Managing Phosphorus *for Agriculture and the Environment*

PENNSTATE

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What are the concerns?

Phosphorus (P) is an essential element for plant and animal growth and is necessary to maintain profitable crop and livestock production. It also can increase the biological productivity of surface waters by accelerating **eutrophication,** the natural aging of lakes or streams brought on by nutrient enrichment. Although eutrophication is a natural process, it can be sped up by changes in the land use of a watershed that increase the amount of nutrients added to an aquatic system (Figure 1). Nitrogen (N) and P both affect eutrophication, but P is the critical element in most fresh waters. Where water salinity increases, as in estuaries, N generally controls aquatic plant growth.

The Environmental Protection Agency has identified eutrophication as the main problem in United States surface waters that have impaired water quality. Because it causes increased growth of undesirable algae and aquatic weeds, as well as oxygen shortages resulting from their die-off and decomposition, eutrophication restricts water use for fisheries, recreation, industry, and drinking.

In addition, associated periodic surface blooms of cyanobacteria (blue-green algae) occur in eutrophic drinking water supplies and may pose a serious health hazard to livestock and humans. Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern U.S., most notably in the lower Chesapeake Bay tributaries, have been linked to high nutrient levels in affected waters. Neurological damage in people exposed to the highly toxic volatile chemical produced by this dinoflagellate has dramatically increased public awareness of eutrophication and the need for solutions.

Complicating the problem is the fact that eutrophication sometimes occurs many miles from where high-P agricultural runoff originally enters the water supply. By the time the water quality effects are noticeable (sometimes years to decades after the runoff occurs), remedial strategies are difficult and expensive to implement. Remediating surface waters that have been affected by P is further complicated by the fact that surface waters often cross political boundaries (e.g., state lines).

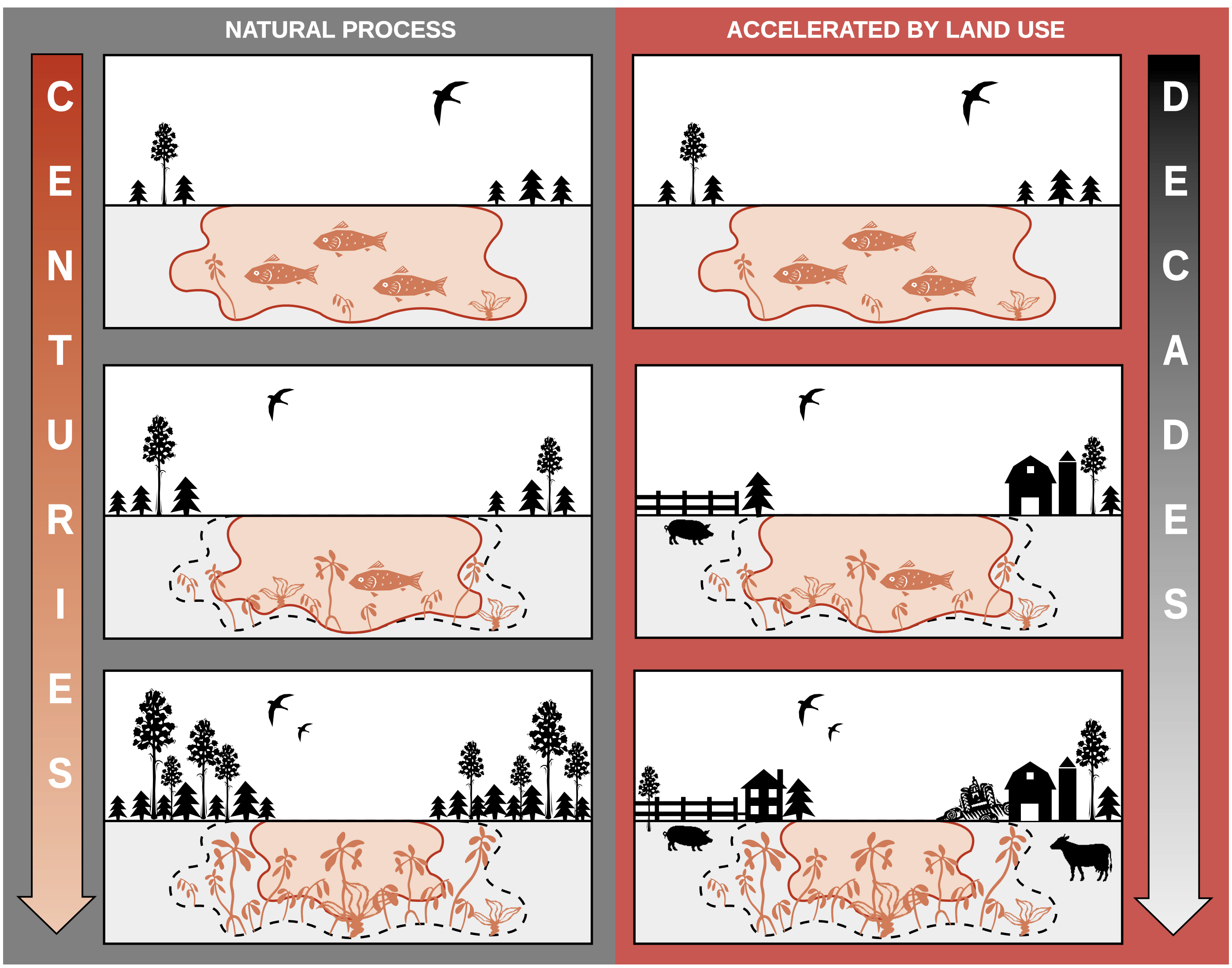

Figure 1. Changes in land use can accelerate the eutrophication of lakes and streams. Aging processes that naturally take place over the course of centuries (left column) may occur much more rapidly when agricultural nutrients are added to the water (right column).

What are the forms of phosphorus in soil?

Soil P exists in **organic** and **inorganic** forms (Figure 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.

Organic P compounds range from readily available undecomposed plant residues and microbes within the soil to stable compounds that have become part of the 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 usually is too slow to provide enough P for crop growth. Immobilization is the formation of more stable organic P, which is resistant to breakdown.

Inorganic P compounds range from soluble fertilizer residues to slowly soluble Ca phosphates to very stable Fe and Al oxides. **Fixation** of P by soil, also referred to as **sorption**, is the conversion of inorganic P from solution through readily available to stable forms. This process also binds the P with soil material by physical or chemical bonds. Up to 90% of inorganic P can become fixed within 2 to 4 weeks of when it is added to a soil. Inorganic P also can be converted from stable to readily available forms, although this conversion usually occurs too slowly to satisfy crop P requirements early in the growing season (dashed arrow on Figure 2).

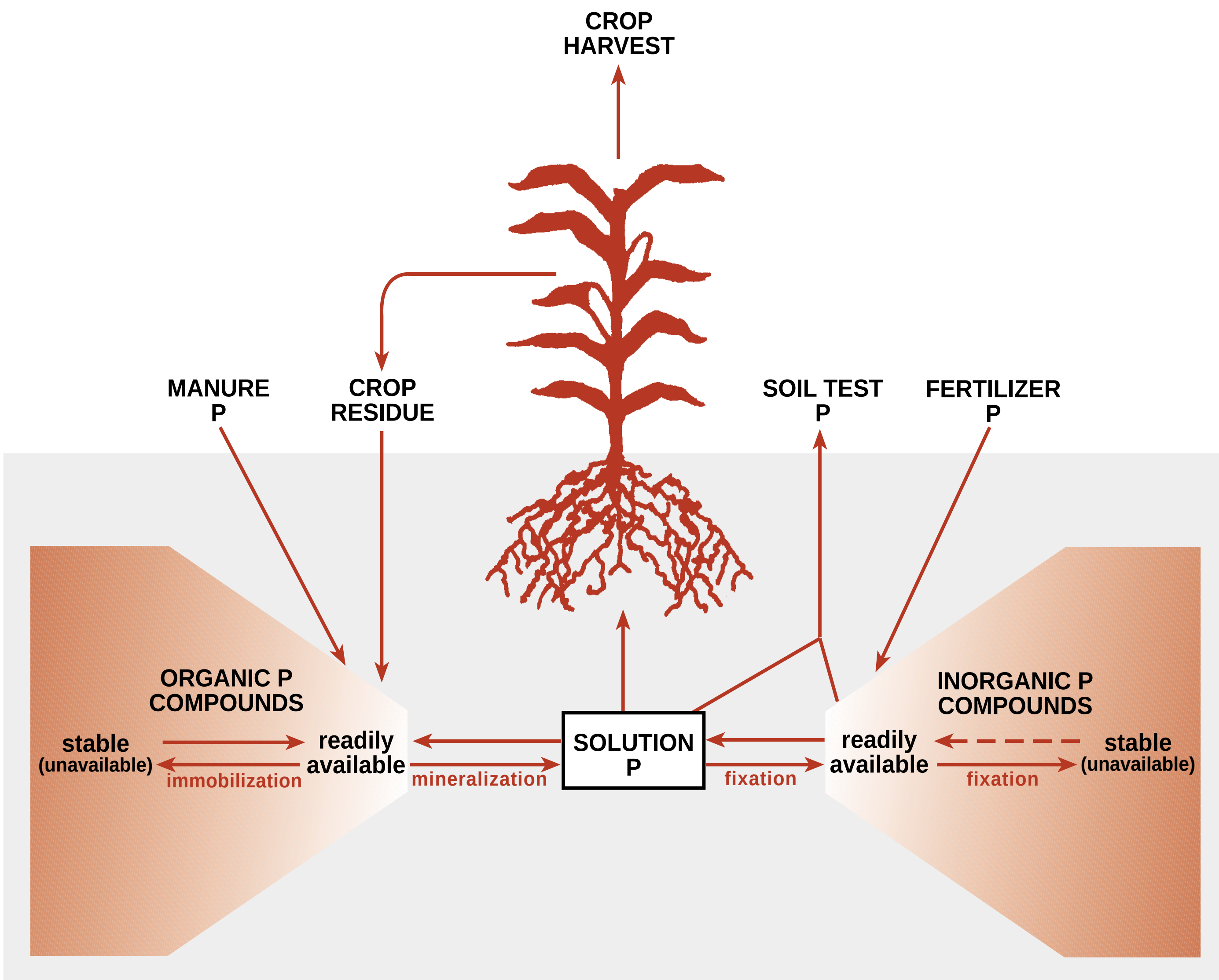

Figure 2. The phosphorus cycle in soil.

How does phosphorus behave in soil?

In most soils, the P content of surface horizons is greater than that of the subsoil (Figure 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 aboveground parts of the plant and is 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 applied to the soil surface with little or no mechanical incorporation, thus exacerbating P buildup in the top 2 to 5 inches of soil.

Phosphorus content and availability vary with the soil parent material, texture, and pH, as well as with management factors such as the rate of application and tillage practices. 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.

What causes soil phosphorus to increase?

Rapid growth and intensification of the livestock industry in certain areas of the U.S. and Europe have created national and regional soil P imbalances. Before World War II, farming communities tended to be self-sufficient, in that they produced enough feed locally to meet livestock 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 4).

After World War II, increased fertilizer use in crop production contributed to the development of specialized farming systems, with crop and livestock operations located in different regions of the country (Figure 5). By the late 1990s, over half the corn grain produced in the cornbelt was exported as animal feed, while states in the Southeast imported most (>80%) of the grain used in confined livestock operations. Today, less than one quarter of farm-produced corn grain is fed on the farm where it is grown. This evolution of our agricultural system is causing a transfer of P from grain-producing areas to livestock-producing areas and a resulting accumulation of P in the soils in those areas.

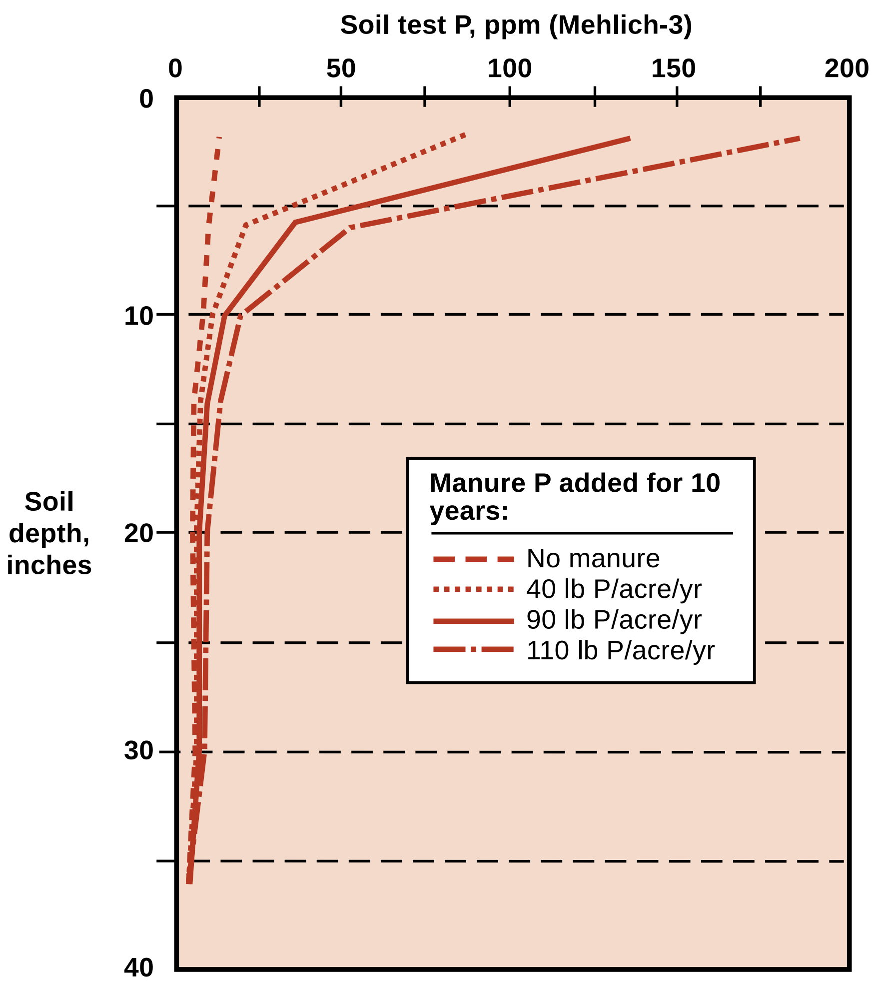

Figure 3. Soil test P accumulates at the surface with repeated phosphorus applications.

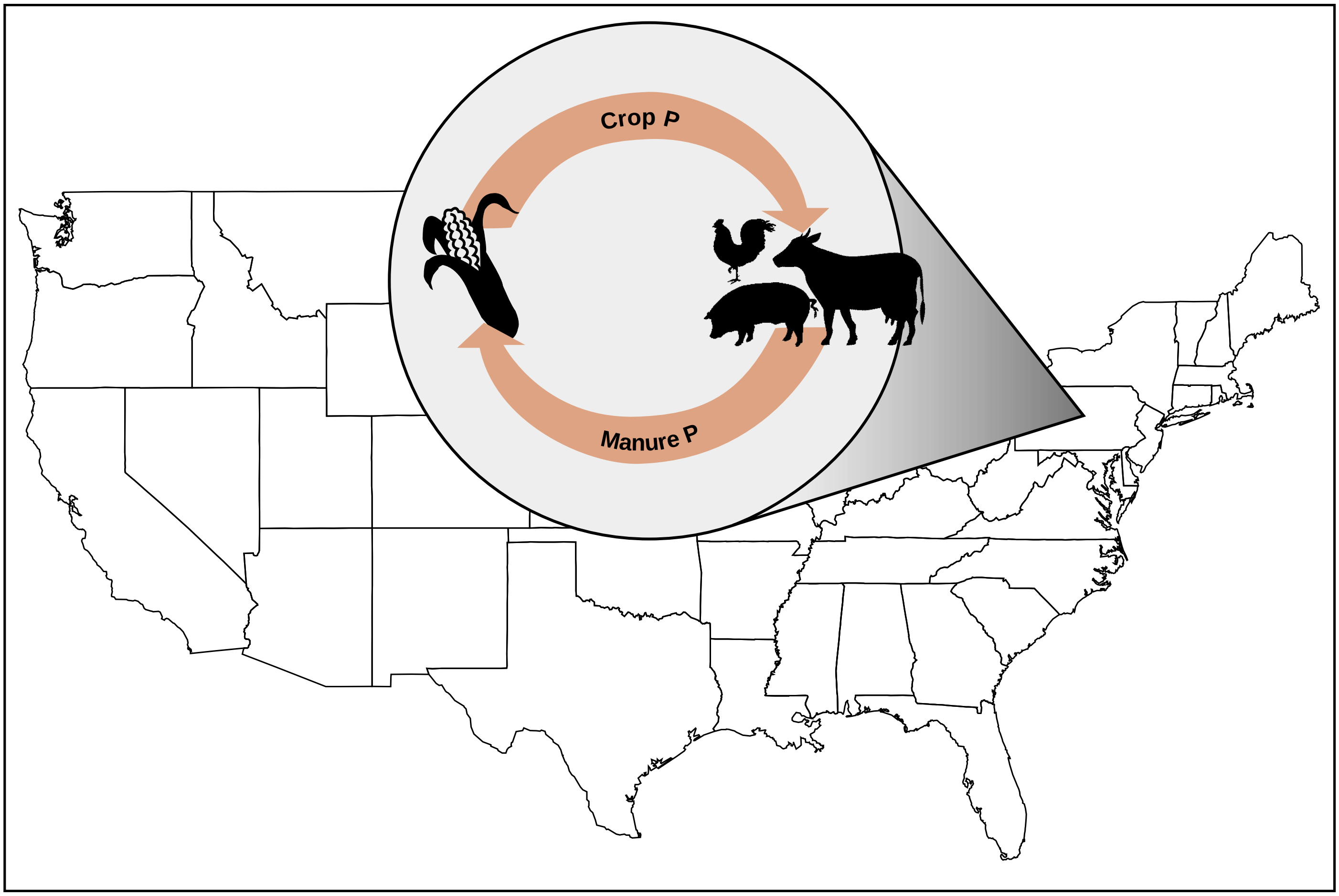

Figure 4. Before World War II, nutrient cycling was localized and sustainable within watersheds.

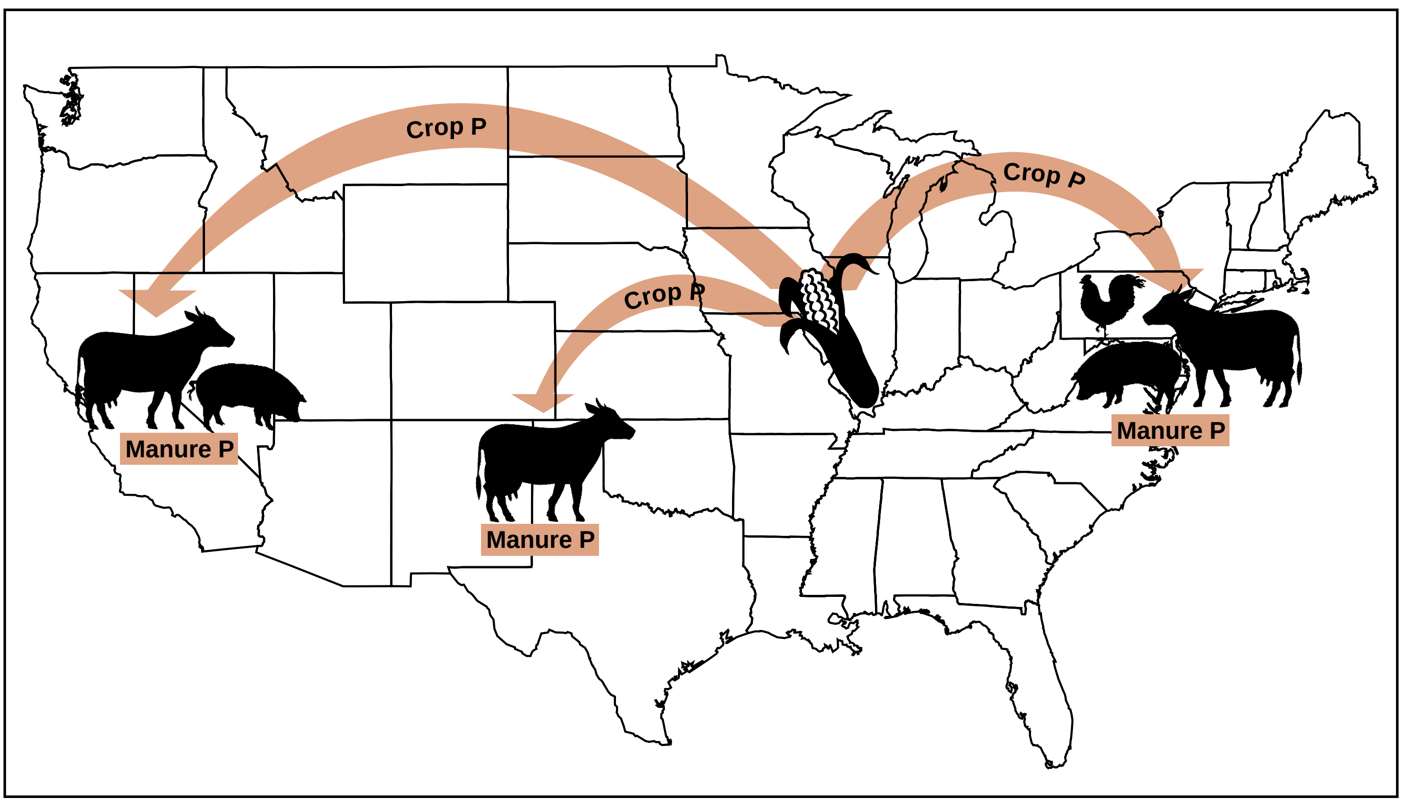

Figure 5. Since World War II, the nutrient cycle has been broken, with P tending to move from areas of grain production to areas of livestock production on a national level.

In many areas of intensive livestock production, manures normally are applied at rates designed to meet crop N requirements and avoid groundwater quality problems created by leaching of excess N. This often causes P to be applied in excess of crop needs, because a mismatch exists between manure nutrient content and crop nutrient needs. Figure 6 illustrates this mismatch for dairy and layer manure applied to corn. Notice that when manure is applied to balance crop N requirements exactly (the left-hand set of columns in the figure), excess P is applied. If manure is applied to balance the crop's P needs (the right-hand set of columns), N fertilizer is required to meet the N needs of the crop. In addition, less manure is applied per acre, and thus two to four times as much land is required to use up the manure.

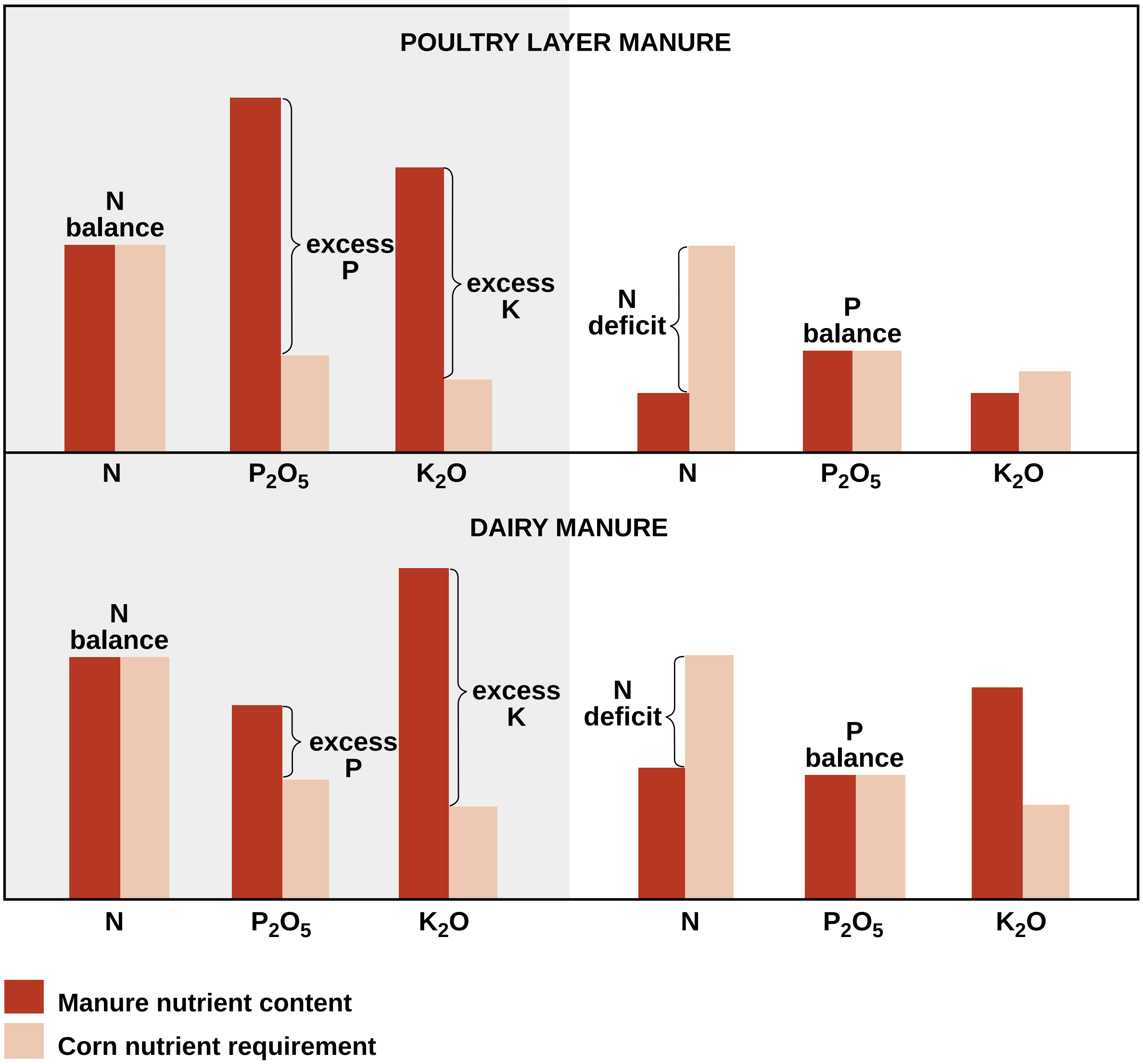

Figure 6. Applying manure to meet crop N needs (gray panel, above) will add much more P and K than is needed by the corn crop. Balancing crop P needs (white panel) adds insufficient N.

The resulting accumulation of P is evident from soil test results. A 1997 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, the Chesapeake and Delaware Bays, Lake Okeechobee, and the Everglades (Figure 7). 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 to produce optimum crop yields.

Areas of P deficit and surplus also exist at a more localized level. For example, in Lancaster County, Pa., which is dominated by intensive animal agriculture, 83% of tested soils rated above optimum; nearby Adams County, on the other hand, was dominated (56%) by low and optimum soil-test P. In addition, large differences may exist even within a farm. For example, fields near the barn sometimes have much higher P levels than more distant fields.

Once available P levels have built up, they decline slowly after applications have stopped. Studies have shown that without additional P applicatons, 10 to 20 years of corn or soybean production are needed to reduce available soil P (Mehlich-3) levels from 150 ppm to agronomic threshold levels of about 20 ppm.

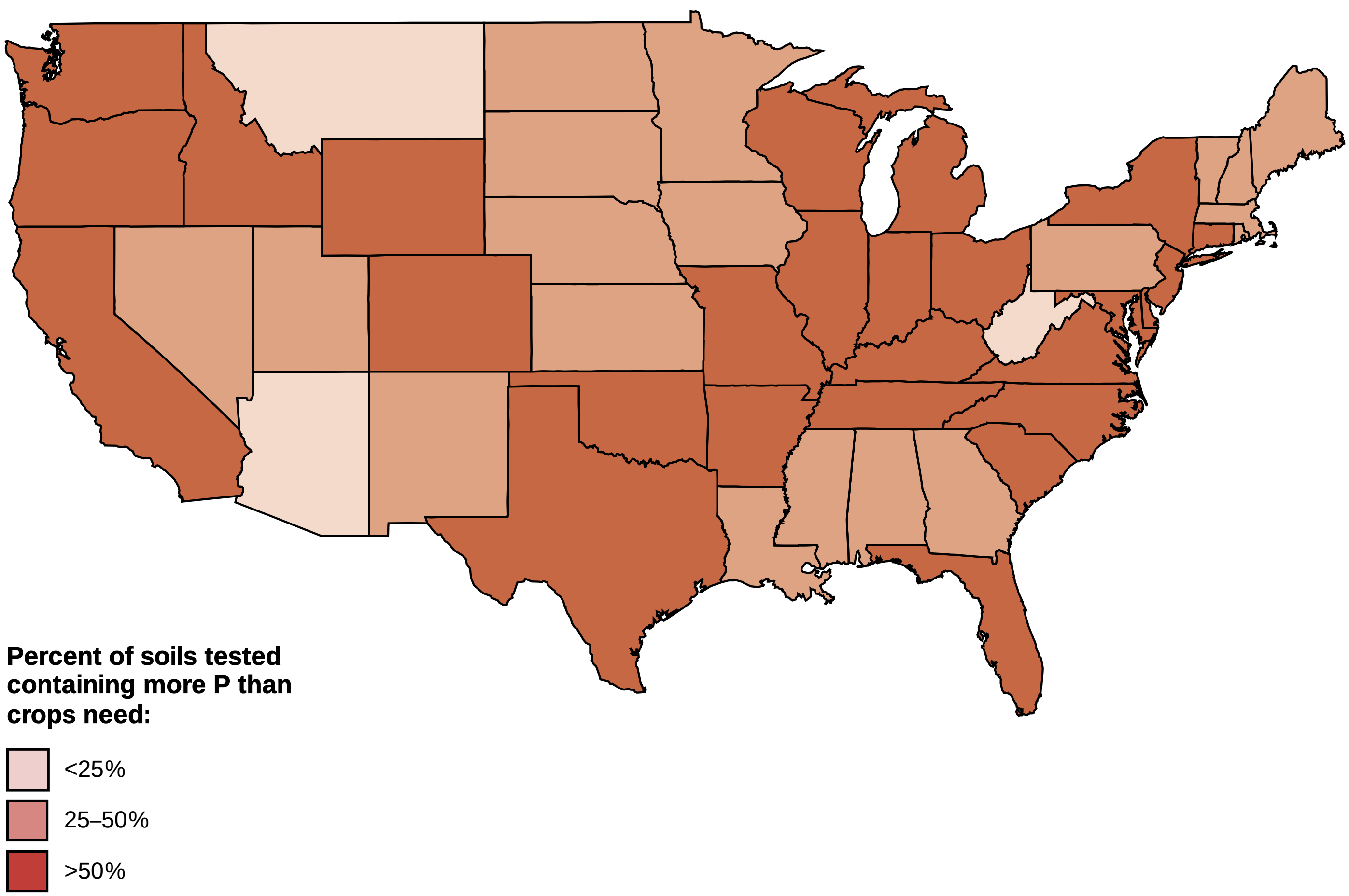

Figure 7. A 1997 survey of soils analyzed by state soil test laboratories shows a regional buildup of soil test P near P-sensitive waters.

How does phosphorus get into water?

The term “agricultural runoff” encompasses both surface runoff and subsurface flow, two dynamic and interrelated processes. For example, surface or overland flow can infiltrate into a soil during movement down a slope, move laterally through the soil, and reappear as surface flow.

The main factors controlling P loss in agricultural runoff are shown in Figure 8. The first step in the movement of P in surface runoff is its release from a thin (1- to 2-inch) surface layer of soil and plant material. Phosphorus often accumulates to higher levels in this surface soil layer than elsewhere in the soil. The remaining water percolates through the soil, where fixation by P-deficient subsoils generally results in low dissolved P concentrations in ground water. Exceptions may occur in organic, highly permeable, or waterlogged soils, which tend to fix less P.

Phosphorus in agricultural runoff may be dissolved or sediment bound. Dissolved P exists mostly in the form of orthophosphate, which is available immediately for uptake by algae. Sediment P, fixed by soil and organic material eroded during surface runoff, provides a variable but long-term source of P to algae in water bodies. Up to 90% of the P transported from cropland is attached to sediment. Thus, erosion control is of prime importance in minimizing P loss from agricultural land. It may not, however, be sufficient in and of itself.

Surface runoff generally occurs only from limited source areas within a watershed. These source areas vary rapidly over time, expanding and contracting quickly during a storm as a function of rainfall intensity and duration, antecedent moisture conditions, temperature, soils, topography, ground water, and moisture status over a watershed. Because surface runoff is the main mechanism by which P and sediment are 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 manure or fertilizer P applications. 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 for farmers.

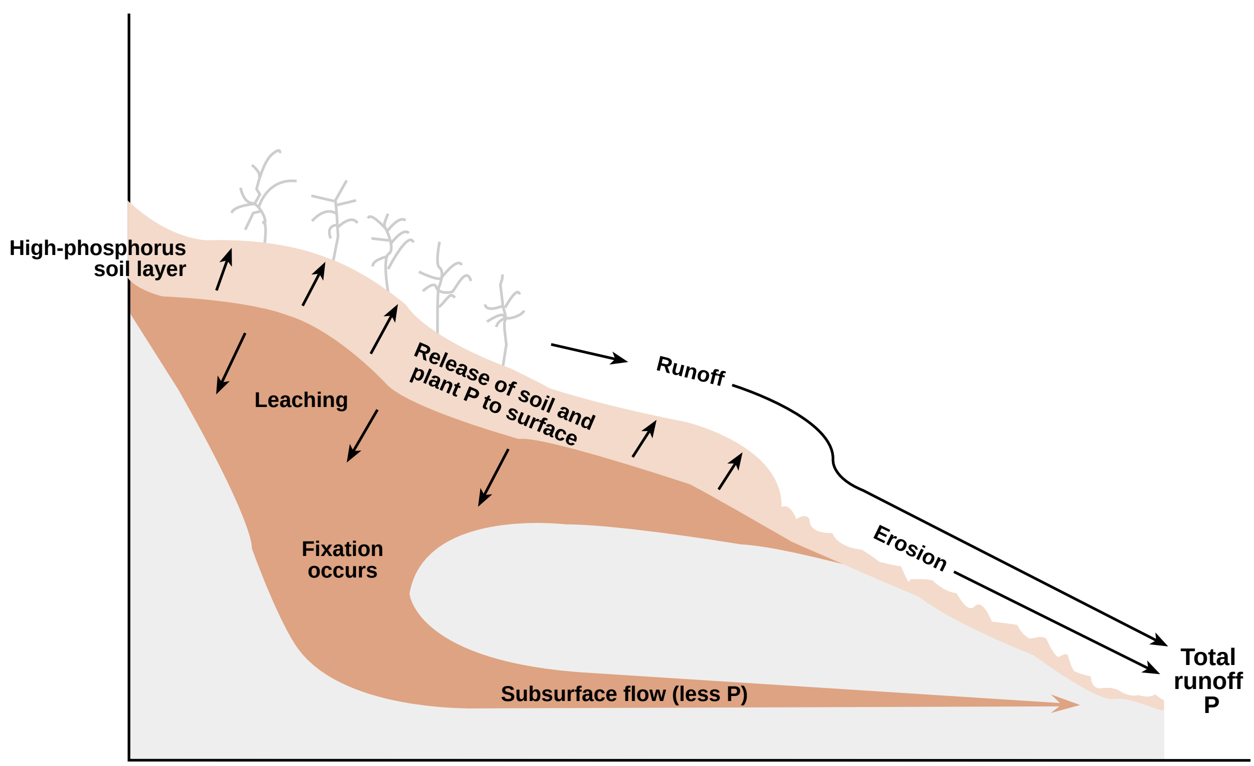

Figure 8. Phosphorus can be lost by erosion or released from soil and plant material to surface and subsurface runoff water.

How can a field's risk for phosphorus loss be monitored with soil tests?

Losses of P in surface runoff increase with an increase in soil test P levels. Although studies currently are limited to only a few soil types and situations, they show the scientific basis for establishing soil test P levels at which P losses in surface runoff reach unacceptable levels. In other words, if maximum allowable P concentrations in agricultural runoff are proposed, we can estimate at what soil test P level these concentrations probably will be met or exceeded. More data of this type are needed for different soil types, crop covers, surface runoff volumes, and erosion potentials, so that scientists can develop recommendations for fertilizer and manure use that will be effective for crop production and farm management, yet flexible enough to be workable and economical for farmers.

The relationship between soil test P and surface runoff P shown by the lower curve in Figure 9 is based on studies using traditional soil test methods that estimate the plant availability of soil P. Although these studies show promise in describing the relationship between the levels of soil and surface runoff P, they have certain drawbacks. For example, soil test chemical extraction methods were developed to estimate the plant availability of soil P; therefore, they may not accurately reflect the release of soil P to surface or subsurface runoff water. In addition, sampling depths can be problematic.

For routine soil fertility evaluation and recommendations, it generally is recommended that soil samples be collected to "plow depth," or the zone of greatest root concentration, which usually is 6 to 8 inches deep. When soil testing is used to estimate P loss, however, it is the surface inch or two of soil that comes in direct contact with runoff that is important. Consequently, different sampling procedures may be necessary for a soil test that is used to estimate the potential for P loss in surface runoff. To overcome the drawbacks of these traditional agronomic chemical extractants and collection techniques, approaches are being developed that provide more theoretically sound estimates of the amount of P in soil that can be released to runoff water and the amount of algal-available P in runoff.

In addition, we must be careful how we interpret soil test results for environmental purposes. Current interpretations of soil test reports (i.e., Low, Optimum, High) were established based on the expected response of a crop to the nutrient being tested (upper curve, Figure 9). Simply extending the interpretation levels for crop response to the potential for P loss has not been confirmed as a reliable approach. In other words, no direct relationship can be assumed to exist between the soil test calibration for crop response to P and the calibration for P loss in surface runoff. The critical soil test level for P loss may be above or even below the critical level for crop yield.

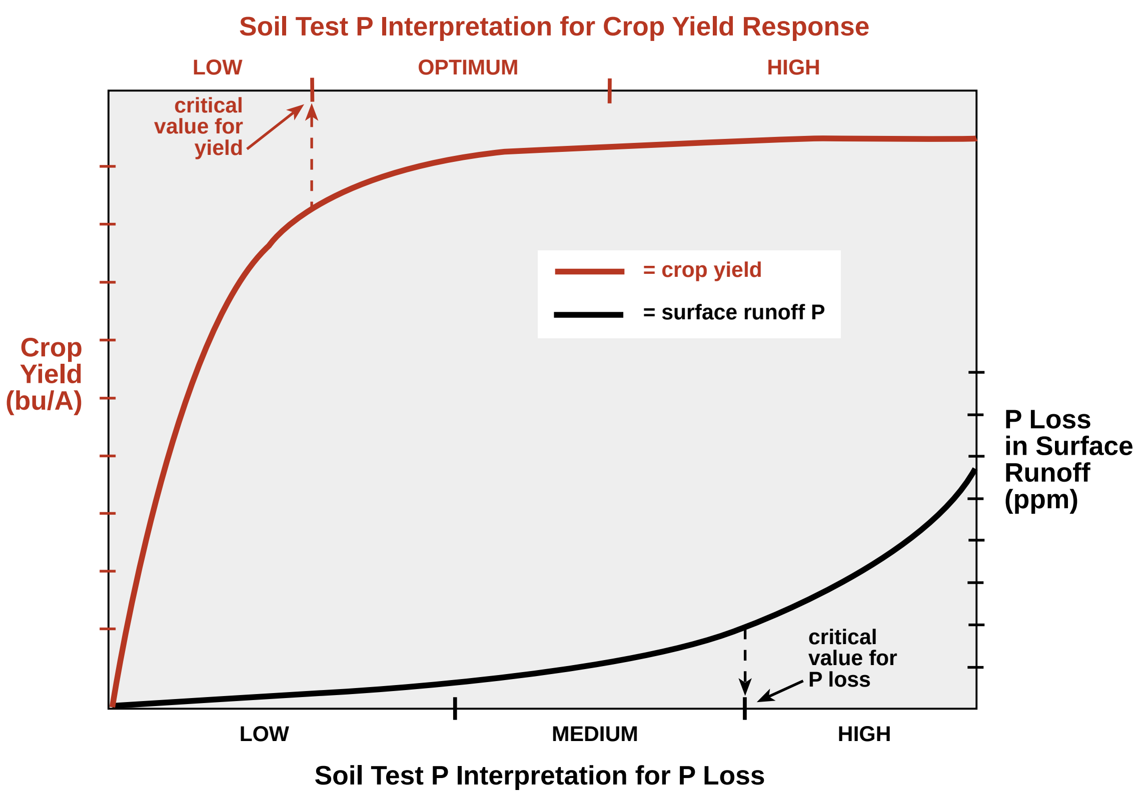

Figure 9. As soil P levels increase (x axis, above), so do crop yields and the potential for P loss in surface runoff. No direct relationship can be assumed to exist, however, between the soil test P interpretations for crop response (upper scale) and those for P loss (lower scale).

If soil tests are to be interpreted for the probability of P loss, calibrations that specifically relate the soil test to some measure of environmental response, such as P in runoff, will be necessary. Unfortunately, even though this currently is a very active research area, a clear consensus has not been reached on interpreting soil P tests for environmental purposes. Most soil scientists agree that it is not likely that there will be a simple critical soil test level for P loss potential. It is more likely that an integrated approach, including many other site-specific factors, will be necessary for interpreting the environmental pollution potential of a field. This approach is the basis for some P management strategies currently being developed, which will be discussed later.

What can we do?

Managing P to minimize environmental impact in runoff involves consideration of several important factors. To cause an environmental problem, there must be a source of P (i.e., a high soil concentration, manure or fertilizer applications, etc.), and it must be transported to a sensitive location (through processes such as leaching, runoff, or erosion). Problems occur where these two factors come together (Figure 10). A source containing a high level of P with little opportunity for transport may not constitute an environmental threat. Likewise, a situation where a high potential for transport exists, but where there is no source of P, also is not a threat. The concern and emphasis of management practices should be focused on areas where the two conditions coincide. These areas are called critical source areas. Strategies for source and transport management are described below, and an explanation is given of how strategies can be targeted to critical source areas.

Source management

Source management attempts to minimize the buildup of P 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. Techniques for doing this include the following:

- Because feed inputs often are the major cause of surplus P on farms, manipulation of dietary P intake by animals may help balance the input and output of P in livestock operations. In the Netherlands, concentrate P reductions are now being implemented to help decrease the amounts of P excreted by animals. Since P intakes above minimum dietary requirements do not seem to confer any growth advantage, carefully matching dietary P inputs to livestock requirements can be an effective technique.
- A significant amount of the P in grain is in phytate form, which cannot be digested by hogs and chickens. Thus, enzyme additives for livestock feed that will increase the efficiency of P uptake during digestion are being used. One example is phytase, an enzyme that allows the digestive systems of chickens and hogs to absorb P in grains. Keeping in mind the need for cost-effectiveness in terms of livestock weight gain, such enzymes could reduce the need for P supplements in feeds and potentially reduce the P content of manure.
- Another approach to better balance farm P inputs and outputs is to increase the quantity of P in corn that is available to chickens and hogs. Corn can be genetically engineered to decrease unavailable phytate-P, which contributes as much as 85% of the P content of corn grain. Studies have shown that poultry that were fed a “low-phytic-acid” grain ration produced manure with almost 25% less P than that of poultry fed a “normal” corn grain ration.

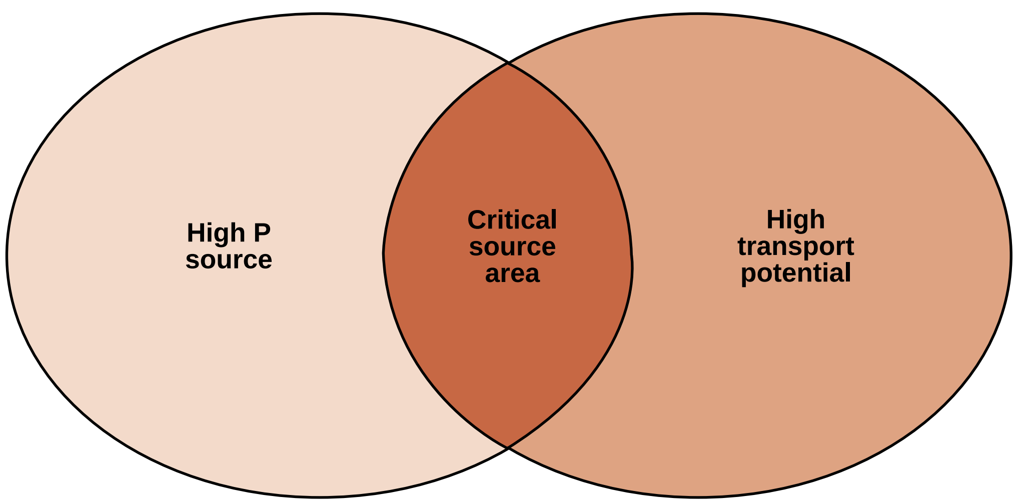

Figure 10. Critical source areas for P loss from a watershed occur where areas of high soil P and transport potential coincide.

- Composting may also be considered as a management tool to improve manure distribution. Although composting tends to increase the P concentration of manures, it reduces the volume and therefore the transportation costs. Additional markets also are available for composted materials. Composting makes manure more uniform in its physical and chemical properties and therefore able to be spread more uniformly and at more accurate rates. Even so, the success of commercial composting and pelletizing of manures for feed or bioenergy probably will require state involvement, since many of these programs will not be initiated without "favorable economics" (e.g., tax breaks) and will have difficulty competing with existing operations such as municipalities that subsidize composting with tax dollars.
- There is interest in using some manures as sources of "bioenergy." For example, dried poultry litter can be burned directly or converted by pyrolytic methods into oils suitable for use to generate electric power. Liquid wastes can be digested anaerobically to produce methane, which can be used for heat and energy. As the value of clean water and the importance of sustainable manure management are realized, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost-effective, and thus create expanding markets.
- Commercially available manure amendments such as slaked lime or alum can reduce ammonia volatilization, leading to improved animal health and weight gains; they also can reduce the solubility of P in poultry litter by several orders of magnitude and decrease dissolved P, metal, and hormone concentrations in surface runoff. An increase in the N:P ratio of manure, via reduced N loss from ammonia volatilization, perhaps is the most important benefit of manure amendments in terms of both air and water quality. An increased N:P ratio in manure would more closely match crop N and P requirements (see Figure 6).
- 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. Although this does not change the total amount of nutrients that must be handled, it may enable better targeting of the individual nutrients to locations where they will do the most good and / or have less potential for causing environmental problems. Also, because the solid fraction is more concentrated, it may be feasible to transport it to more remote fields.
- At the moment, manures are rarely transported more than 10 miles from where they are produced. A mechanism should be established to facilitate movement of manure from surplus to deficit areas. Although this initially may require financial incentives, some farmers already are using innovative methods to transport manure. For example, some grain or feed trucks and railcars are transporting dry manure back to the grain source area instead of returning empty. In some areas of Pennsylvania and other states, extension and trade organizations have established networks that put manure-needy farmers in contact with manure-rich poultry growers. Even so, large-scale transportation of manure from manure-producing to non-manure-producing areas is not occurring, mostly because of the concern that avian diseases will be transferred from one farm (or region) to the next. Consequently, the biosecurity of any manure transportation network that is developed must be ensured.

Transport management

Transport management refers to efforts to control the movement of P 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 (e.g., settling basins). These practices reduce the impact of rainfall on the soil surface, reduce surface runoff volume and velocity, and increase soil resistance to erosion. Riparian and buffer zones can also reduce P export in surface runoff and subsurface flow.

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 generally are more efficient at reducing sediment P than dissolved P. Also, note that P stored in lake and stream sediments can provide a long-term source of P in waters even after inputs from agriculture have been reduced. Several researchers have found little decrease in eutrophic plant growth in lakes with reduced P inputs following implementation of conservation measures. Thus, the effect of remedial measures in the contributing watershed will be slow for many cases of poor water quality.

Targeting management

Environmental concern has forced many states in the U.S. 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 in developing recommendations has been the identification of a threshold soil test P level that can be used to indicate when unacceptable P enrichment of agricultural runoff is likely. Examples of these proposed environmental thresholds from several states in the U.S. are given in Table 1. Environmental threshold levels generally range from two to four times the agronomic thresholds.

In most cases, the agencies that hope to use these levels are promoting a standard threshold value to all areas and states under their jurisdiction. Establishing these levels often is a highly controversial process for several reasons. The research relating soil test P to surface runoff P has been limited to a few soils and crops, making scientists understandably reluctant to generalize the data to other regions. Also, establishing soil test P levels that could limit manure applications has serious economic implications for growers. The future resale value of land with high-P soils could decrease with such rigid limits, and the possibility exists that the number of animals allowed in an area could be limited

Table 1. Proposed threshold soil test P values and P management recommendations.

STATE	ENVIRONMENTAL SOIL P THRESHOLD MG KG^{-1}	SOIL TEST P METHOD	MANAGEMENT RECOMMENDATIONS FOR WATER QUALITY PROTECTION
Arkansas	150†	Mehlich-3	At or > 150 mg P kg^{-1}: apply no P, provide buffers next to streams, overseed pastures with legumes to aid P removal, and provide constant soil cover to minimize erosion.
Colorado	100	Olsen	> 100 mg P kg^{-1}: hog producers with > 80,000 lbs capacity, no P applied unless overland flow is minimal.
Delaware	50	Mehlich-1	> 50 mg P kg^{-1}: apply no more P until soil is significantly decreased.
Idaho	50 & 100	Olsen	Sandy soils > 50 mg P kg^{-1} or silt loam soils > 100 mg P kg^{-1}: Apply no more P until soil P is significantly decreased.
Kansas	100–200	Bray-1	Regions of the state coincide with high (eastern) to low (western) overland flow. Swine producers must eliminate manure applications above the threshold.
Ohio	150	Bray-1	> 150 mg P kg^{-1}: decrease erosion and/or eliminate P additions.
Oklahoma	130	Mehlich-3	30–130 mg P kg^{-1}: half P rate on slopes > 8%. 130–200 mg P kg^{-1}: half P rate and adopt measures to decrease overland flow and erosion. > 200 mg P kg^{-1}: P rate not to exceed crop removal.
Maine	40–100	Morgan	In sensitive watersheds apply no P above 40 mg P kg^{-1} . In nonsensitive watersheds apply no P above 100 mg P kg^{-1}.
Maryland	75	Mehlich-1	Use P index > 75 mg P kg^{-1}: soils with high index must reduce or eliminate P additions.
Michigan	75	Bray-1	75–150 mg P kg^{-1}: P application should equal crop removal. > 150 mg P kg^{-1}: apply no P from any source.
Mississippi	70	Lancaster	> 70 mg P kg^{-1} no P added.
Texas	200	Texas A&M	> 200 mg P kg^{-1}: P addition not to exceed crop removal.
Wisconsin	75	Bray-1	< 75 mg P kg^{-1}: rotate to P demanding crops and decrease P additions. > 75 mg P kg^{-1}: discontinue P additions.

by the area's ability to absorb the P in the manure produced. Such limits would be unacceptable in many areas dominated by animal-based agriculture, where at present there simply is no economically viable alternative to land-applying manure.

Finally, threshold soil P levels are too limited to be the sole criterion to guide P management and P applications. In fact, these values will have little meaning unless they are used in conjunction with an estimate of the potential for surface runoff and erosion. This is based on the general observation that most of the annual P export from watersheds occurs from only a small percentage of the land area and during a relatively few large storms.

A sounder approach advocated by researchers and an increasing number of advisory personnel is to link areas of surface runoff and high soil P content in a watershed (Figure 11). Preventing P loss now is taking on the added dimension of defining, targeting, and remediating source areas of P that combine high soil P levels with a high potential for surface runoff and erosion. This approach addresses P management at multifield or watershed scales. Further, a comprehensive P management strategy must address down-gradient water quality effects such as the proximity of P-sensitive waters. Without using this source-area perspective to target P applications, the conventionally applied remediations of surface runoff and erosion control technology may not produce the desired results and may prove to be an inefficient and costly approach to the problem.

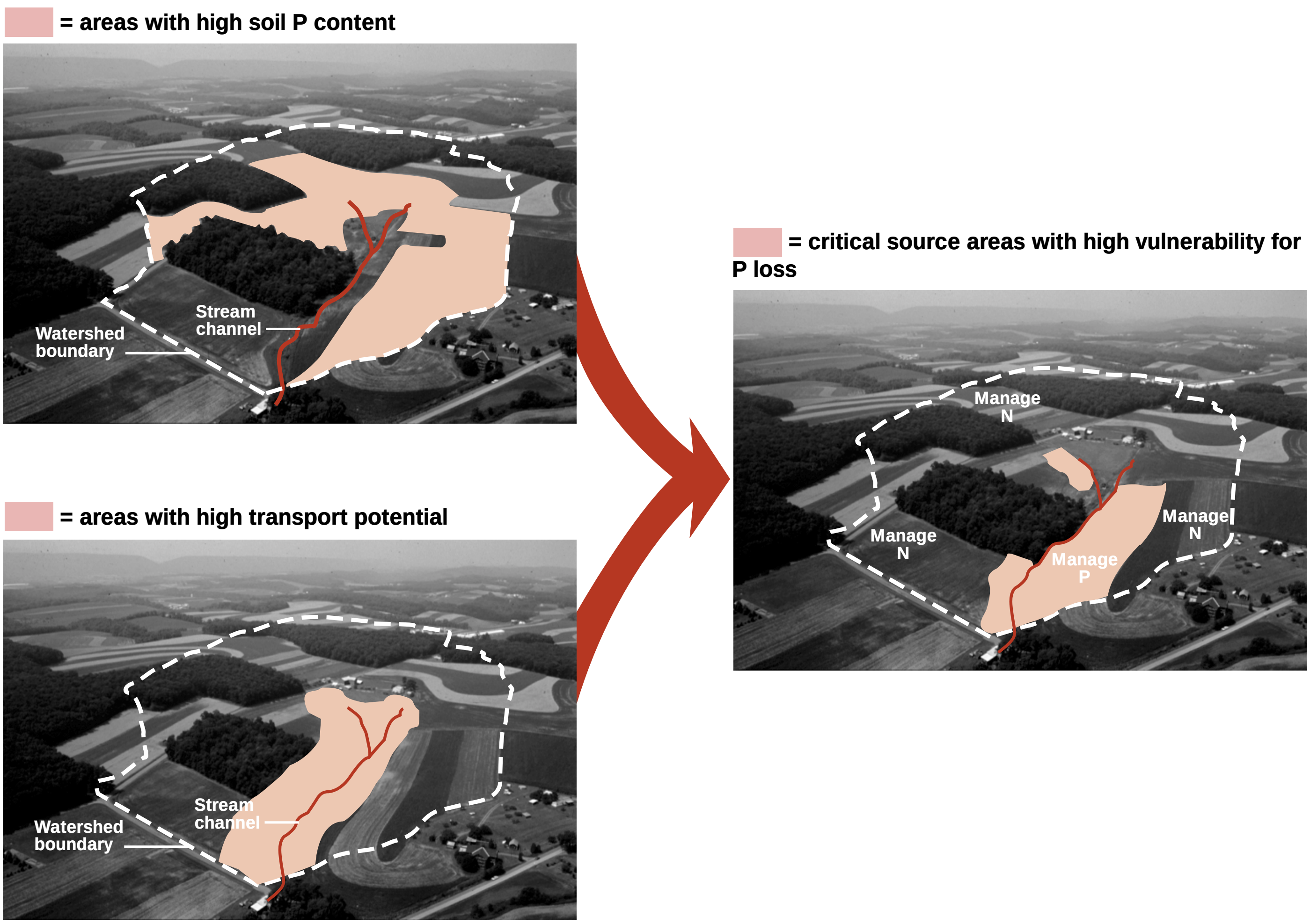

Figure 11. The principle of source-area management targets P reductions at areas in a watershed that have both high soil P content and high transport potential.

In cooperation with research scientists, USDA-NRCS has developed the concept for a simple P index that could be used as a screening tool for use by field staff, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in surface runoff. The index would account for and rank transport and source factors controlling P loss in surface runoff, and indicate sites where the risk of P movement is expected to be higher than others. The index is intended for use as a tool for field personnel to easily identify agricultural areas or practices that have the greatest potential to accelerate eutrophication, and to allow farmers more flexibility in developing remedial strategies. For example, adjacent fields that have similar soil test P levels but differing susceptibilities to surface runoff and erosion because of contrasting topography and management may not need similar P management recommendations. Also, the P Index provides guidance for management options beyond simply reducing or eliminating manure applications. For example, using BMPs to reduce transport may lower the threat of P loss to where manure applications do not have to be reduced below N based rates to meet environmental standards.

It is unlikely that a single P index will work across the country. Instead, P indexes are being developed to account for local soil, climatic, and hydrologic conditions. Such an index has been developed for Pennsylvania conditions. This index includes: soil test P, fertilizer P rate and method of application, and manure P availability, rate, and method of application as source factors; and erosion, runoff, subsurface drainage, distance, and connectivity to water as transport factors.

Extensive research on all components of the index, as well as its use in writing P based nutrient management plans on a number of Pennsylvania farms, has aided its acceptance by a broad range of stakeholders including farmers, environmentalists, and public officials.

Summary

The long-term goal of efforts to reduce P losses from agriculture to surface waters should be to balance off-farm inputs of P in feed and fertilizer with outputs in produce, and to manage soils in ways that retain nutrient and added P resources. Increasing the use-efficiency of P in agricultural systems may be brought about by source and transport control strategies. Although we have the knowledge and general ability to reduce the transport of P from agricultural land in runoff and erosion, less attention has been directed toward P management at the source.

In areas with confined or concentrated animal operations, continual land application of manure has increased the potential for P enrichment of surface runoff and N leaching to ground waters. In the past, separate strategies for P and N have been developed and implemented at farm or watershed scales. But because of differing chemistry and flow pathways of P and N in soil, these narrowly targeted strategies often lead to conflicting and compromised water quality remediation practices. For example, basing manure application on crop N requirements to minimize nitrate leaching to ground water 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.

A significant difference between strategies for P and N control is that N losses can occur from any location in a watershed, whereas areas prone to surface runoff contribute most to P losses. Because of this, remedial strategies for N can be applied to the whole watershed. The most effective P strategy, however, would be to apply not only simple measures to the whole watershed to avoid excessive P buildup, but also more stringent measures to the most vulnerable sites to minimize losses of P in surface runoff.

Implementation of such an approach will be complex, both technically and politically. It is clear, however, that a technically sound framework must be developed that addresses the differences between critical sources of P and N export from agricultural watersheds. Future advisory programs should reinforce the fact that all fields do not contribute equally to P export levels. Often, most P comes from only a small portion of the watershed in relatively few storms. In addition, if water or soil does not move from a field, then P will not move. Clearly, best management systems will be most effective if they are targeted to the hydrologically active source areas operating in a watershed during these storms.

It is often assumed that basing manure management on soil P will limit manure applications to large areas. But because not all soils and fields have the same potential to transfer P to surface runoff, management recommendations will have to account for site vulnerability to surface runoff and erosion as well as soil P content. Threshold soil P levels should be indexed against P transport potential, with higher values for source areas than for areas not contributing to surface runoff.

Phosphorus applications at recommended rates can reduce P loss in surface runoff when they increase crop uptake and cover. Nevertheless, it is of vital importance that we implement management practices that minimize soil test P buildup in excess of crop requirements, reduce surface runoff and erosion, and improve the ease and reliability with which we can identify the fields that are the major sources of P loss to surface waters. In summary:

- Best management systems should attempt to balance P inputs and outputs.
- Source and transport controls should be targeted to identified 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.

Research and education will increase our understanding and awareness of the agronomic, economic, and environmental issues related to nutrients such as N and P. This will enable us to develop sound solutions to these water quality problems while sustaining productive and profitable agriculture. This is not a simple problem and the solutions will not be simple. We must be careful not to jump on seemingly easy solutions, such as across-the-board P limits, without carefully considering their implications and looking at possible alternatives.

Perhaps the most critical and challenging way of initiating real and lasting changes in agricultural production and P imbalances is to focus on consumer-driven programs and education rather than on farm production. Farmers are at the bottom of the food chain, and their decisions often are influenced by regional and even global economic pressures over which they have little or no control. Therefore, we have to look at new ways of using incentives to help farmers implement innovative measures to minimize on-farm surpluses of P. The challenge is to recognize how social policy and economic factors influence the nutrient management agenda. Equally important is that everyone is affected by and can contribute to a resolution of P-related concerns.

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Penn State College of Agricultural Sciences research, extension, and resident education programs are funded in part by Pennsylvania counties, the Commonwealth of Pennsylvania, and the U.S. Department of Agriculture.

This publication is available from the Publications Distribution Center, The Pennsylvania State University, 112 Agricultural Administration Building, University Park, PA 16802. For information telephone (814) 865-6713.

Issued in furtherance of Cooperative Extension Work, Acts of Congress May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture and the Pennsylvania Legislature. T. R. Alter, Director of Cooperative Extension, The Pennsylvania State University.

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Produced by Information and Communication Technologies in the College of Agricultural Sciences

4M11 / 01comm4276(b)

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