operations.

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 due to 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? Studies in North Carolina found it would take almost 20 years, without further P additions, for corn and soybean production to decrease soil test P (Mehlich-1 P) from 100 ppm to the agronomic threshold of 20 ppm for a Portsmouth fine sandy loam (McCollum 1991)

Processes and Pathways of P Transport 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 to describe 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 lesson, we use agricultural runoff when referring to the total loss of water from a watershed by all surface and subsurface pathways. The main factors influencing P losses are summarized in Table 34-4.

Forms and processes

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms (Figure 34-11). Sediment P includes P associated with soil particles and organic material eroded during flow events and constitutes 60% to 90% of P transported in surface runoff from most cultivated land. Surface runoff from grass, forest, or uncultivated soils carries little sediment, and therefore, is generally dominated by dissolved P. Thus, erosion control is of

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms…

Table 34-4. Factors influencing P loss.

Factors	Description
Erosion	Total P loss is strongly related to erosion.
Surface runoff	Water serves as the transport mechanism for P either off or through the soil.
Subsurface flow	In sandy, organic, and P-saturated soils or soils with preferential pathways, P can leach through the soil.
Soil texture	Influences relative volumes of surface and subsurface flow
Irrigation runoff	Improper irrigation management can increase P loss by increasing surface runoff and erosion.
Connectivity to stream	The closer the field is to the stream, the greater the chance of P reaching it.
Proximity of P-sensitive water	Some watersheds are closer to P-sensitive waters than others (that is, point of impact).
Sensitivity to P inputs	Shallow lakes with large surface areas tend to be more vulnerable to eutrophication.
Soil P	As soil P increases, P loss in sediment, surface runoff, and subsurface flow increases.
Application rate	The more P (fertilizer or manure) applied, the greater th e risk of P loss
Application method	P loss increases in the following order: subsurface injection, plowed under, and surface broadcast with no incorporation.
Application source	The P in some fertilizers and manure is more soluble than in others, and thus , more susceptible to runoff.
Application timing	The sooner it rains after P is applied, the greater the risk for P loss.

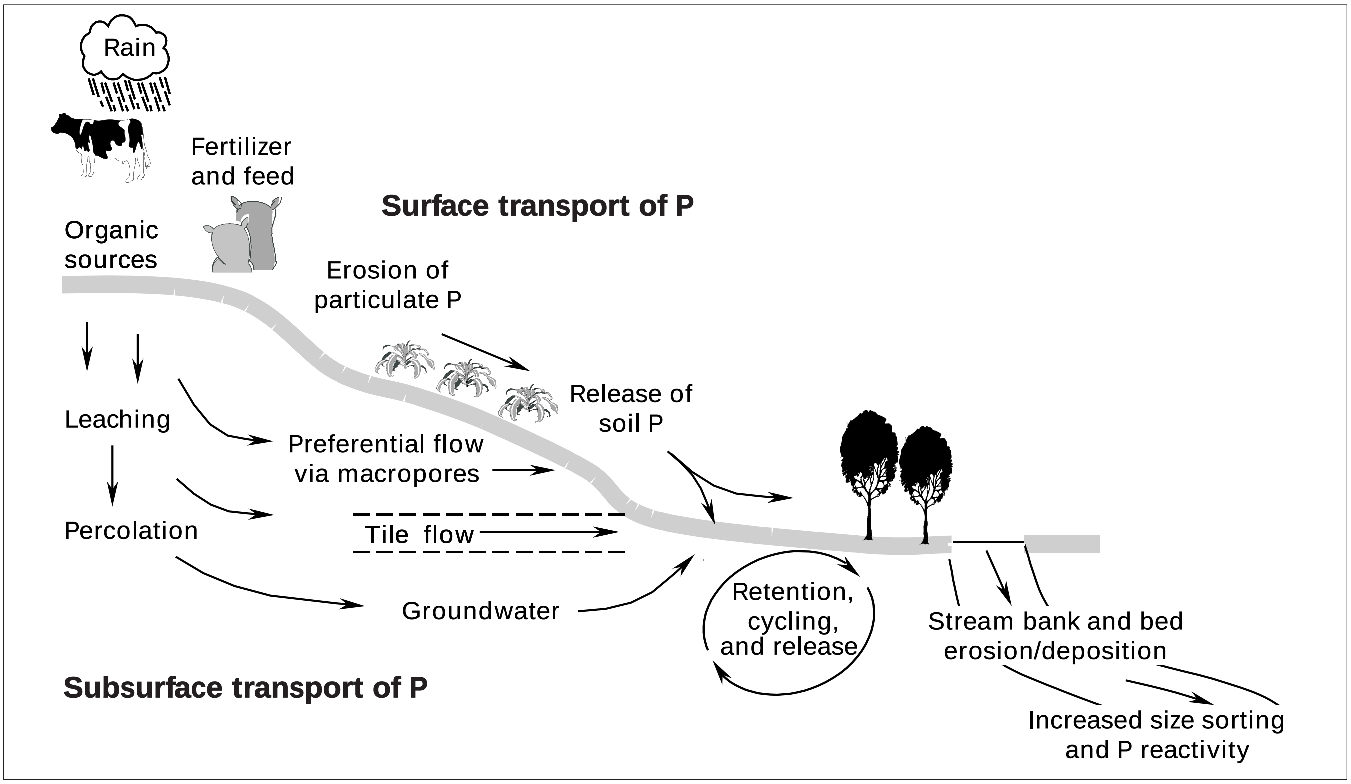

Figure 34-11. Factors affecting P transport to surface waters in agricultural ecosystems.

prime importance in minimizing P loss from agricultural land. However, it may not be sufficient in and of itself.

The dissolved form of P comes from the release of P from soil and plant material (Figure 34-11). This release occurs when rainfall or irrigation water interacts with a thin layer of surface soil (1-2 inches) and plant material before leaving the field as surface runoff. Most dissolved P is immediately available for biological uptake. Sediment P is not readily available but can be a long-term source of P for algae.

...P export occurs mainly in surface runoff rather than in subsurface flow.

Pathways

In most watersheds, P export occurs mainly in surface runoff rather than in subsurface flow. However, in some regions, notably the Coastal Plains, Florida, and fields with subsurface drains, P can be transported in drainage waters. Generally, the concentration of P in water percolating through the soil profile is small due to fixation of P 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.

Irrigation, especially furrow irrigation, can significantly increase the potential for soil and water contact, and thus, 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. This source of P movement is especially important in the western United States.

The loss of dissolved P in surface runoff depends on the P content of surface soil...

The loss of dissolved P in surface runoff depends on the P content of surface soil (Figure 34-12). These data were obtained from several locations within a

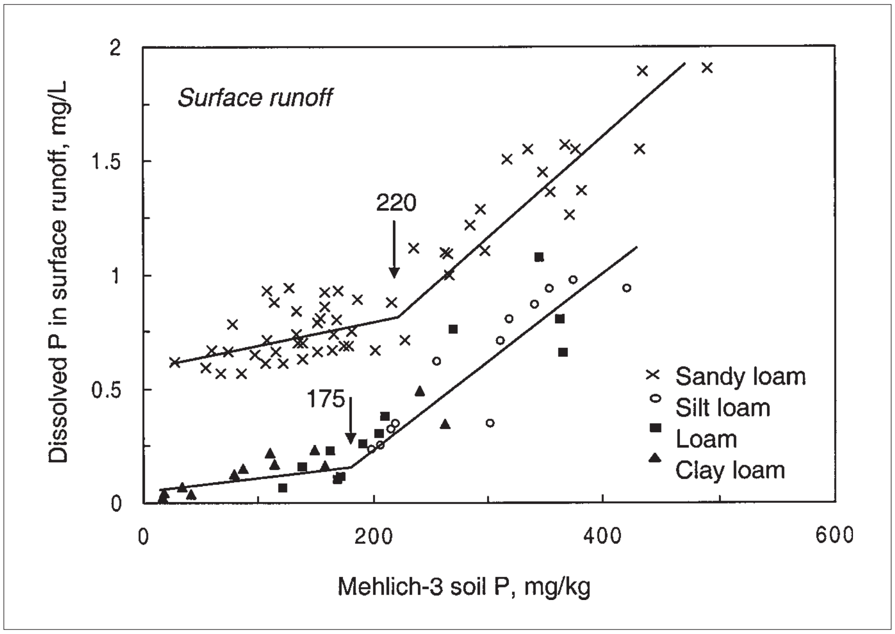

Figure 34-12. Relationship between the concentration of dissolved P in surface runoff and Mehlich-3 extractable soil P concentration of surface soil (0-2 inch depth) from a central PA watershed.

40-ha watershed (FD-36) in south-central Pennsylvania (Northumberland County). Locations were selected to give a wide range in soil test P concentration as Mehlich-3 P (15-500 mg/kg). A change point in the relationship between soil and surface runoff P was determined (220 and 175 mg/kg, Figure 34-12). The potential for soil P release above this point is greater than below it. The variation in this soil P change point or threshold among soils (Figure 34-12) shows the ability of soils to release P to runoff is a function of soil type. Clearly, several soil and site management factors influence P loss.

The P concentration in subsurface flow is also related to surface soil P (Figure 34-13). Thirty-cm deep lysimeters were taken from the same Pennsylvania watershed as the preceding and subject to simulated rainfall (6.5 cm/hr for 30 min). The concentration of dissolved P in drainage from the lysimeter increased (0.07 to 2.02 mg/L) as the Mehlich-3 P concentration of surface soil increased (15 to 775 mg/kg, Figure 34-13). This data manifest a change point that was similar to the change point identified for surface runoff. The dependence of leachate P on surface soil P is evidence of the importance of P transport in preferential flow pathways such as macropores, earthworm holes, and old root channels.

Surface runoff generally occurs only from limited source areas within a watershed. These source areas vary rapidly in time, expanding and contracting quickly during a storm as a function of rainfall intensity and duration, antecedent moisture conditions, temperature, soils, topography, groundwater, and moisture status over a watershed. Because surface runoff is the main mechanism by which P and sediment is exported from most watersheds, it is clear that P export will be negligible if surface runoff does not occur. Thus, consideration of how water moves and where surface runoff occurs is critical to a more detailed understanding of P export from agricultural watersheds.

Also, the amount of P loss necessary to cause water quality problems usually is very small compared to the amounts required by crops or contained in typical

…the P concentration in subsurface flow is also related to surface soil P...

For P to be lost, surface or sub-surface runoff must occur…

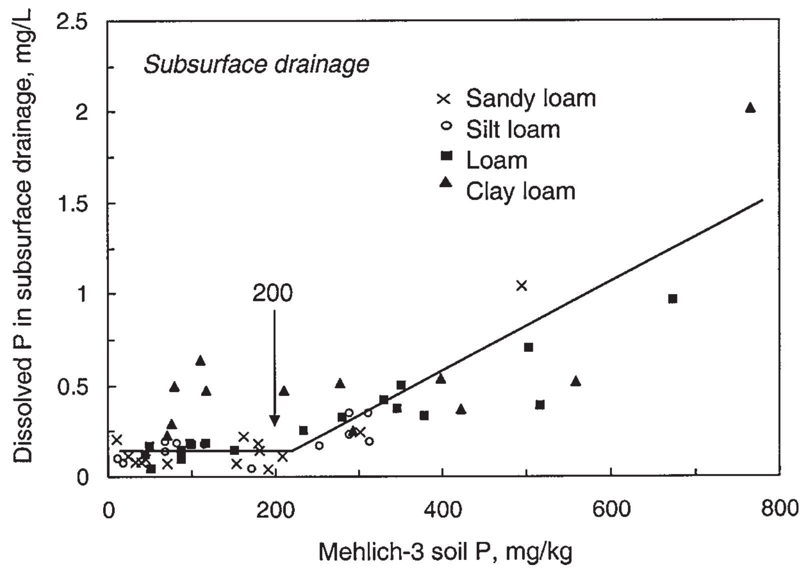

Figure 34-13. Relationship between the concentration of dissolved P in subsurface drainage from 30 cm deep lysimeters and the Mehlich-3 extractable soil P concentration of surface soil (0-2 inch depth) from a central PA watershed.

manure or fertilizer P applications. For example, lake water concentrations of P above 0.02 mg/L generally accelerate eutrophication. These values are an order of magnitude lower than P concentrations in soil solution critical for plant growth (0.2-0.3 mg/L), emphasizing the disparity between critical lake and soil P concentrations. Consequently, this complicates strategies to change farm management, because the loss is too small to show up in most standard practical or economic indicators of crop production efficiency used in farm management.

Environmental Risk Assessment and P Management

The USDA and EPA have developed a Unified Strategy for AFOs to address water quality concerns related to nutrient management (USDA and U.S. EPA 1999). An important part of this strategy is that it spells out how acceptable manure application rates will be determined in these plans. Both N and P must be considered in plans developed under this strategy. The strategy outlines three options for determining appropriate P-based nutrient management plans: agronomic soil test P, environmental soil P thresholds, and P indexing of site vulnerability.

Agronomic soil test P

In this option, manure application rates are based on the recommendations for optimum production of the crop. In other words, if the soil test called for a P addition to grow the crop, manure could be applied only to supply the recommended P. If the soil P test did not recommend any P addition, little or no manure could be applied.

There are several problems with this approach. The most important is that the agronomic soil test sampling, extraction, and interpretations were developed strictly from crop response. In the process of developing the soil test program, no environmental P loss potentials were measured. Therefore, there is no scientific basis for assuming that an agronomic soil test based on crop response will be correlated with environmental impact. Also, this option only measures the plant-available P in the soil that could become an environmental problem. It does not include the probability that this P source will be transported to water and thus have an environmental impact.

Sampling depths can also be problematic. For routine soil fertility evaluation and recommendations, it is generally recommended that soil samples be collected to "plow depth," or the zone of greatest root concentration, which is usually 6 to 8 inches deep. When soil testing is used to estimate soil P loss, however, it is the surface inch or two that comes into direct contact with runoff that is important. One exception is the need to consider the amount of subsoil P in soils with high water tables where shallow lateral flow may be a concern.

...there is no scientific basis for assuming that an agronomic soil test based on crop response will be correlated with environmental impact.

Environmental soil P threshold

Environmental concern has forced many states to consider the development of 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 34-5 gives examples from several states, along with agronomic threshold concentrations for comparison. Environmental threshold levels range from the same as (Maine, Idaho) to almost 5 (Texas) times agronomic thresholds. Determining these thresholds is currently a very contentious and active research area.

The USDA-Agricultural Research Service (ARS) is coordinating a National Phosphorus Research Project in cooperation with EPA, NRCS, and universities to provide a sound scientific basis for establishing threshold soil P levels in areas where accelerated P enrichment of water is known to exist and to define critical sources of P exported from watersheds to better target cost-beneficial remediation (Sharpley et al. 2002). Presently, the project encompasses field-based research to be conducted at over 20 ARS and university locations across the United States. The results of this research will provide defensible nutrient management planning recommendations for utilizing manure and protecting water quality at a watershed scale.

The difference between these first two options is illustrated in Figure 34-14. The critical level for crop response is the point on the dashed line in Figure 34-14 where the yield no longer increases as soil P test levels increase. The environmental critical level (threshold P) is the soil test P level on the solid line where the potential environmental impact becomes unacceptably large. Even if the same soil test extractant is used, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and runoff enrichment potential. What will be crucial in terms of managing P based in part on soil test levels will be the interval between the threshold soil P value for crop yield and runoff P (Figure 34-14). The critical soil test level for P loss may be above or even below the critical level for crop yield.

We do know, however, that threshold soil P levels are too limited to be the sole criterion guiding P management and P applications. For example, adjacent fields having similar soil test P levels but differing susceptibilities

...threshold soil P levels are too limited to be the sole criterion guiding P management and P applications.

Table 34-5. Threshold soil test P values and P management recommendations.

State	Threshold Values, ppm		Soil test P Method	Management Recommendations for Water Quality Protection
	Agronomic[1]	Environmental		
Arkansas	50	150	Mehlich-3	**Above 150 ppm soil P:** Apply no more P, provide buffers next to streams, overseed pastures with legumes to aid P removal, and provide constant soil cover to minimize erosion.
Delaware	50	150	Mehlich-1	**Above 150 ppm soil 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 soil P:** Apply no more P until soil test is < 40 ppm and minimize transport potential.
Kansas	50	200	Bray-1	**Above 200 ppm soil P:** No further P additions.
Maine	20	20	Morgan	**Above 20 ppm soil P:** *Row crops:* Added P not to exceed crop removal in highly erodible soils or soils in P sensitive watershed. *Sod crop:* Added P not to exceed crop removal if soil test P is > 5 times crop removal.
Maryland	25	75	Mehlich-1	**Above 75 ppm soil P:** Use P index. Soils with high index must reduce or eliminate P additions.
Michigan	40	75 and 100	Bray-1	**75 – 150 ppm soil P:** Added P not to exceed crop removal. **Above 150 ppm soil P:** Apply no P until soil test P is < 150 ppm.
Mississippi	40	70	Lancaster	**Above 70 ppm soil P:** No P added
Ohio	40	150	Bray-1	**Above 150 ppm soil P:** Apply no P until soil test P is < 150 ppm.
Oklahoma	30	130 and 200	Mehlich-3	**Non-nutrient limited watershed 130– 200 ppm soil P:** Halve P rate and adopt measures to decrease runoff and erosion. **> 200 ppm soil P** –Added P not to exceed crop removal. **Non-nutrient limited watershed 60-130 ppm soil P:** Halve P rate. **> 130 ppm soil P** – add no P. **Slope – 8%-15%** half P rate: **> 15%** no P.
Pennsylvania	50	200	Mehlich-3	**Above 200 ppm soil P and < 150 ft from stream:** Use P Index.
Texas	44	200	Texas A&M	**Above 200 ppm soil P:** Added P not to exceed crop removal.
Wisconsin	30	50 and 100	Bray-1	**50-100 ppm soil P:** Added P not to exceed crop removal. **Above 150 ppm soil P:** Added P must be < crop removal or use P Index to deter mine if P additions are restricted.

[1]Agronomic threshold concentrations are average values for non -vegetable crops; actual values vary with soil and crop type. Also, vegetables have higher agronomic P requirements.
Adapted from Sharpley et al. 2001.

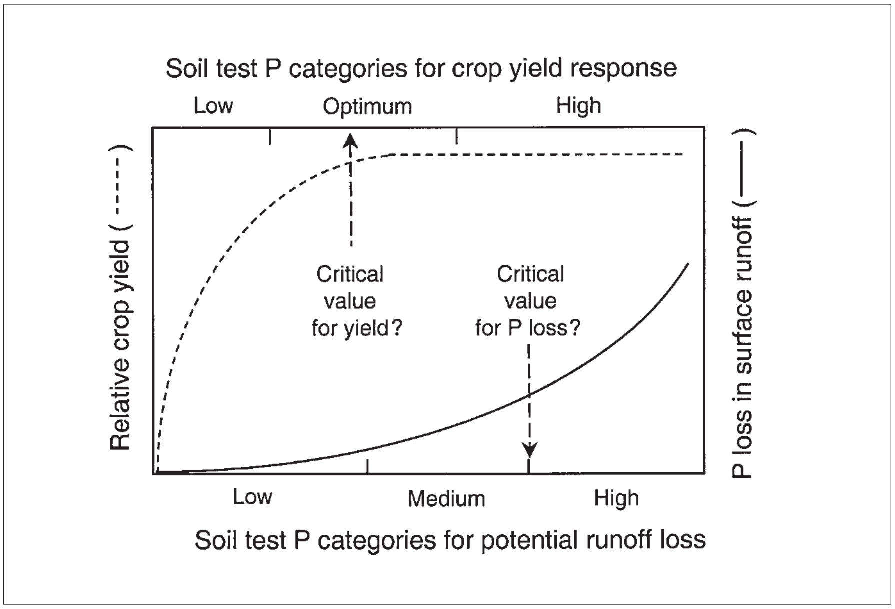

Figure 34-14. As soil P increases, so does crop yield and the potential for P loss in surface runoff. The interval between the critical soil P value for yield and runoff P is important for P management.

to surface runoff and erosion, due to contrasting topography and management, should not have similar restrictions on P use and management. Also, it has been shown that in some agricultural watersheds, 90% of annual algal-available P export from watersheds comes from only 10% of the land area during a few relatively large storms. For example, more than 75% of the annual water discharge from watersheds in Ohio (Edwards and Owens 1991) and Oklahoma (Smith et al. 1991) occurred during one or two severe storms events. These events contributed over 90% of annual total P export (0.2 and 5.6 lb/acre/yr, 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.

The P Index: A risk site assessment tool

To be effective, risk assessment must consider "critical source areas" within a watershed that are most vulnerable to P loss in surface runoff. Critical source areas are dependent on the coincidence of "transport" (surface runoff, erosion, and subsurface flow) and "source" (soil, fertilizer, manure) factors as influenced by site management (Table 34-4, Figure 34-15). Transport factors mobilize P sources, creating pathways of P loss from a field or watershed. Source and site management factors are typically well defined and reflect land use patterns related to soil P status, mineral fertilizer and manure P inputs, and tillage (Table 34-4).

Preventing P loss is now taking on the added dimension of defining risk, then targeting and remediating source areas of P where the risk of P loss is potentially greatest. This approach addresses P management at multi-field or watershed scales and is done using a P Index. In cooperation with several research scientists, USDA-NRCS developed a simple index as a screening tool for use by field staffs, watershed planners, and farmers to rank a field's likelihood of being a source of P loss in surface runoff (Gburek et al. 2000, Lemunyon and Gilbert 1993).

...USDA-NRCS developed a simple index as a screening tool ... to rank a field's likelihood of being a source of P loss in surface runoff.

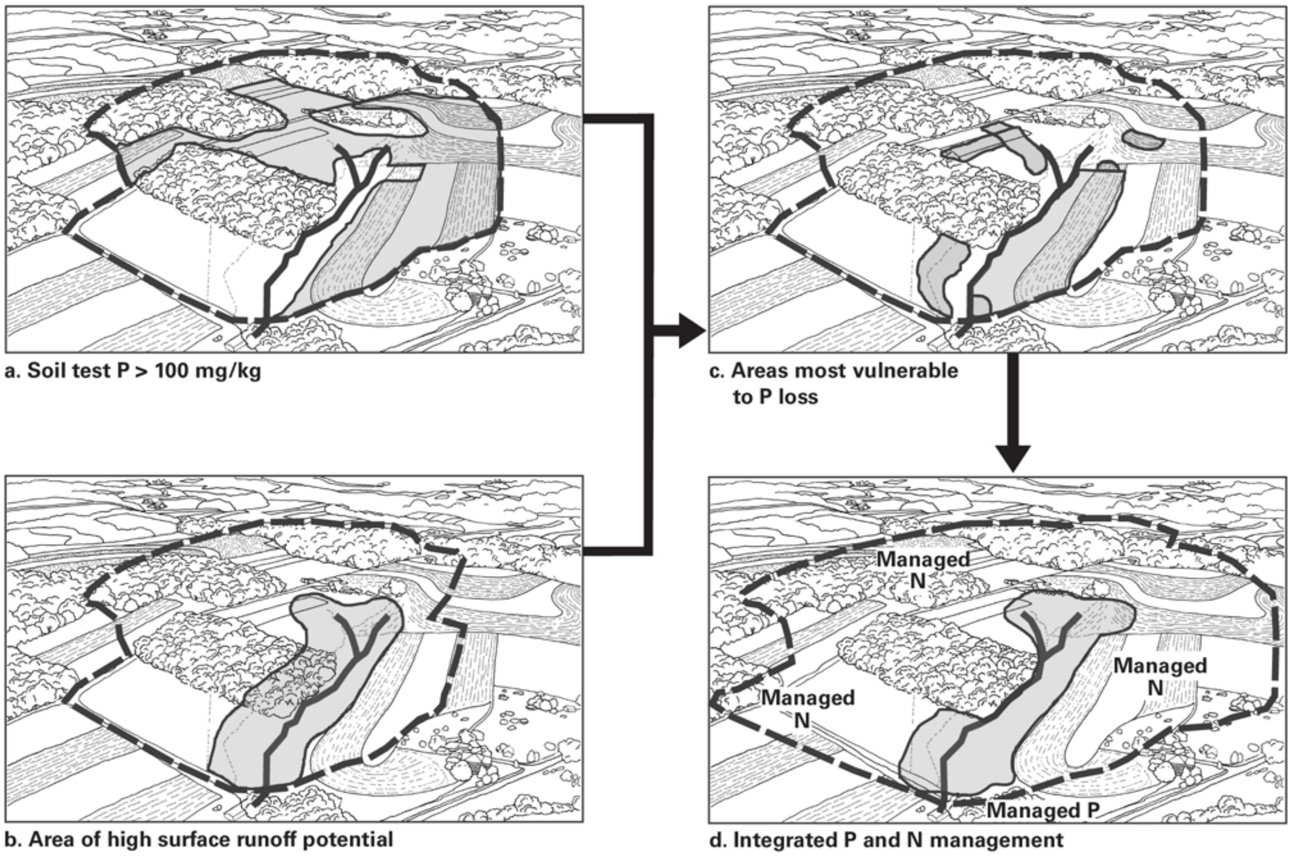

Figure 34-15. The principle of source-area management to more effectively reduce P export in surface runoff from watersheds.

The index accounts for and ranks transport and site management factors controlling P loss in runoff and sites where the risk of P movement is expected to be higher than that of others (Tables 34A-1 and -2, Appendix A). These factors have been chosen because they determine P loss in most cases (Table 34-2). Generally, source management factors include soil test P and applied P source, rate, method, and timing, and transport factors include erosion, surface runoff, subsurface P loss, and distance to receiving water body. While these represent the general categories of parameters, many indices have been selected to include specialized parameters and categories that appropriately represent their unique regional conditions or areas of environmental concern.

The most recent developments of this indexing procedure have been incorporated into the Pennsylvania P Index, which is used as the example for this lesson (Weld et al. 2003). Included as an initial step in the Pennsylvania P Index is a “screening tool” (Table 34A-1, Appendix A). If a field has an STP greater than 200 ppm Mehlich-3 P and is 150 feet or closer to a stream or water body, then a more comprehensive evaluation of the field using the “full” P Index (Tables 34A-2, -3, -4, -5, and -6; Appendix A) is required. The corollary is that if a field has a soil test P less than 200 ppm and is located more than 150 feet from a stream, the full P Index does not need to be run.

In this last situation, the field is assumed to be of a lower risk to contribute P. Thus, time and effort expended in calculating P Index ratings can be directed to those fields that are more likely to be at risk of P loss.

Transport potential for each site is calculated by first summing erosion, surface runoff, leaching potential, and connectivity values (Table 34A-3, Appendix A). To determine a relative transport potential (Table 34A-3, Appendix A), the summed value is then divided by 24, the value corresponding to "high" transport potential (erosion is 6, surface runoff is 8, subsurface drainage is 2, leaching potential is 0, and connectivity is 8). This normalization process assumes that when a site's full transport potential is realized, 100% transport potential is realized. Thus, transport factors < 1 represent a fraction of the maximum potential (Table 34A-3, Appendix A). However, because erosion is open-ended, it is possible to have a transport factor > 1 at high erosion rates.

In the Pennsylvania P Index, site management factors of the P Index, soil test P, fertilizer and manure rate, method, and timing of application (Table 34A-4 and 5, Appendix A) do not all have the same quantitative effect on P loss. In the original P Index, this was addressed with different weighting factors. In the Pennsylvania P Index, a coefficient of 0.2 is used to convert soil test to a value that directly relates to P in manure and mineral fertilizers. This conversion is based on field data that show a fivefold greater concentration of dissolved P in surface runoff with an increase in mineral fertilizer or manure addition compared to an equivalent increase in Mehlich-3 soil test P.

A final P Index value, representing cumulative site vulnerability to P loss, is obtained by multiplying the summed transport and source factors (Table 34A-6, Appendix A). Pennsylvania P Index values are normalized so that the break between "high" and "very high" categories is 100, representing an initiative by Northeastern and Mid-Atlantic states to ensure that P Index output is consistent across state boundaries. Normalization is done by calculating the site P Index value in which all transport and source factors are assumed to be "high." In the Pennsylvania P Index, erosion is set at 6 ton/acre and STP is set at 200 ppm Mehlich-3 P. Breaks between "medium" and "high" and between "low" and "medium" are calculated using the same method, with STP set at 50 and 30 ppm Mehlich-3 P, respectively. These Mehlich-3 P levels correspond to crop response and fertilizer recommendations for Pennsylvania, where > 50 ppm is sufficient for production and no P addition is recommended, 30 to 50 ppm where no crop response is expected but maintenance P is recommended, and < 30 ppm is low and will respond to added P.

The P Index is a tool that helps farmers, consultants, extension agents, and animal producers identify and rank (1) agricultural areas or practices at greatest risk of P loss and (2) management options that give land users flexibility in developing remedial strategies. Determination of the P Index for soils adjacent to sensitive waters is the first step to prioritize the efforts needed to reduce P losses. Then management options appropriate for soils with different P Index ratings can be implemented. Some general recommendations are given in Table 34-6; however, P management is very site specific and requires a well-planned, coordinated effort among farmers, extension agronomists, and soil conservation specialists.

The P Index... helps... identify and rank
(1) agricultural areas or practices at greatest risk of P loss and
(2) management options that give land users flexibility in developing remedial strategies.

Comparing P management strategies

The three options for developing a P-based nutrient management plan described earlier—agronomic soil test P, environmental soil P thresholds, and P indexing of site vulnerability—were evaluated and compared on a 40-ha

Table 34-6. Management options to minimize nonpoint source (NPS) pollution of surface waters by soil P based on the P Index ranking of site vulnerability to P loss.

Phosphorus Index	Management Options
Low	• **Soil testing:** Have soils tested for P at least every three 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 P transport from site. • **Nutrient management:** Consider effects of any major changes in agricultural practices on P losses *before* implementing them. Examples include increasing the number of animal units on a farm or changing to crops with a high demand for fertilizer P.
Medium	• **Soil testing:** Have soils tested for P at least every three years to monitor buildup or decline in soil P. Conduct a more comprehensive soil-testing program in areas that have been identified by the P Index as being most sensitive to P loss by surface runoff, subsurface flow, and erosion. • **Soil conservation:** Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., 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 lower P index values.
High	• **Soil testing:** A comprehensive soil-testing program should be conducted on the entire farm to determine fields that are most suitable for further P additions. For use in the long-range planning of fields that have excessive P, develop estimates of the time required to deplete soil P to optimum levels. • **Soil conservation:** Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., 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, fertilizer P, other than a small amount used in starter fertilizers, will not be 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.
Very High	• **Soil testing:** A comprehensive soil-testing program must be conducted on the entire farm to determine fields that are most suitable for further additions of P. • **Soil conservation:** Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., 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 at least three years and perhaps longer. A comprehensive, long-term P management plan must be developed and implemented.

watershed in Pennsylvania (FD-36). The watershed is 30% row crops (corn and soybean), 30% pasture, and 40% wooded, which is typical of land use in this part of the Northeast. In the fall of 1998, soil test P (as Mehlich 3) was determined on a 30-m^2 grid over the watershed. For the managed part of the watershed (excluding the wooded area), it was found that 5% of the land area had soil test P < 50 ppm P, 10% between 50 and 100, 25% between 100 and 200 ppm P, and 60% > 200 ppm P. These groups of soil P are based on agronomic and environmental response because below 50 ppm P, application is recommended. As soil test P increases from 50 to 100 ppm P, there is a decreasing response to applied P, with no yield response to applied P expected when soil P is above 100 ppm P (Beegle 2002). The environmental threshold of 200 ppm P equated to that proposed by several states (Table 34-5).

If P applications to FD-36 were based on an agronomic soil test P of 100 ppm P, P application would not be recommended for crop yield response on 85% of the managed part of the watershed (Figure 34-16a). Based on an environmental soil P threshold of 200 ppm P, 40% of the managed part of the watershed would receive no P (Figure 34-16b). Finally, using the P index to identify those areas at risk for P loss (as shown in Tables 34A-1, -2, -3, and -4; Appendix A; and Table 34-6), 20% of the watershed is ranked at a high and very high risk for P loss in runoff (Figure 34-16c). These areas are where high soil P, manure and fertilizer application, and the risk of surface runoff or erosion coincide. Using the P Index option, P application would not be recommended on only 20% of the managed part of the watershed.

Each of the three P management strategies is intended to reduce the risk of P loss from a watershed. Clearly, there will be different impacts on farm operations depending on which option or strategy is adopted. Although these are hypothetical situations, more research is needed on the actual impacts of the strategies on actual P loss from a watershed as well as farm production. For example, in watershed FD-36, poultry manure from an egg-laying operation and swine slurry from a pig farm are applied to several cropped fields in the watershed. Obviously, selection of the appropriate P management strategy will impact these operations. Research is thus needed on the effect of changing P management, by using these strategies, on actual P loss from the watershed. In other words, would focusing P remedial efforts on the critical high-risk areas in 20% of the area (P Index option) result in as great a reduction in P export as remediating 85% of the watershed?

Remedial Measures

Any approach to controlling P losses from agriculture to water must begin with the long-term objective of increasing P use efficiency by attempting to balance P inputs within a watershed with P outputs, while simultaneously improving management of soil, manure, and mineral fertilizer P at farm, watershed, or regional scales. Reducing P loss in agricultural runoff may be brought about by Best Management Practices (BMPs) that control the source and transport of P, such as those listed in Table 34-7.

...attempt to (1) balance P inputs within a watershed with P outputs [and] (2) improve management of soil, manure, and mineral fertilizer P at farm, watershed, or regional scales.

Source management

Source management attempts to minimize P buildup in the soil above levels sufficient for optimum crop growth, by controlling the quantity of P in manure and the amount of P that is applied in a localized area. For more information, see the dietary strategy lessons, Lessons 10, 11, 12, and 13.

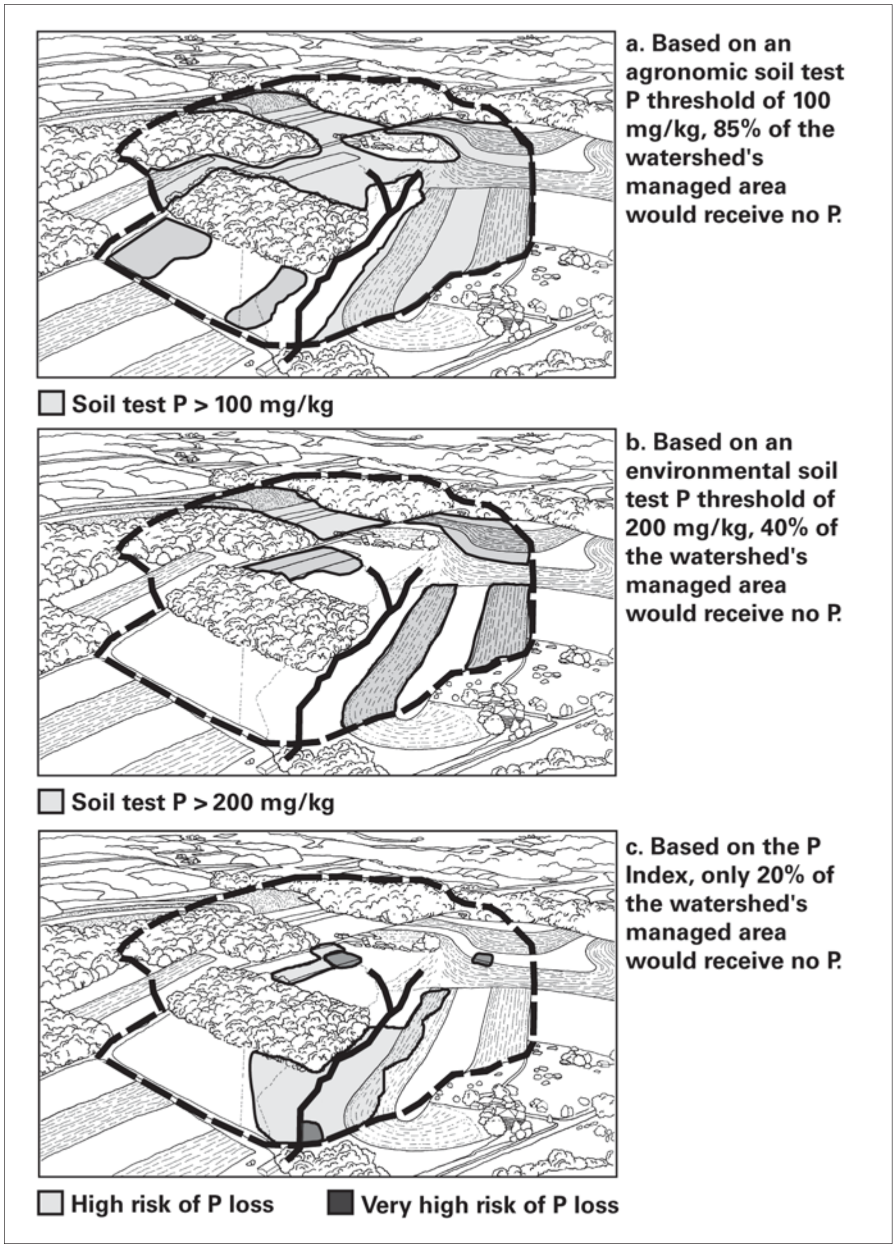

Figure 34-16. Comparison of the three options for P-based management: agronomic soil test P, environmental soil test P, and P indexing of site vulnerability.

Techniques for doing this include

- Manipulating animal intake of dietary P.
- Managing inorganic and protein supplements that contain P.
- Using enzyme additives for animal feed.
- Using corn hybrids with less phytate P.
- Before the land application of manure, determining the P content of both manure and soil.
- Using commercially available manure amendments.
- Physically treating manure to separate solids from liquids.
- Facilitating the movement of manure from surplus to deficit areas.
- Using innovative methods to transport manure.

Table 34-7. Best management practices for the control of NPSs of agricultural P.

Source BMPs: Practices that minimize P loss at the origin

- Balance P inputs with outputs at farm or watershed scale
- Add enzyme to feed to increase nutrient utilization by animals
- Minimize P in livestock feed by not overfeeding P
- Feed low phytic acid corn to reduce P in manure
- Test soil and manure to optimize P management
- Physically treat manure to separate solids from liquid
- Chemically treat manure to reduce P solubility, for example, alum, flyash, water treatment residuals
- Biologically treat manure, for example, microbial enhancement
- Calibrate fertilizer and manure application equipment
- Apply proper application rates of P
- Use proper P application method, that is, broadcast, plowed in, injected, subsurface placement, banding
- Carefully time P application to avoid imminent heavy rainfalls
- Use remedial management of excess P areas (spray fields, disposal sites)
- Compost and/or pelletize manures and waste products to provide alternate use
- Mine P from high P soils with certain crops and grasses
- Manage urban P use (lawns and gardens)

Transport BMPs: Practices that minimize P transport

- Minimize erosion, runoff, and leaching
- Plant cover crops to protect soil surface from erosion
- Implement terracing, strip cropping, and contour farming to minimize runoff and erosion
- Practice irrigation management and furrow management to minimize runoff and erosion
- Install filter strips, grass waterways, and other conservation buffers to trap eroded P and disperse runoff
- Manage riparian zones and wetlands to trap eroded P and disperse runoff
- Practice drainage ditch management and streambank stabilization to minimize erosion
- Build streambank fencing to exclude livestock from water
- Use wellhead protection to minimize by-pass flow to groundwater
- Install and maintain impoundments to trap sediment and P

Source and Transport BMPs: Systems approach to minimize P loss

- Retain crop residues to minimize erosion and runoff
- Consider reduced tillage systems to minimize erosion and runoff
- Practice grazing (pasture and range) management to minimize erosion and runoff
- Exclude animals from certain sites
- Install and maintain manure-handling systems (houses/lagoons)
- Practice barnyard storm water management
- Install and maintain milkhouse waste filtering systems
- Implement a comprehensive nutrient management plan (CNMP)
- Construct tailwater return flow ponds

Water Body Treatment BMPs: Practices designed to correct problems associated with excess P in the water

- Remove sediment from water bodies
- Inactivate sedimentary P with alum or straw
- Stimulate aerobic conditions
- Enhance vegetative growth in littoral zones to decrease water column mixing
- Mine sedimentary P with vegetation
- Harvest aquatic vegetation

- Composting manure.
- Using some manure as “bioenergy” sources.

Manipulating animal intake of dietary P will help balance farm P inputs and outputs in animal operations because feed inputs are often the major cause of P surplus (Table 34-3). Phosphorus intakes above minimum dietary

...matching dietary P inputs to animal requirements can reduce the amount of P that they excrete...

...enzyme additives in feed can reduce the need for P supplements...

requirements do not seem to confer any growth advantage and are excreted. Thus, carefully matching dietary P inputs to animal requirements can reduce the amount of P that they excrete (Table 34-8). This reduction will have an obvious impact on farm P balance by reducing the potential on-farm accumulation of P and decreasing the land base needed for a balanced P-management plan. For example, a survey of Wisconsin dairy farms by Powell et al. (2002) showed that on farms where manure P exceeds crop P requirements, reducing dietary P to the National Research Council (NRC) recommendation would reduce the number of farms and acreages with an excess P balance by approximately two-thirds.

In addition to inorganic P supplementation of animal feed, some protein supplements can contribute substantial amounts of P to animal diets (NRC 2001). Common protein supplements vary greatly in cost and P content (0.3-4.7% P), and producers often select protein sources based on economics, not P content. For animal operations where an excess P balance exists, protein supplements with lower P concentrations should be selected (Table 34-8).

A significant amount of the P in grain is in phytate (phytic acid), an organic form of P that is digested in low proportions by monogastric animals such as pigs and chickens. As a result, feed is commonly supplemented with mineral forms of P that are readily digestible. This supplementation contributes to P enrichment of manure and litter. Enzymes such as phytase, which break down phytate into forms available to monogastric animals, can be added to feed to increase the efficiency of grain P absorption by pigs and poultry. Such enzyme additives in feed can reduce the need for P supplements and potentially reduce the total P content of manure (Table 34-8).

Another approach to better balance farm P inputs and outputs is to increase the quantity of P in corn that is available to hogs and chickens. Corn hybrids are available that contain low amounts of indigestible phytate P. Without the phytase enzyme, hogs and chickens cannot digest this phytate P, which is excreted. Pigs and chickens fed “low-phytic acid” corn grain excreted 10% to 40% less P in manure than those fed conventional corn varieties. This study also showed that P availability to non-ruminants from low-phytate, high available phosphate (HAP) corn is about two to three times higher than that from normal corn (Figure 34-17). Currently, the challenge to plant breeders is to incorporate the low-phytate trait into commercial corn hybrids with other agronomically

Table 34-8. Potential for feed management strategy to affect manure P.

Feeding Strategy	P Loss Reduction, %
Ruminants and Non-Ruminants	
Formulate diet closer to requirement	10-15
Growth promotion	5
Protein/carbohydrate enzymes	5
Use of highly digestible feeds	5
Phase feeding	5-10
Ruminants	
Reduced P in diet	20-30
Non-Ruminants	
Phytase/low-P diet	20-30
Phytase/low-P diet/HAP corn	40-60

Adapted from Ertl et al. 1998, Federation of Animal Sciences Societies 2001, and Baxter et al. 1998.

Figure 34-17. A geneticist examines a new line of corn he developed. The new corn is designed to be lower in phytic acid, a compound suspected of reducing nutrient absorption during human digestion.
Photo by Keith Weller.

desirable traits. Combining use of phytase feed amendments and low-phytate corn resulted in a 60% reduction in P excreted by swine (Table 34-8).

Farm advisors and resource planners are now recommending that the P content of both manure and soil should be determined by soil test laboratories before land application of manure. Without these tests, farmers and their advisors tend to underestimate the fertilizer value of manure.

Commercially available manure amendments, such as slaked lime or alum (Figure 34-18), can reduce ammonia (NH_3) volatilization, leading to improved animal health and weight gains. They can also 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 et al. 2000). Perhaps the most important benefit of manure amendments for both air and water quality is 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.

Separating the solids from the liquids may increase the management options for some types of manure, such as dairy and swine. This process results in some separation of the nutrients as well, leaving a large proportion of the available N in the liquid fraction and a large proportion of the P in the solid fraction. Also, large dairy and swine operations commonly rely on flush-water system for managing their manure. While such systems are very efficient and rank high in overall cleanliness, large volumes of slurry high in solids and soluble nutrients are produced (Figures 34-19 and -20). Coagulant and flocculent techniques commonly used by municipalities are being used to solve such problems. For example, researchers have shown that using a metal coagulant, such as aluminum, in combination with commercial polymers (polyacrylamide) doubles the removal of solids and also dramatically reduces the soluble P in the effluent. While this does not change the total amount of nutrients that must be handled, it enables better targeting of the individual nutrients to locations where they are most needed, reducing the

...the P content of both manure and soil should be determined... [so] the fertilizer value of manure [is not underestimated].

Chemical and physical treatment of manure can improve air and water quality by decreasing N loss and P solubility as well as increasing the end-use options for manure...

Figure 34-18. A soil scientist looks for signs of dermatitis on a chicken raised in a poultry house with alum-treated litter. Alum reduces dermatitis in chickens, ammonia emissions to the air, and P losses in runoff water. Photo by Rob Flynn.

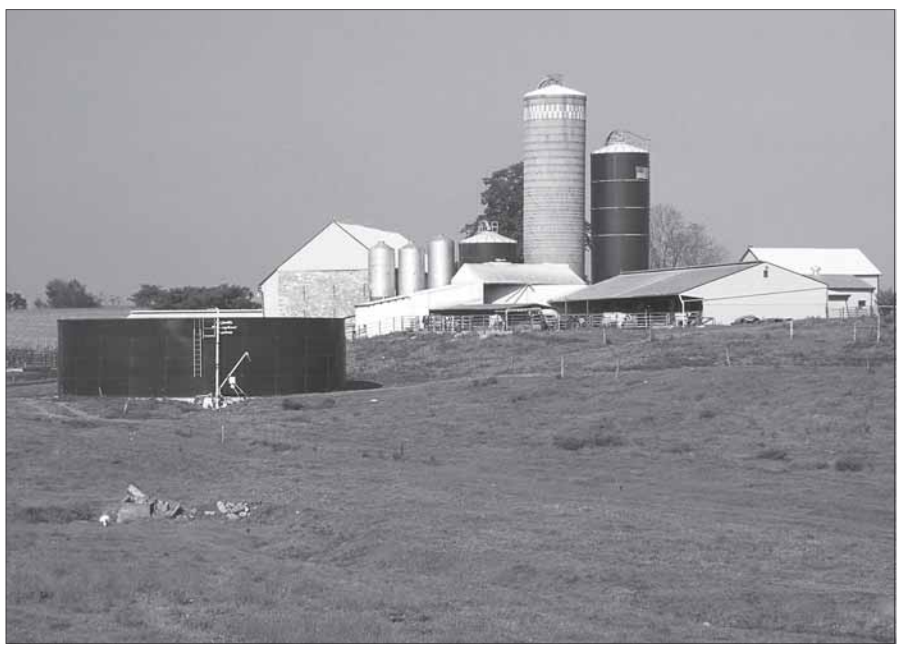

Figure 34-19. This manure storage tank is part of a conservation plan for a dairy farm. Photo courtesy of USDA NRCS.

A program should be established to facilitate movement of manure from surplus to deficit areas.

potential for environmental problems to occur. Also, because the solid fraction is more concentrated, it is more feasible to transport it to remote fields or it can serve as an input for other related biosolid products (Figure 34-21).

Currently, manure is rarely transported more than 10 miles from where it is produced. A program should be established to facilitate movement of manure from surplus to deficit areas. 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

Figure 34-20. State-of-the-art lagoon manure management system for a hog farm. The facility is completely automated and temperature controlled.
Photo courtesy of USDA NRCS.

Figure 34-21. Poultry litter can be transported from a farm with surplus nutrients and land applied on another farm in lieu of mineral fertilizer.
Photo courtesy of USDA NRCS.

farms are unsuitable for manure application, based on soil properties, crop nutrient requirements, hydrology, actual P movement, and sensitive water bodies. Conversely, it must be shown that the recipient farms are more suitable for manure application. The greatest success with re-distribution 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, farm communities, and the animal industry.

Some farmers are already using innovative methods to transport manure. In some states, extension and local trade organizations have established "manure bank" networks that put manure-surplus producers in contact with manure-deficit farmers. To prevent the spread of diseases, however, the biosecurity of any proposed manure transportation network must be ensured.

Composting, another potential tool, may also be considered as a management tool to improve manure distribution (Figure 34-22). Although composting tends to increase the P concentration of manure, the volume is reduced, and thus, transportation costs are reduced.

There is interest in using some manure as sources of "bioenergy." For example, dried poultry litter can be burned directly or converted by pyrolytic methods into oils suitable for the generation of electric power. Liquid manure can be digested anaerobically to produce methane that can be used for heat and energy.

Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops, and impoundments...

Transport management

Transport management refers to efforts to control P movement from soils to sensitive locations, such as bodies of fresh water. Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops and impoundments (for example, settling basins). Basically, these practices reduce rainfall impact on the soil surface, reduce runoff volume and velocity, and increase soil resistance to erosion (Figure 34-23). However, none of these measures should be relied on as the sole or primary practice to reduce P losses in agricultural runoff. Conversion from furrow irrigation to sprinkler to drip irrigation significantly reduces irrigation erosion and runoff. Furrow treatments such as straw mulching and use of polyacrylamides will also reduce in-furrow soil movement. Transport management techniques include

- Conservation tillage.
- Cover crops.

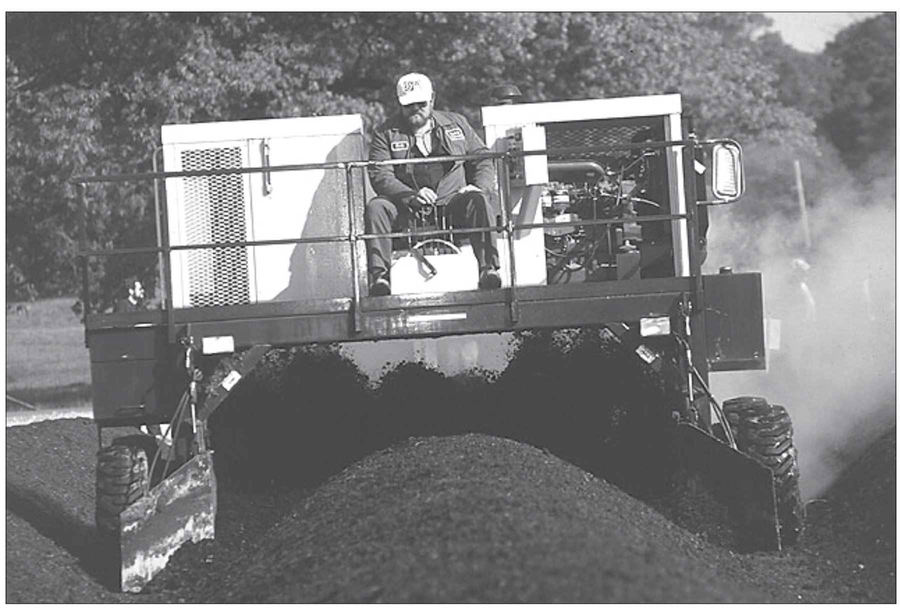

Figure 34-22. A compost site operator turns the windrows to replenish oxygen and mix the organic material for efficient composting.

Photo courtesy of USDA NRCS.

- Grassed waterways.
- Conservation buffers.
- Barnyard runoff management.
- Streambank protection.
- Constructed wetlands and sediment basins.

Conservation tillage practices are designed to reduce runoff and erosion and associated P losses. However, if manure is surface applied to maintain no-till residue compliances, the potential for P loss, particularly in the dissolved form, can be greater than for conventional tillage (Figure 34-24). Thus, the subsurface application of manure by injection, for example, should be considered as part of conservation tillage, particularly no-till, in order to minimize runoff P losses (Figure 34-25).

Cover crops serve to protect the soil surface from raindrop impact, improve infiltration relative to bare soil, and trap eroded particles. In areas where dissolved P transport is the primary concern, cover crops may reduce runoff, and consequently, runoff P load (mass) but are unlikely to impact dissolved P in runoff.

Grassed waterways are designed to trap sediment and reduce channel erosion (Figure 34-26). In some cases, they may be constructed as cross-slope diversions installed to intercept runoff and break up effective slope length. Riparian areas or buffers can reduce erosion and P losses as well as increase wildlife diversity, numbers, and aquatic habitat (Figure 34-27). In addition to acting as physical buffers to sediment-bound nutrients, plant uptake captures P, resulting in a short-term and long-term accumulation of nutrients in biomass. However, the effectiveness of conservation buffer areas as nutrient buffers can vary significantly. For example, the route and depth of subsurface water flow paths though riparian areas can influence nutrient retention. Conservation buffers are most efficient when sheet flow occurs, rather than channelized flow, which often bypasses some of the

Figure 34-23. Controlling erosion is probably still the number one way of minimizing the potential for P loss in runoff.

Photo courtesy of USDA NRCS.

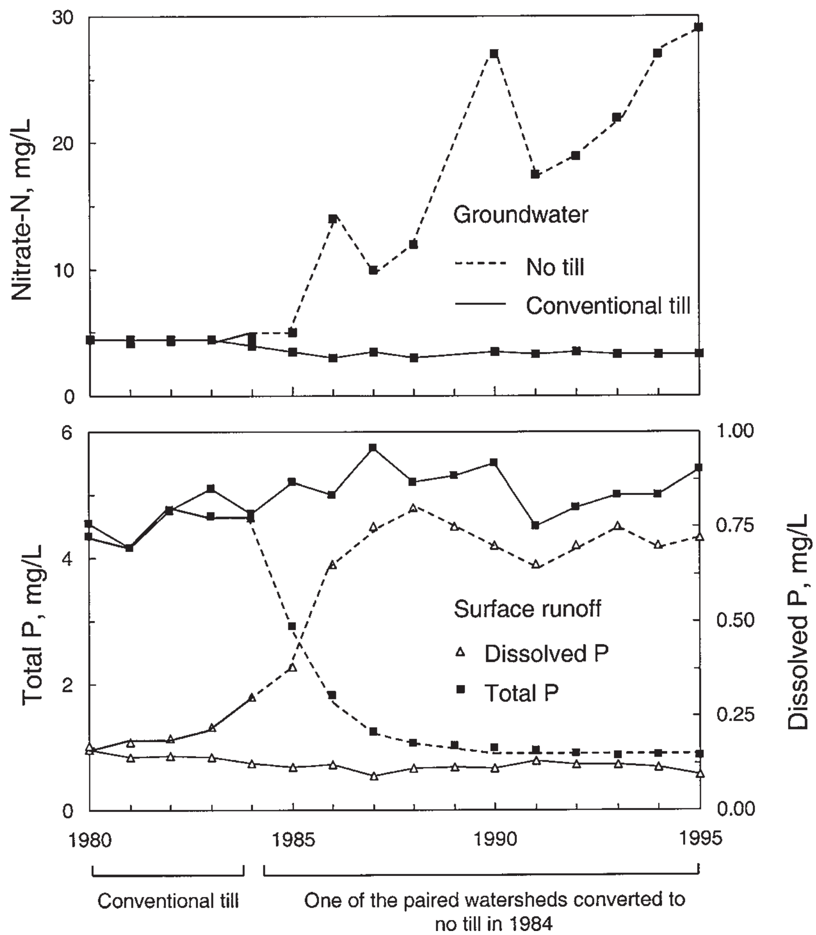

Figure 34-24. Mean annual nitrate-N concentration of groundwater and dissolved and total P concentration of runoff as a function of tillage management of watersheds in Oklahoma.
Adapted from Sharpley and Smith 1994.

retention mechanisms. Thus, these areas must be carefully managed to realize their full retention and filtration capabilities.

A fairly inexpensive transport BMP associated with feedlots or animal loafing areas is the installation of gutter and downspouts on barns and sheds. This BMP is a simple way to divert clean rain water away from these areas and also reduce runoff volumes from the area. Similarly, a berm, constructed around the upslope side of the feedlots or loafing areas, can divert clean water and minimize the potential for P runoff and erosion.

Streambank protection and fencing (for animal exclusion) is another simple BMP that can reduce erosional inputs of P and direct deposition of manure in streams, respectively (Figures 34-28 and -29). However, streambank protection and fencing has not been a popular practice with many farmers, and thus, not widely implemented due to high costs, maintenance needs, and removal of a cheap, readily available drinking water source for animals.

Constructed wetlands and sediment basins both serve to reduce particulate P by intercepting sediment-laden flow and certain wetland plant species (for example, *Phragmites spp.*), substantially improving nutrient removal efficiency (Figures 34-30 and -31).

Figure 34-25. Subsurface injection of manure can decrease losses in runoff and the concentration of P at the soil surface.
Photo courtesy of USDA-ARS.

Figure 34-26. Grassed waterways prevent erosion on cultivated fields.
Photo courtesy of USDA NRCS.

Despite these advantages, any one of these measures should not be relied upon as the sole or primary means of reducing P losses in agricultural runoff. These practices are generally more efficient at reducing sediment P than dissolved P. Also, P stored in stream and lake sediments can provide a long-term source of P in waters even after inputs from agriculture have been reduced.

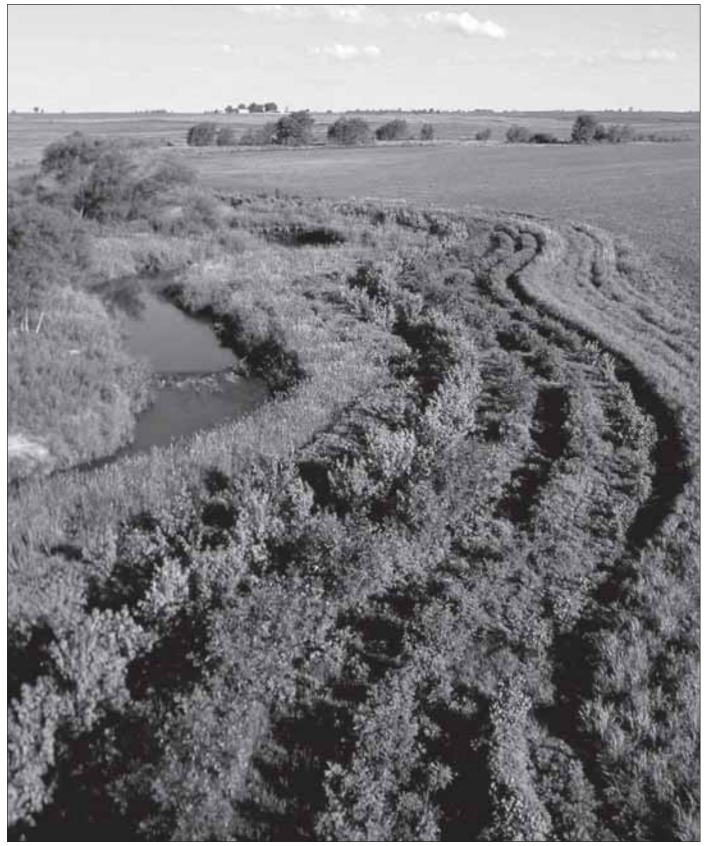

Figure 34-27. A riparian buffer of trees and shrubs along a creek creates shade that lowers the water temperature, improving aquatic habitat. Conservation riparian areas must be carefully managed to ensure that they effectively filter P from runoff. Photo courtesy of USDA NRCS.

Figure 34-28. Cattle crossing on a stream. The crossing keeps the cattle out of the stream except at the time of crossing.
Photo courtesy of USDA NRCS.

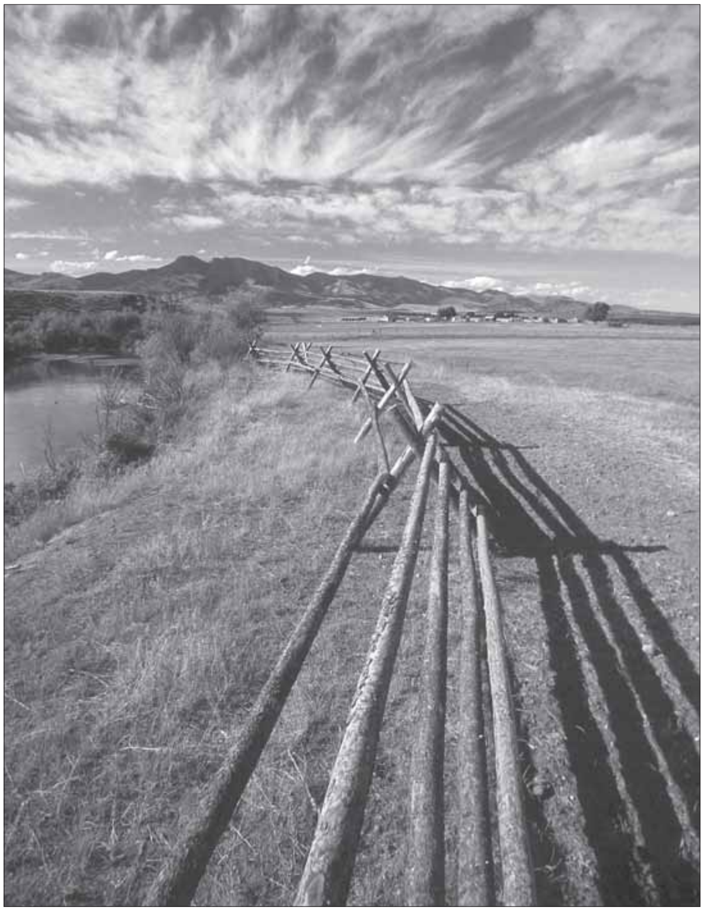

Figure 34-29. Riparian exclusion.
Photo courtesy of USDA NRCS.

Figure 34-30. Restored wetlands can be used to trap P in runoff from cornfields.
Photo courtesy of USDA NRCS.

Figure 34-31. A small dam, terraces, buffer strips, and grass plantings are designed to improve the quality of water entering a lake.
Photo courtesy of USDA NRCS.

Thus, the effect of remedial measures on the contributing watershed will be slow for many cases of poor water quality. Therefore, immediate action may be needed to reduce future problems.

Integrated Nutrient Management

Farm N inputs can usually be more easily balanced with plant uptake than can P inputs, particularly where CAFOs exist. In the past, separate strategies for either N or P have been developed and implemented at farm or watershed scales. Because of different critical sources, pathways, and sinks controlling N and P export from watershed, remedial efforts directed to either N or P can negatively impact the other nutrient. For example, basing manure application on crop N requirements, thus minimizing nitrate leaching to groundwater, can increase soil P and enhance potential surface runoff losses. In contrast, reducing surface runoff losses of P via conservation tillage can enhance N leaching.

...critical sources of N and P export from agricultural watersheds [must be recognized] so optimal strategies can be implemented ... to best manage both N and P.

These positive and negative impacts of conservation practice on resulting water quality should be considered in the development of sound remedial measures. Clearly, a technically sound framework must be developed that recognizes critical sources of N and P export from agricultural watersheds so optimal strategies can be implemented at farm and watersheds scales to best manage both N and P. An example of this principle can be seen in Figure 34-15d.

Summary

The overall goal of efforts to reduce P losses from agriculture should be to balance off-farm P inputs in feed and fertilizer with outputs in products while managing soils in ways that maintain productivity. Source and transport control strategies can provide the basis to increase P use efficiency in agricultural systems.

...all fields do not contribute equally to P export from watersheds.

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 P concentration in agricultural runoff, surface runoff and erosion potential will often override soil P levels in determining P export. If water or soil does not move from a field or below the root zone, then P will not move. Clearly, remedial efforts 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 must be tailored to 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 important that management practices be implemented that 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 attempt to balance P inputs and outputs at farm and watershed scales.
- Source and transport controls should be targeted to identify critical source areas of P export from watersheds.
- Threshold soil P levels that guide manure applications should be linked with site vulnerability to P loss

...remedial efforts will be most effective if targeted to the hydrologically active source areas in a watershed...

Manure management recommendations must be tailored to site vulnerability to surface runoff and erosion as well as soil P content...

APPENDIX A
Environmental Stewardship Assessment: Phosphorus Index

The goal of this assessment tool is to help you confidentially evaluate the risk of P loss from farm fields. The first step in this process is to consult Part A. Screening Tool. The screening tool is intended to reduce your potential workload by easily identifying those fields at greatest risk of P loss.

Part A. Screening tool

Table 34A-1. The P Indexing approach using Pennsylvania's 2002 Index version as an example.

Evaluation category		
Soil test P	> 200 mg P kg^{-1}	If yes to either factor, then proceed to Part B.
Contributing distance	< 150 ft	

Part B. Transport factors (Refer to Tables 34A-2 and -3.)

For each contributing transport factor listed (left column, Table 34A-3), identify the appropriate risk level or complete the calculation (center column, Table 34A-3) and enter the result into the Risk Value column (right column, Table 34A-3).

1. Soil erosion: The calculated soil erosion, using RUSLE, taken directly from a conservation plan. If a conservation plan is not available, soil erosion can be calculated using RUSLE 1.06c, documented at http://www.sedlab.olemiss.edu/rusle1new/description106.html. Description: RUSLE1.06c uses an index method to estimate soil erosion. It uses factors that represent how climate, soil, topography, and land use affect rill and interrill (sheet and rill) soil erosion caused by raindrop impact and surface runoff. In general, erosion depends on the amount and intensity of rainfall and runoff, protective cover provided by land use, susceptibility of soil to erosion as a function of intrinsic soil properties and soil properties modified by land use, and the topography of the landscape as described by slope length, steepness, and shape.

These influences are described in RUSLE1.06c with the equation:

$$A = R\ K\ L\ S\ C\ P$$

where: A = Average annual soil loss (tons/acre), R = K = Soil erodibility factor, L = Slope length factor, S = Slope steepness factor, C = Cover-management factor, and P = Support practices factor. A soil loss (erosion rate) in tons per acre per year is computed by substituting values for each RUSLE1.06c factor to represent conditions at a specific site. RUSLE1.06c is based primarily on the analysis of a large mass of experimental data and uses equations based on fundamental erosion processes so that it can be applied to situations where experimental data are inadequate to define RUSLE1.06c factor values.

K factor: The K factor is an empirical measure of soil erodibility as affected by intrinsic soil properties. Erosion measurements based on unit plot conditions are used to experimentally determine values for K.

R factor: The R factor represents the erosivity of the climate at a particular location. An average annual value of R is determined from historical weather records and is the average annual sum of the erosivity of individual storms. The erosivity of an individual storm is computed as the product of the storm's total energy, which is closely related to storm amount, and the storm's maximum 30-minute intensity.

LS factor: The L and S factors jointly represent the effect of slope length, steepness, and shape on sediment production. RUSLE1.06c estimates the total of rill and interrill erosion combined. Rill erosion is primarily caused by surface runoff and increases in a downslope direction because runoff increases in a downslope direction. Interrill erosion is caused primarily by raindrop impact and is uniform along a slope. Therefore, the influence of slope length, which is represented by the L factor, is greater for those conditions where rill erosion is greater than interrill erosion.

C factor: The C factor for the effects of cover management, along with the P factor, is one of the most important factors in RUSLE1.06c because it represents the effect of land use on erosion. It is the most easily changed single

APPENDIX A
Environmental Stewardship Assessment: Phosphorus Index (continued)

factor and is the factor most often considered in developing an erosion control plan. For example, the C factor describes how vegetation, tillage systems, and addition of mulches affect soil loss.

P factor: The support practice P factor describes how practices such as contouring, strip cropping, concave slopes, terraces, sediment basins, grass hedges, silt fences, straw bales, and subsurface drainage affect rill and interrill erosion. These practices are applied to support the basic cultural practices used to control erosion, such as vegetation, cover management system, and mulch additions that are represented by the C factor.

2. Runoff potential: Based on the soil type and can be determined using tables provided by USDA-NRCS regional nutrient management coordinators.

Estimation: Runoff potential class is estimated by using Table 34A-2. This table uses a combination of surface slope and the saturated hydraulic conductivity (Ksat) representative value (RV) of the upper 1.0 m of soil material including bedrock or other restrictive material as criteria. Determine the minimum Ksat of the upper 1.0 meter of material. If that minimum Ksat is at or above 0.5 m, use the following table as shown. If the minimum Ksat of the upper 1 m of material occurs between 0.5 and 1.0 m, use the following table but reduce the runoff by one runoff class (for example, from medium to low). For soils with seasonal free water within 50 cm of the soil surface, use a Ksat of <0.01 ¼m s^{-1} in the table.
The concept indicates relative runoff for very specific conditions: (1) The soil surface is assumed to be bare and surface water retention due to irregularities in the ground surface is low. (2) Steady ponded infiltration rate is the applicable infiltration stage. (3) Ice is assumed to be absent unless otherwise indicated. (4) Both the maximum bulk density in the upper 25 cm and the bulk density of the uppermost few centimeters are assumed within the limits specified for the mapping concept. (5) The concept assumes a standard storm or amount of water addition from snowmelt of 50 mm in a 24-hour period with no more than 25 mm in any single 1-hour period. (6) The soil moisture state is assumed to be very moist or wet to the base of the soil, to 0.5 m, or through the horizon or layer with minimum Ksat within 1.0 m, whichever is the greatest depth.

Table 34A-2. Surface runoff potential classes as a function of soil slope and saturated hydraulic conductivity.

Surface runoff potential classes						
Slope percentage	Saturated hydraulic conductivity (¼m s^{-1}), Ksat					
	e•100	< 100-10	< 10-1.0	< 1.0-0.1	< 0.1-0.01	< 0.01
Concave	N	N	N	N	N	N
< 1	N	N	N	L	M	H
1 - 5	N	LV	L	M	H	HV
5 - 10	LV	L	M	H	HV	HV
10 - 20	LV	L	M	H	HV	HV
e•20	L	M	H	HV	HV	HV

Abbreviations: Negligible-N, Very low-LV, Low-L, Medium-M, High-H, and Very high-HV.

Adapted from USDA-NRCS, 2003. *National Soil Survey Handbook*, Title 430-VI. Available online at http://soils.usda.gov/technical/handbook/.

3. Subsurface drainage: Based on whether there is artificial drainage in the field or if the field is near a stream and has rapidly permeable soils. "Random" drainage is a single or a few tile lines in a field, and "Patterned" drainage is when most or the entire field is drained with a fill patterned drainage system.

4. Leaching potential: Based on soil texture
- Low potential–Clay, sandy clay, silty clay, and silty clay loam
- Medium potential–Loam, silt loam, and silt
- High potential–Sandy loam, loamy sand, and sand

5. Contributing distance: The contributing distance to a stream or other water body from the lower edge of the field. Choose the distance category in the P Index that contains the majority of the lower edge of the field.

APPENDIX A
Environmental Stewardship Assessment: Phosphorus Index (continued)

6. Modified connectivity: Accounts for management practices that modify P transport.
   - If the field is within 150 ft of water and a riparian buffer is present, select the appropriate Modified connectivity factor (that is, reduces transport value).
   - If a field is more than 150 ft from water but a direct connection, such as a pipe or ditch from field to water, is present, select appropriate Modified connectivity factor (that is, increases transport value).

The transport factor is determined by first adding the transport factors together to get the transport sum, next multiplying by the Modified connectivity, and then dividing by 24.

Table 34A-3. Transport factors.

Characteristics	Risk levels					Risk value
Soil erosion	Risk value = Annual soil loss = ___________ tons/acre/year					
Runoff potential	Very low **0**	Low **1**	Medium **2**	High **4**	Very high **8**	
Subsurface drainage	None **0**		Random **1**		Patterned** **2**	
Leaching potential	Low **0**		Medium **2**	High **4**		
Contributing distance	> 500 ft **0**	500 to 350 ft **1**	350 to 250 ft **2**	150 to 250 ft **4**	< 150 ft **8**	
Transport sum = Erosion + Runoff potential + Subsurface drainage + Leaching potential + Contributing distance						
Modified connectivity	Riparian buffer *Applies to distances < 150 ft* **0.7**		Grassed waterway or None **1.0**		Direct connection *Applies to distances > 150 ft* **1.1**	
Transport factor = Transport sum x Modified connectivity/24						

**Or a rapidly permeable soil near a stream.

The transport value is divided by 24 (that is, the highest value obtainable) in order to normalize site transport to a value of 1, where full transport potential I realized.

Caution: Many states have a state-specific P Index. Although the principles of most P Index tools are similar, individual factors or weightings of those factors varies among states. If available, review your own state's P Index. For more specific information on the various indices adopted by various states, see Sharpley et al. 2003.

Part C. Source and site factors (Refer to Tables 34A-4 and -5.)

1. Soil test P: The soil test level is taken from a soil test report as either ppm (multiplied by 0.20 for the Risk Value) or lbs P_2O_5/acre (multiplied by 0.05 for the Risk Value). A coefficient of 0.20 or 0.05 is used to convert soil test P to a value that directly relates to the risk of P loss in surface runoff from P in manure and mineral fertilizers. This conversion is based on field data that show a fivefold greater concentration of dissolved P in surface runoff with an increase in mineral fertilizer or manure addition compared to an equivalent increase in soil test P (as Mehlich-3 extractable soil P).

2. Fertilizer P risk is the product of
   - The Fertilizer P Rate (amount of chemical fertilizer P being applied to the field in lbs P_2O_5/acre).
   - The Loss Rating for P application (reflects the timing and method of application).

3. Manure P Risk is the product of
   - The Manure P Rate (amount of chemical fertilizer P being applied to the field in lbs P_2O_5/acre).
   - The Loss Rating for P application (reflects the timing and method of application).
   - Manure P Availability Coefficient (reflects the availability of P in manure or biosolid to be released to surface runoff). This coefficient is greatly affected by manure or biosolid treatment, such as alum addition to poultry manure and litter, and can be determined using Table 34A-4.

APPENDIX A

Environmental Stewardship Assessment: Phosphorus Index (continued)

Table 34A-4. Organic P source availability coefficients.
Updates on these coefficients can be checked at http://panutrientmgmt.cas.psu.edu/.

Swine	
Swine slurry	1.0
Poultry	
Broiler	0.8
Layer	0.9
Turkey	0.9
Duck	0.9
Dairy	
Liquid	0.9
Bedded pack	0.8
Beef	0.8
Alum treated	0.5
Biosolids	
Biological nutrient removal	0.8
Alkaline stabilized	0.4
Conventionally stabilized	0.3
Composted	0.3
Heat-dried	0.2
Advanced-alkaline stabilized	0.2

Table 34A-5. Phosphorus loss potential due to source and site management factors in the P index.

Contributing factors	Risk levels: Very low	Low	Medium	High	Very high	Risk value
Soil test P risk	Risk value = soil test P (ppm) x 0.20 = ______ ppm x 0.20 = **OR** Risk value = Soil test P (lbs P_2O_5/acre) x 0.05 = ______ lbs P_2O_5/acre x 0.05 =					
Loss rating for P application method and timing	Placed with plant-er or injected more than 2" deep **0.2**	Incorporated < 1 wk after application **0.4**	Incorporated > 1 wk or not incorporated > 1 following application in spring-summer **0.6**	Incorporated > 1 wk or not incorporated following application in autumn – winter **0.8**	Surface applied on frozen or snow-covered soil **1.0**	
Fertilizer P risk	Risk value = Fertilizer P application rate x Loss rating for P application = Risk value = ______ lbs P_2O_5/acre x ______ =					
Manure P availability	Refer to Table 34A -4. Organic P source availability coefficients.					
Manure P risk	Risk value = Manure P application rate x Loss rating for P application x P availability coefficient = Risk value = ______ lbs P_2O_5/acre x ______ x ______ =					
Total of management risk factors	**Sum of management factors =**					

Caution: Many states have a state-specific P Index. Although the principles of most P Index tools are similar, individual factors or weightings of those factors varies among states. If available, review your own state's P Index. For more specific information on the various Indices adopted by other states, see Sharpley et al. 2003.

APPENDIX A

Environmental Stewardship Assessment: Phosphorus Index (continued)

To solve for the P Index,

1. Sum all numbers in Part B (Table 34A-3 and divide by 24) and all numbers in Part C (Table 34A-5).
2. Write these numbers in the worksheet below.
3. Multiply Part B by Part C by 2. The factor of 2 normalizes the final Index rating to 100. This is your fine P Index rating.
4. Look up Interpretation of P Index risk in Table 34A-6 below.

Field	Part A Transport risk	Part C Management risk	P Index B x C	Interpretation of the P index
Example	*0.55*	*92*	*101*	*Very high*

Table 34A-6. General interpretations and management guidance for the P Index.

P Index Value	Rating	General Interpretation	Management Guidance
< 59	Low	If current farming practices are maintained, there is a low risk of adverse impacts on surface waters.	N-based applications
60 - 79	Medium	Chance of adverse impacts on surface waters exists, and some remediation should be taken to minimize P loss.	N-based applications
80 - 100	High	Adverse impact on surface waters. Conservation measures and P management plan are needed to minimize P loss.	P application limited to crop removal of P
> 100	Very high	Adverse impact on surface waters. All necessary conservation measures and P management plan must be implemented to minimize P loss.	No P applied

Caution: Many states have a state-specific P Index. Although the principles of most P Index tools are similar, individual factors or weightings of those factors varies among states. If available, review your own state's P Index. For more specific information on the various Indices adopted by other states, see Sharpley et al. 2003.

APPENDIX B
Regulatory Compliance Assessment: Phosphorus Management

The goal of this assessment tool is to help you identify the regulations related to P management that apply to your operation. For each issue listed (left column) of the worksheets, identify if this issue is currently regulated and determine if your operation is in compliance with these rules (right column).

Regulatory Issue	**Is this issue addressed by regulations? If "Yes," summarize those regulations.**	**Is my livestock/ poultry operation in compliance?**
Are there P-specific regulations that apply to your livestock or poultry operation?	___ Yes ___ No If Yes, summarize:	___ Yes ___ No ___ Not applicable ___ Don't Know
Do these regulations limit soil P accumulation based upon		
• An agronomic soil test level (only P needed to grow a crop)?	___ Yes ___ No	___ Yes ___ No ___ Not applicable ___ Don't Know
• An environmental soil P threshold?	___ Yes ___ No	___ Yes ___ No ___ Not applicable ___ Don't Know
• A P Index that considers multiple transport and source factors?	___ Yes ___ No	___ Yes ___ No ___ Not applicable ___ Don't Know
Do these regulations set a maximum P application rate?	___ Yes ___ No If Yes, summarize:	___ Yes ___ No ___ Not applicable ___ Don't Know
If P accumulation in the soil is regulated, what management changes must occur if a field exceeds mandatory standards?		___ Yes ___ No ___ Not applicable ___ Don't Know
Must soil P samples be collected at some minimum required interval?	___ Yes ___ No If Yes, summarize:	___ Yes ___ No ___ Not applicable ___ Don't Know
Must soil P sample results be submitted to a regulatory agency?	___ Yes ___ No If Yes, summarize:	___ Yes ___ No ___ Not applicable ___ Don't Know
Must soil P records be maintained for future regulatory agency inspection?	___ Yes ___ No For _______ years	___ Yes ___ No ___ Not applicable ___ Don't Know
Other:	___ Yes ___ No If Yes, summarize:	___ Yes ___ No ___ Not applicable ___ Don't Know

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References

Bacon, S.C., L.E. Lanyon, and R.M. Schlauder, Jr. 1990. Plant nutrient flow in the managed pathways of an intensive dairy farm. *Agronomy Journal* 82:755-761.

Baxter, C.A., B.C. Joern, L. Adeola, and J.E. Brokish. 1998. Dietary P management to reduce soil P loading from pig manure. Annual progress report to Pioneer Hybrid International, Inc., 1-6.

Beegle, D.B. 2002. Soil fertility management. In E. Martz (ed.), *Agronomy Guide 2002*. Publications Distributions Center, College of Agricultural Sciences, The Pennsylvania State University, University Park, PA, 18-42.

Breeuwsma, A., and S. Silva. 1992. Phosphorus fertilization and environmental effects in The Netherlands and the Po region (Italy). Rep. 57. Agric. Res. Dep. The Winand Staring Centre for Integrated Land, Soil and Water Research. Wageningen, The Netherlands.

Burkholder, J.A., and H.B. Glasgow, Jr. 1997. Pfiesteria piscicidia and other Pfiesteria-dinoflagellates behaviors, impacts, and environmental controls. *Limnology and Oceanography* 42:1052-1075.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8:559-568.

Edwards, W.M., and L.B. Owens.1991. Large storm effects on total soil erosion. *Journal of Soil and Water Conservation* 46:75-77.

Ertl, D.S., K.A. Young, and V. Raboy. 1998. Plant genetic approaches to phosphorus management in agricultural production. *Journal of Environmental Quality* 27:299-304.

Federation of Animal Science Societies. 2001. Effects of diet and feeding management on nutrient contents of manure. Published by Federation of Animal Sciences Society, Washington, DC. 4 pp.

Fixen, P.E., and J.N. Grove. 1990. Testing soils for phosphorus. In R.L. Westerman (ed.), *Soil Testing and Plant Analysis*, 3rd ed. SSSA Book Series No. 3. Soil Sci. Soc. Am., Madison, WI, 141-180.

Fixen, P.E., and T.L. Roberts. 2002. Status of soil nutrients in North America. In *Plant Nutrient Use in North American Agriculture*. Potash and Phosphate Institute of Canada, Foundation for Agronomic Research Technical Bulletin 2001-1, 9-12.

Gardner, G. 1998. Recycling organic wastes. In L. Brown, C. Flavin, and H. French (eds.), *State of the World*. New York: W.W. Norton, 96-112.

Gburek, W.J., A.N. Sharpley, L. Heathwaite, and G.J. Folmar. 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index. *Journal of Environmental Quality* 29:130-144.

Kotak, B.G., E.E. Prepas, and S.E. Hrudey. 1994. Blue green algal toxins in drinking water supplies: Research in Alberta. *Lake Line* 14:37-40.

Kotak, B.G., S.L. Kenefick, D.L. Fritz, C.G. Rousseaux, E.E. Prepas, and S.E. Hrudey. 1993. Occurrence and toxicological evaluation of cyanobacterial toxins in Alberta lakes and farm dugouts. *Water Research* 27:495-506.

Lanyon, L.E. 2000. Nutrient management: Regional issues affecting the Chesapeake Bay. In A.N. Sharpley (ed.), *Agriculture and Phosphorus Management: The Chesapeake Bay*. Boca Raton, FL: CRC Press.

Lanyon, L.E., and P.B. Thompson. 1996. Changing emphasis of farm production. In M. Salis and J. Popow (eds.), *Animal agriculture and the environment: Nutrients, pathogens, and community relations*. Northeast Regional Agricultural Engineering Service, Ithaca, New York, 15-23.

Lawton, L.A., and G.A. Codd. 1991. Cyanobacterial (blue-green algae) toxins and their significance in UK and European waters. *Journal Institute of. Water Environmental Management* 5:460-465.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. *Journal of Production Agriculture* 6:483-496.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umprabuult. *Agronomy Journal* 83:77-85.

Martin, A., and G.D. Cooke. 1994. Health risks in eutrophic water supplies. *Lake Line* 14:24-26.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. *Journal of Environmental Quality* 29: 37-49.

National Research Council. 1993. Soil and water quality: An agenda for agriculture. Washington, DC: National Academy Press.

National Research Council. 2001. Nutrient requirements of dairy cattle. 7th rev. ed. National Academy of Science, Washington, DC.

Palmstrom, N.S., R.E. Carlson, and G.D. Cooke.1988. Potential links between eutrophication and formation of carcinogens in drinking water. *Lake and Reservoir Management* 4:1-15.

Powell, J.M., D.B. Jackson-Smith, L.D. Satter, and L.G. Bundy. 2002. Whole-farm phosphorus management on dairy farms. *Proceedings of 2002 Wisconsin Fertilizer, Aglime, and Pest Management Conf*erence, Madison, WI, 13-24.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. *Science* 195:260-262.

Sharpley, A.N., and S.J. Smith. 1994. Wheat tillage and water quality in the Southern Plains. *Soil Tillage Research* 30:33-38.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2001 Phosphorus loss from land and water: Integrating agricultural and environmental management. *Plant and Soil*. 237:287-307.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. *Journal of Soil and Water Conservation* 51:160-166.

Sharpley, A.N., S.J. Smith, B.A. Stewart, and A.C. Mathers. 1984. Forms of phosphorus in soil receiving cattle feedlot waste. *Journal of Environmental Quality* 13:211-215.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. *Journal of Environmental Quality* 23:437-451.

Sharpley, A.N., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. 1998. Impacts of animal manure management on ground and surface water quality. In J.L. Hatfield and B.A. Stewart (eds.), *Animal Waste Utilization: Effective use of manure as a soil resource*. Boca Raton, FL: Ann Arbor Press, 173-242.

Sharpley, A.N., P.J.A. Kleinman, R.J. Wright, T.C. Daniel, B. Joern, R. Parry, and T. Sobecki. 2002. The National Phosphorus Project: Addressing the interface of agriculture and environmental phosphorus management in the USA. Section 2.3 Indicators for Environmental Performance. In J. Steenvoorden, F. Claessen, and J. Willems (eds.), *Agricultural Effects on Ground and Surface Waters: Research at the Edge of Science and Society.* International Association of Hydrological Sciences. Publication No. 273. Wallingford, England: IAHS Press, 95-100.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, G. Mullins. 2003. Development of Phosphorus Indices for nutrient management planning strategies in the U.S. *Journal of Soil Water Conservation*. 58:137-152.

Sims, J.T. 1997. Agricultural and environmental issues in the management of poultry wastes: Recent innovations and long-term challenges. In J. Rechcigl and H.C. MacKinnon (eds.), *Uses of By-products and Wastes in Agriculture*. Am. Chem. Soc., Washington, DC, 72-90.

Sims, J.T., Editor. 1998. Soil testing for phosphorus: Environmental uses and implications. A publication of SERA-IEG 17, USDA-CSREES Regional Committee. Southern Cooperative Series Bulletin No. 398:43.

Smith, S.J., A.N. Sharpley, J.R. Williams, W.A. Berg, and G.A. Coleman. 1991. Sediment-nutrient transport during severe storms. In S.S. Fan and Y.H. Kuo (eds.), *Fifth Interagency Sedimentation Conference*, March 1991, Las Vegas, NV. Federal Energy Regulatory Commission, Washington, DC, 48-55.

Smith, V.H. 1998. Cultural eutrophication of inland, estuarine and coastal waters. In *Successes, Limitations and Frontiers in Ecosystem Science*. New York: Springer-Verlag.

U.S. Department of Agriculture, Natural Resources Conservation Service, 2003. *National Soil Survey Handbook*, Title 430-VI. Available online at http://soils.usda.gov/technical/handbook/.

U.S. Department of Agriculture and U.S. Environmental Protection Agency. 1999. Unified national strategy for Animal Feeding Operations. March 9, 1999. Available online at http://www.epa.gov/owm/finafost.htm.

U.S. Environmental Protection Agency. 1996. Environmental indicators of water quality in the United States. EPA 841-R-96-002. USEPA, Office of Water (4503F), U.S. Govt. Printing Office, Washington, DC. 25 pp.

U.S. Geological Survey. 1999. The quality of our nation's waters: Nutrients and pesticides. U.S. Geological Survey Circular 1225, 82 pp. USGS Information Services, Denver, CO. Available online at http://www.usgs.gov.

Weld, J.L., D. Beegle, W.J. Gbuerk, P.J.A. Kleinman, and A.N. Sharpley. 2003. *The Pennsylvania Phosphorus Index: Version 1*. CAT UC 180 5M3/03ps4591. Publications Distribution Center, Pennsylvania State University, University Park.

Glossary

Agricultural runoff. Total loss of water from a watershed by all surface and subsurface pathways.

Confined animal feeding operation (CAFO). Operation that has more than a specified number of animals confined for a total of 45 days or more in any 12-month period.

Critical source area. Area where a source contains a high level of P to move and has a high potential for transport.

Eutrophication. Natural aging of lakes or streams caused by nutrient enrichment.

Immobilization. Formation of more stable organic P, which is resistant to breakdown.

Mineralization. Breakdown or conversion of readily available organic P to inorganic solution P.

Nonpoint source (NPS). Entry of contaminant or pollutant into a water body in a diffuse manner so there is no definite point of entry.

P Index. An index, matrix, or model that accounts for and ranks transport and source factors controlling P loss in runoff and provides a numeric representation of site vulnerability to P loss.

Soil test P. Estimated amount of plant-available soil P.

Source management. Minimizing the P buildup in the soil above levels sufficient for optimum crop growth by controlling the quantity of P in manure and the amount of P that is applied in a localized area.

Transport management. Efforts to control P movement from soils to sensitive locations, such as bodies of freshwater.

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FUNDING

This material is based upon work supported by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture; the U.S. Environmental Protection Agency, National Agriculture Assistance Center; and the University of Nebraska Cooperative Extension, University of Nebraska-Lincoln, under Cooperative Agreement Number 2001-48537-01136.

Reviewers

Many colleagues reviewed drafts of the Livestock and Poultry Environmental Stewardship curriculum and offered input over a two-year period. Thus, it is impossible to list all reviewers; however, certain reviewers provided in-depth reviews, which greatly improved the curriculum's overall quality, and pilot tested the curriculum within their state. These reviewers, also members of the Review and Pilot Team, are listed below.

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Finally, recognition must also be given to three individuals, members of the Access Team, who helped determine the final appearance of the curriculum lessons: Don Jones, Purdue University; Jack Moore, MidWest Plan Service; and Ginah Mortensen, EPA Ag Center.

Livestock and Poultry Environmental Stewardship Curriculum: Lesson Organization

This curriculum consists of 27 lessons arranged into six modules. Please note that the current lesson is highlighted.

Module A. Introduction

1. Principles of Environmental Stewardship
2. Whole Farm Nutrient Planning

Module B. Animal Dietary Strategies

10. Reducing the Nutrient Excretion and Odor of Pigs Through Nutritional Means
11. Using Dietary and Management Strategies to Reduce the Nutrient Excretion of Poultry
12. Feeding Dairy Cows to Reduce Nutrient Excretion
13. Using Dietary Strategies to Reduce the Nutrient Excretion of Feedlot Cattle

Module C. Manure Storage and Treatment

20. Planning and Evaluation of Manure Storage
21. Sizing Manure Storage, Typical Nutrient Characteristics
22. Open Lot Runoff Management Options
23. Manure Storage Construction and Safety, New Facility Considerations
24. Operation and Maintenance of Manure Storage Facilities
25. Manure Treatment Options

Module D. Land Application and Nutrient Management

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32. Land Application Best Management Practices
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51. Mortality Management
52. Environmental Risk and Regulatory Assessment Workbook