

Soil Testing for Phosphorus:

Environmental Uses and Implications

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*Minimizing Agricultural Phosphorus Losses for
Protection of the Water Resource*

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Phosphorus Management for Water Quality Protection: A National Effort

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Runoff, erosion, and leaching from agricultural lands are the major sources of contamination of the nation's aquatic resources. Indeed, in a recent report to congress, the U.S. Environmental Protection Agency (USEPA, 1996) identified agricultural nonpoint source pollution as the major cause of the stream and lake contamination that prevents the attainment of the water quality goals established in the Clean Water Act. Specifically, nutrients from agricultural sources were identified as the major anthropogenic cause of eutrophication ("*..enrichment of surface waters by plant nutrients .. a form of pollution that restricts the potential uses of impacted water bodies*"; Foy and Withers, 1995) of the fresh waters and estuaries in the United States.

Phosphorus (P) is the single most important nutrient that must be managed if we are to control the accelerated eutrophication of fresh waters. Although nitrogen (N) may limit plant and algal growth during certain periods of the year, P is most often the nutrient of concern. In estuaries, both P and N must be controlled because P is the limiting nutrient in the upper, fresh water portions and N in the more saline regions. Controlling P inputs to surface waters can be difficult, but is usually easier than preventing N inputs. For example, certain blue-green algae can obtain the N needed for their growth from the atmosphere; N can also be added to water bodies by rainfall and wind-borne particulates. Inputs such as these are virtually impossible to prevent. In general, as N concentrations in surface waters have increased, P has become the limiting nutrient for the growth of aquatic organisms and thus the primary factor that must be controlled to prevent eutrophication.

To reduce the impacts of P on surface water quality we must first identify the combinations of land use and water body sensitivity that are most likely to result in eutrophication. Generally speaking, improved P management is most needed in regions where agricultural practices result in very high concentrations of P in soils and climatic and topographic conditions promote P loss via erosion and runoff (surface and subsurface). If these conditions occur in close proximity to surface waters known to be sensitive to P inputs, impairment of surface water quality is likely. Therefore, developing systematic approaches to target watersheds where improved agricultural management practices will minimize P loss from soil to water is a key first step in the cost-effective prioritization of the national and local resources used to minimize nonpoint source pollution of surface waters. At the national level USEPA and the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) use state nonpoint source pollution assessment reports and the Agricultural Census to broadly target technical assistance and financial support to watersheds where agriculture's contribution to water quality impairment is substantial. Unfortunately, until recently the tools needed by state and local resource planners to target specific areas where these resources can best be used to prevent nonpoint source pollution of surface waters by P have not been readily available.

REGIONAL AND NATIONAL EFFORTS TO ASSESS THE ENVIRONMENTAL IMPACT OF AGRICULTURAL PHOSPHORUS

Many studies have shown the agronomic benefits of P fertilization. Today, however, agricultural P is increasingly viewed as a potential contaminant of surface waters. Research on soil P has evolved accordingly, changing in focus from studies of the factors controlling the plant availability of soil P to investigations on the release and transport of P from soils to surface waters. Along with this there has been an increase in research and extension efforts to develop cost-effective, farm-scale, best management practices (BMPs) to prevent P loss to surface waters. *SERA-IEG 17* (Southern Regional Extension and Research Activity Information and Exchange Group) was formed in 1993, as described below, to provide a means for research and extension scientists to translate recent advances in soil P management into the assessment tools needed to minimize nonpoint source pollution of surface waters by agricultural P. Some background on the activities of this group to date is provided to put the current national efforts of SERA-IEG 17 into perspective.

The Phosphorus Index

In the early 1990's USDA began to develop assessment tools for areas with water quality problems. While some models, such as USLE for erosion, NLEAP for nitrogen leaching, and GLEAMS for ground water pollution, were already being used to screen watersheds for potential agricultural impacts on water quality, there was no model considered suitable for the field-scale assessment of the potential movement of P from soil to water. A group of scientists from universities and governmental agencies met in 1990 to discuss the P issue and later formed a work group (PICT: Phosphorus Index Core Team) to more formally address this problem. Members of PICT soon realized that despite the many scientists conducting independent research on soil P, there was a lack of integrated research that could be used to develop the field-scale assessment tool for P needed by USDA. Consequently, the first priority of PICT was a simple, field-based, planning tool that could integrate, through a multi-parameter matrix, the soil properties, hydrology, and agricultural management practices within a defined geographic area, and thus to assess, in a relative way, the risk of P movement from soil to water. This planning tool, now referred to as the *Phosphorus Index* (Lemunyon and Gilbert, 1993; described in Chapter 4) has since been used in several U.S. states to enhance efforts to prevent nonpoint source pollution of surface waters by agricultural P.

Phosphorus SERA-IEG 17

After the development of the *Phosphorus Index*, interest grew within PICT to expand the scope of research and extension activities related to P management for water quality protection. In 1992 PICT organized a symposium at the national meetings of the American Society of Agronomy (published in the *Journal of Production Agriculture*, 1993) highlighting the *Phosphorus Index* and the need to expand our knowledge on the role of agricultural P in eutrophication. The original PICT soon grew to over 50 scientists from the U.S. and other countries. The efforts of PICT were formalized in 1993 by establishing a USDA research and information group (SERA-IEG 17) within the Cooperative States Research, Education, and Extension Service (CSREES). A major goal of the group has been to bring together a greater diversity of disciplines to discuss the research and management needs related to agricultural P and water quality. SERA-IEG 17 has expanded rapidly

since in 1993 and now has over 75 members with expertise in disciplines ranging from soil science and corn genetics to hydrology and limnology. It has become a valuable informational resource for agencies (USEPA, USDA) and state universities that are addressing the need for best management practices (BMPs) to prevent nonpoint source pollution of surface waters by agricultural P. In 1996 SERA-IEG 17 co-sponsored a symposium entitled *Agricultural Phosphorus and Eutrophication*. at the national meetings of the American Society of Agronomy with Division S-6 (Soil and Water Management & Conservation) of the Soil Science Society of America. Topics included hydrologic controls on P loss from uplands, P losses in agricultural drainage, watershed modeling of P transport, and plant genetic approaches to P management for agriculture. The symposium will be published in the *Journal of Environmental Quality* in 1997.

SERA-IEG 17 is gaining national and international recognition as an unbiased source of scientific knowledge on P research, management, and policy. Members of this regional committee regularly make presentations on various aspects of P at national and international scientific meetings and have frequently been asked to provide guidance to state and federal advisory and regulatory agencies and the agricultural industry. Most recently, members of SERA-IEG 17 were invited to participate in a congressional inquiry concerning the potential environmental impacts of agricultural P. In 1997 an Internet web site (<http://ces.soil.ncsu.edu/sera17>) and list-server were established to disseminate information and publications developed by SERA-IEG 17. The synergism developed within the SERA-IEG 17 committee has created an international framework for the exchange of information and the development of new ideas useful to the resolution of the problems related to the environmental impact of agricultural P.

In summary, SERA-IEG 17 has adopted a broad, long-term perspective on the issue of minimizing P losses from agriculture for water quality protection. It has also identified the following specific objectives, now being addressed by separate task forces:

- a) To develop an interdisciplinary approach to identify P sensitive watersheds and water bodies, expanding and improving upon the *Phosphorus Index*.
- b) To develop best management practices (BMPs) to reduce agricultural P losses to surface and ground waters by erosion and runoff (surface and subsurface).
- c) To develop an animal manure application strategy based on both P and N.
- d) To develop upper, environmentally-based, critical limits for soil test P and new soil testing methods that can more accurately identify soils where P loss will be of environmental concern.

AGRICULTURAL P AND WATER QUALITY - THE FUTURE

The diversity of scientists that have come together in SERA-IEG 17 reflects the complexity of the relationship between nonpoint source pollution and water quality. Because of this complexity, the members of SERA-IEG 17 feel strongly that no single solution exists that will be appropriate for all situations; rather the process of reducing P risk to the environment must build upon the combined expertise of many scientific disciplines. Multi-disciplinary efforts are needed to understand the pathways of P movement from soil to water, and to offer solutions at each stage that

can reduce the impact of agricultural P on the environment. Before we can develop agricultural systems that are agronomically and environmentally sound for P, we need to understand the chemical and physical characteristics of the water bodies that are sensitive to P, the causes behind the buildup of P in soils to excessive levels, the dynamics of soil P cycling, the mechanisms that control P transport from soil to water, and the cycling of P in aquatic systems. From this information we can identify the means to manage agricultural P to both optimize soil productivity and minimize environmental impacts on our surface waters within the limits now set by social and economic constraints. Water bodies impaired due to excess P are costly and difficult to restore and take many years to recover. In the long-term, the most cost-effective means to minimize the impacts of agricultural P is to understand and control nonpoint source pollution. This publication represents a first step in that direction.

LITERATURE CITED

Foy, R.H., and P.J.A. Withers. 1995. The contribution of agricultural phosphorus to eutrophication. The Fertilizer Society. Proc. No. 365. Greenhill House, Thorpe Wood, Petersborough, UK.

ASA Symposium on Phosphorus Loss from Soil to Water:

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

Stevens, R. G., T. M. Sobecki, and T. L. Spofford. 1993. Using the phosphorus assessment tool in the field. J. Prod. Agric. 6:487-491.

Sharpley, A. N., T. C. Daniel, and D. R. Edwards. 1993. Phosphorus movement in the landscape. J. Prod. Agric. 6:492-500.

Sims, J. T. 1993. Environmental soil testing for phosphorus. J. Prod. Agric. 6:501-506.

Truman, C. C., G. J. Gascho, J. G. Davis, and R. D. Wauchope. 1993. Seasonal phosphorus losses in runoff from a coastal plain soil. J. Prod. Agric. 6:507-512.

Pierzynski, G. M. and T. J. Logan. 1993. Crop, soil, and management effects on phosphorus soil test levels. J. Prod. Agric. 6:513-519.

U.S. Environmental Protection Agency (USEPA). 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, D. C.

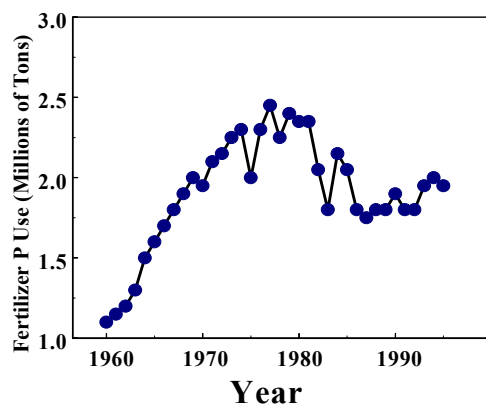
Chapter 1:

Agricultural Phosphorus and Water Quality: An Overview

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ROLE OF PHOSPHORUS IN AGRICULTURE

Phosphorus (P) is a key essential element for modern agriculture. Fertilization of crops comprises the largest proportion of P used in agriculture and P fertilizer use has increased steadily since 1960 in an effort to balance gradual depletion of soil P caused by removal of P in harvested biomass (e.g. grain, forage). The importance of P to agricultural productivity is illustrated by the amount of fertilizer P consumed during the last 35 years which has doubled since 1960, stabilizing at slightly under two million tons per year over the last 10 years (Fig. 1-1).



*Figure 1-1. Fertilizer P use in the United States
(Adapted from Terry et al., 1996).*

Phosphorus has many important functions in plants, the premier one being energy storage and transfer. Adenosine diphosphate (ADP) and adenosine triphosphate (ATP) are compounds with high-energy phosphate groups that drive most physiological processes in plants including photosynthesis, respiration, protein and nucleic acid synthesis, and ion transport across cell membranes. Phosphorus also functions as a vital structural component of nucleic acids, phospho-proteins, sugar phosphates, enzymes, and chloroplasts. It is also well-known that P: (1) is essential for seed production; (2) enhances plant root growth; (3) promotes early plant maturity thus decreasing time required for grain ripening; and, (4) promotes stalk strength, resistance to root rot diseases, and resistance to winter kill. In addition to the essentiality of P to these vital plant physiological processes, the agronomic literature is replete with examples of grain, fiber, and forage yield increases owing to proper maintenance of P fertility in arable soils. Clearly, P is a necessary and beneficial input for modern agricultural cropping systems.

Crop production, however, is not the only segment of agriculture that uses P. Livestock producers often supplement P contained in feed grains and forages with inorganic P to improve animal performance. Many confined

animal operations are located in grain deficient areas where feed is not produced locally and must be imported. Manure generated by these livestock operations must be disposed of and, in most cases, the only economically viable option for disposal is land application. Unfortunately, intensive animal operations often do not have sufficient land

wastes in an environmentally acceptable manner. This combination of factors often results in P surpluses on farms and buildup of P to excessive levels in the soils and subsoils of cropland surrounding confined animal farms (Fig. 1-2), even when fertilizer P is not used for crop production.

available to use the P contained in animal

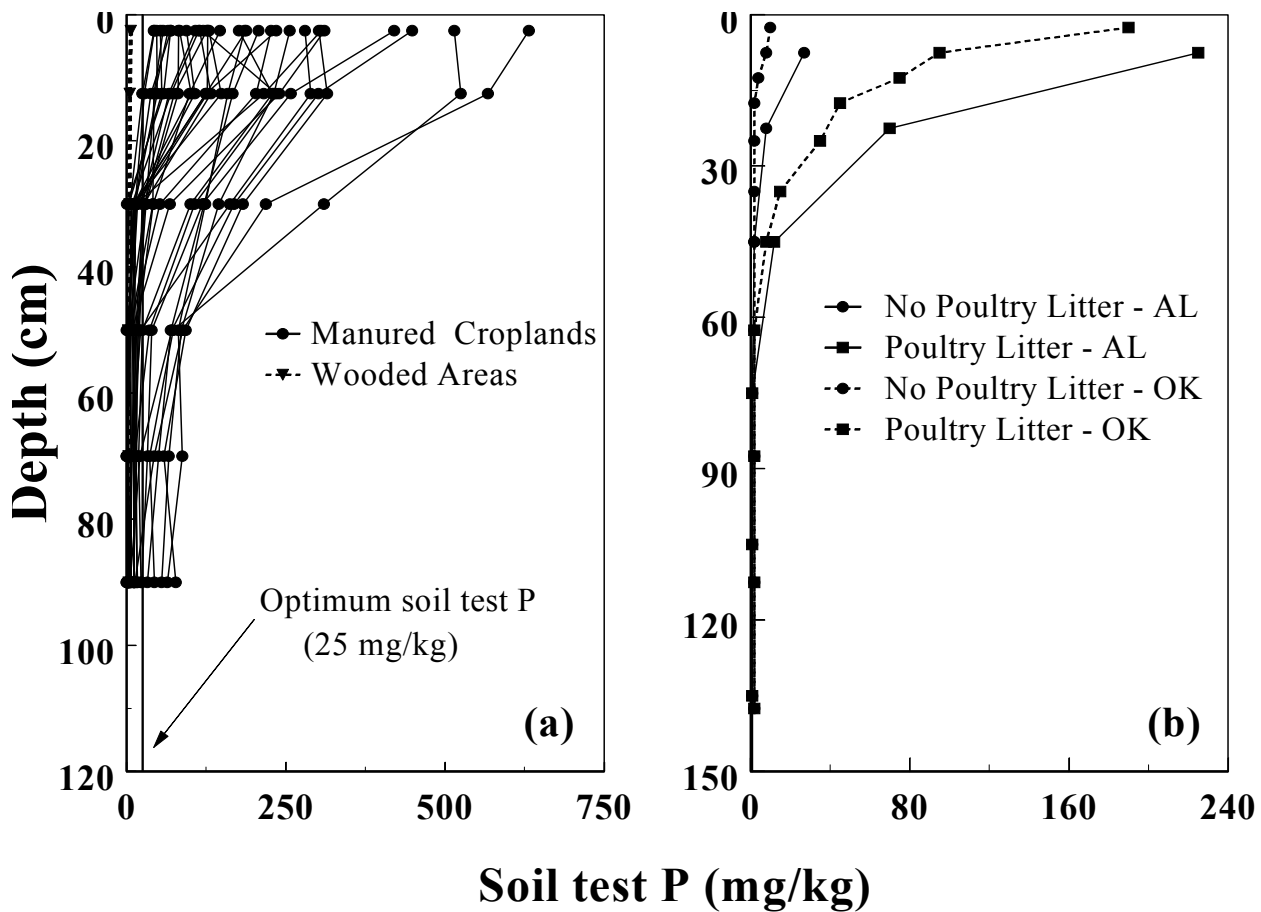


Figure 1-2. Effect of long term applications of poultry litter on the accumulation and leaching of P in (a) cropland in Delaware (Mozzaffari and Sims, 1994) and (b) pastures in Alabama (Kingery et al., 1994) and Oklahoma (Sharpley et al., 1984)

ENVIRONMENTAL IMPACTS OF AGRICULTURAL PHOSPHORUS

Although the salutary effects of P on agricultural production are well-known, P can also be a pollutant if it moves from the site of intended use (agricultural soils) to surface waters sensitive to eutrophication. The large number of U.S. soils now testing “high” or “excessive” in P, many in close proximity to important surface waters, has increased national concerns about the transport of P in surface or subsurface flow from soils to streams, rivers, lakes, and eventually to oceans (Figure 1-3).

dissolved oxygen, and reduced water transparency. Algal growth in surface waters is usually limited by P availability, although no clear guidelines exist regarding concentrations of total or dissolved P in runoff that will induce eutrophication. However, recommendations have been put forward in regard to critical P concentrations that are expected to cause noxious aquatic growth in downstream waters (Table 1-1).

Phosphorus transported from agricultural soils can promote *eutrophication*, which is enrichment of surface waters with nutrients that leads to increased algal growth, decreased

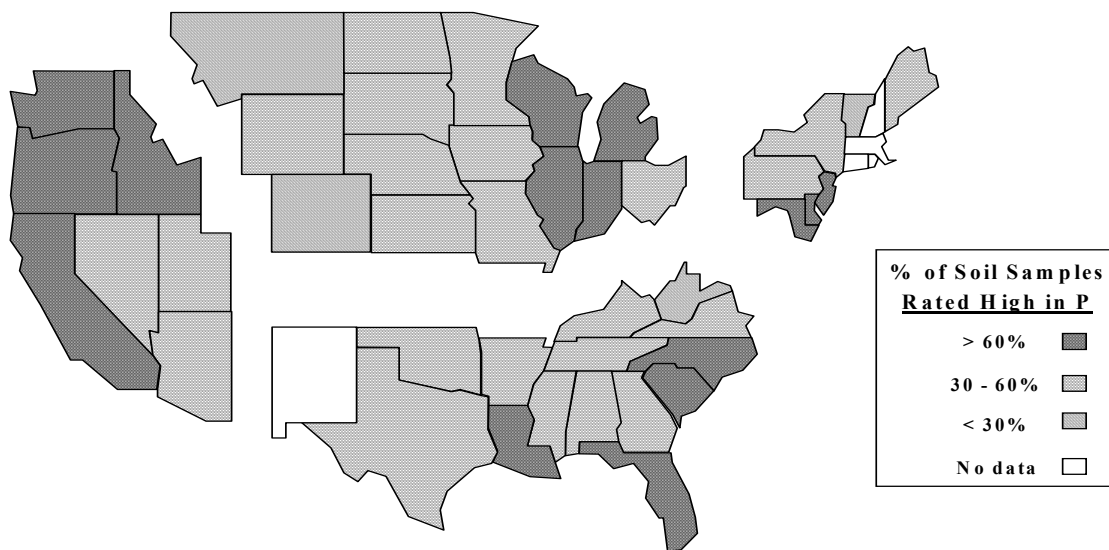


Figure 1-3. Geographic distribution of high P agricultural soils in the U.S. (Adapted from PPI, 1994).

Table 1-1. Critical phosphorus concentrations reported for surface waters.

Phosphorus Concentration (mg/L)	Comment	Source(s)
0.01	Dissolved P: critical concentration for lakes	Sawyer (1947) Vollenweider (1968)
0.10	Total P: critical concentration for streams	USEPA (1986)
0.50	Total P: critical concentration for lakes	USEPA (1986)
0.50	Dissolved P: critical concentration allowed to enter Florida Everglades	USA vs. South Florida Water Management District (1994)
0.01	Dissolved P: target concentration allowed to enter Florida Everglades by the year 2000	USA vs. South Florida Water Management District (1994)
1.0	Flow-weighted annual dissolved P: Proposed allowable limit for agricultural runoff	USEPA (1986)

Waters receiving agricultural runoff will remain in an unpolluted, aesthetically pleasing state when biological production, i.e., algal growth, is approximately equal to respiration (decomposition). In this balanced state, algal photosynthesis produces oxygen gas and organic matter. Oxygen produced is used by heterotrophic organisms (those requiring complex organic compounds for metabolic synthesis) that decompose organic matter produced. When a change in environmental conditions occurs, such as P enrichment, biological alterations follow.

Because P usually limits algal production in fresh waters, enrichment with P stimulates

algal growth. Algae are only found in upper euphotic zones (where sufficient light penetration occurs for the growth of green plants) of receiving waters. Oxygen is evolved to the atmosphere as algal photosynthesis occurs and, upon completion of their life cycle, algae and other organic detritus settle to the bottom of the receiving water. On the bottom there is little to no photosynthesis and thus oxygen production, and as organic matter accumulates, microbial decomposers rapidly deplete dissolved oxygen. Thus, P enrichment results in accumulation of organic sediment with a high biological oxygen demand. Production of algae is then out of balance with

respiration (decomposition), and gradually a receiving water fills with sediment.

In receiving waters, such as lakes, accumulation of P, other nutrients, and organic matter usually occurs during late summer, fall, and winter. With increasing spring temperatures, lake water columns invert and mixing occurs. The result is an increase in biologically available P and other nutrients in the water column, which along with increased periods of sunlight promotes algal blooms. Formation of dense algal mats prevents gas exchange necessary to maintain sufficient dissolved oxygen in the water body, which can then result in fish kills.

Eutrophication of surface waters via P enrichment cause numerous environmental and ecological problems. Depletion of dissolved oxygen in eutrophic waters causes many dissolved constituents to be in forms (e.g., ammonia, hydrogen sulfide, methane) that are potentially toxic to wildlife and livestock. The costs and difficulty of water purification for drinking purposes, done to remove odor, turbidity, and color, are also increased with eutrophication. The ecological consequences of eutrophication include replacement of high quality edible fish, submerged macrophytic vegetation, and benthic organisms with coarse, rapid-growing fish and algae and noxious aquatic plants. Increased sedimentation with eutrophication impairs navigational and recreational use: lake depths are reduced; enhanced vegetative growth blocks navigable waterways; decaying algal biomass produces surface scums; undesirable odors occur (hydrogen sulfide, methane, etc.); and, populations of insect pests such as mosquitos are increased. Clearly, enrichment of surface waters with P is undesirable.

TRANSPORT OF AGRICULTURAL PHOSPHORUS TO SURFACE WATERS

To understand how P can escape from agroecosystems and become a pollutant, it is necessary to examine the P cycle (Fig. 1-4) beginning with sources of P in soils. Origins of P in soils include residual soil minerals, or inputs of P from commercial fertilizers and organic fertilizers/wastes. Over 200 forms of naturally occurring P minerals are found in soils, the most common being: (1) apatite (calcium phosphate), which is found in unweathered and moderately weathered soils; and (2) iron and aluminum phosphates, which are found in highly weathered soils. The raw material for commercial fertilizer P is apatite mined from various deposits around the world and treated with sulfuric or phosphoric acids to increase the solubility of P. Organic fertilizers/wastes are derived from a variety of sources including animal manures, crop residues, and municipal and industrial wastes.

In the soil environment P is subject to several soil processes that control its availability to plants and potential movement to surface waters (Fig. 1-4). In the soil solution, P is present as either a monovalent ($\text{H}_2\text{PO}_4^{-1}$; acid soils) or divalent (HPO_4^{-2} ; alkaline soils) anion. Phosphorus enters the soil solution via either: (1) dissolution of primary minerals; (2) dissolution of secondary minerals; (3) desorption of P from clays, oxides, and minerals; (4) and, biological conversion of P in organic materials to inorganic forms (mineralization). It should be noted that all of these processes are reversible (Fig. 1-4). In most soils, soil solution P ranges between <0.01 and 1 mg/L, and a value of 0.2 mg P/L is commonly accepted as the solution P concentration needed to meet the nutritional needs of most agronomic crops.

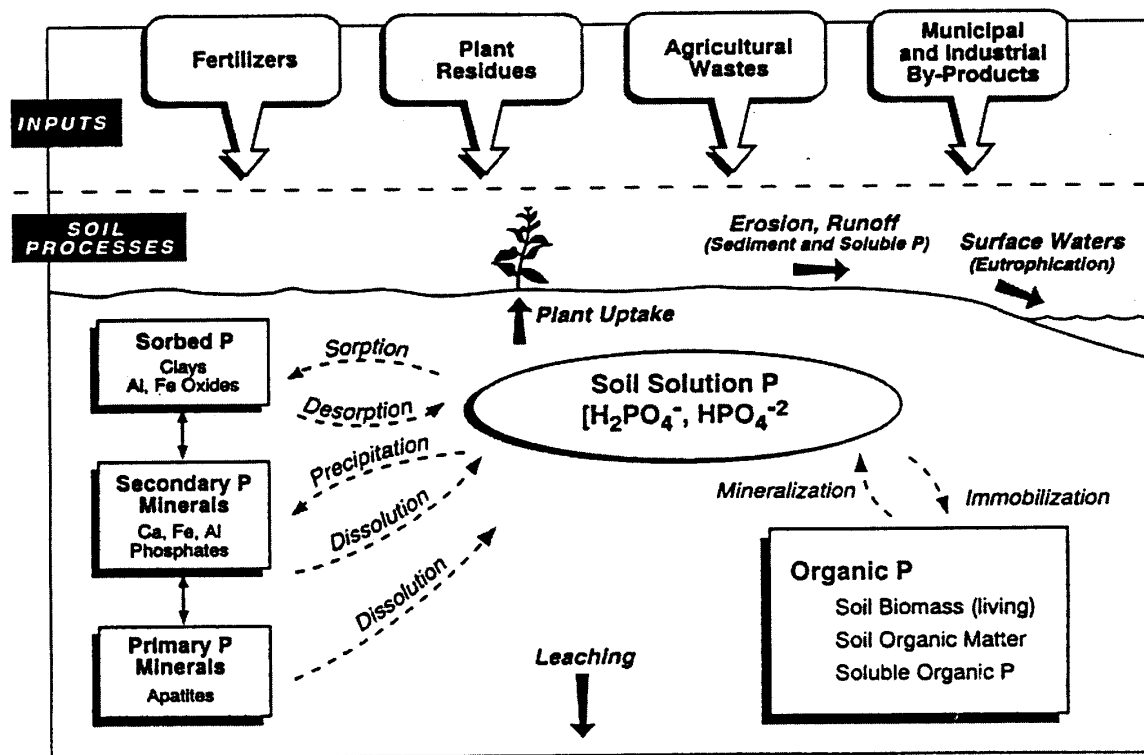


Figure 1-4. The soil phosphorus cycle (from Pierzynski et al., 1994).

Runoff (surface and subsurface) and erosion are the processes by which soil P moves from agricultural fields to surface waters (Fig. 1-5). Desorption or dissolution of P from a thin zone of surface soil and vegetative material yields dissolved P which is immediately available for uptake by aquatic biota (Sharpley et al, 1996). Soil erosion transports particulate P in the form of soil and vegetative matter; only that portion of particulate P in equilibrium with dissolved P is available for aquatic biota. Thus, *bioavailable P* includes dissolved P and a

portion of particulate P. Once bioavailable P moves from agricultural fields into receiving waters it contributes to eutrophication.

Although generally considered a less important mechanism than surface runoff, P leaching followed by shallow lateral subsurface flow can contribute dissolved P to surface waters under high water table conditions. This mechanism becomes more important in soils with large accumulations of P (e.g. Fig. 1-2) that saturate surface soil sorption capacity leading to downward movement of P.

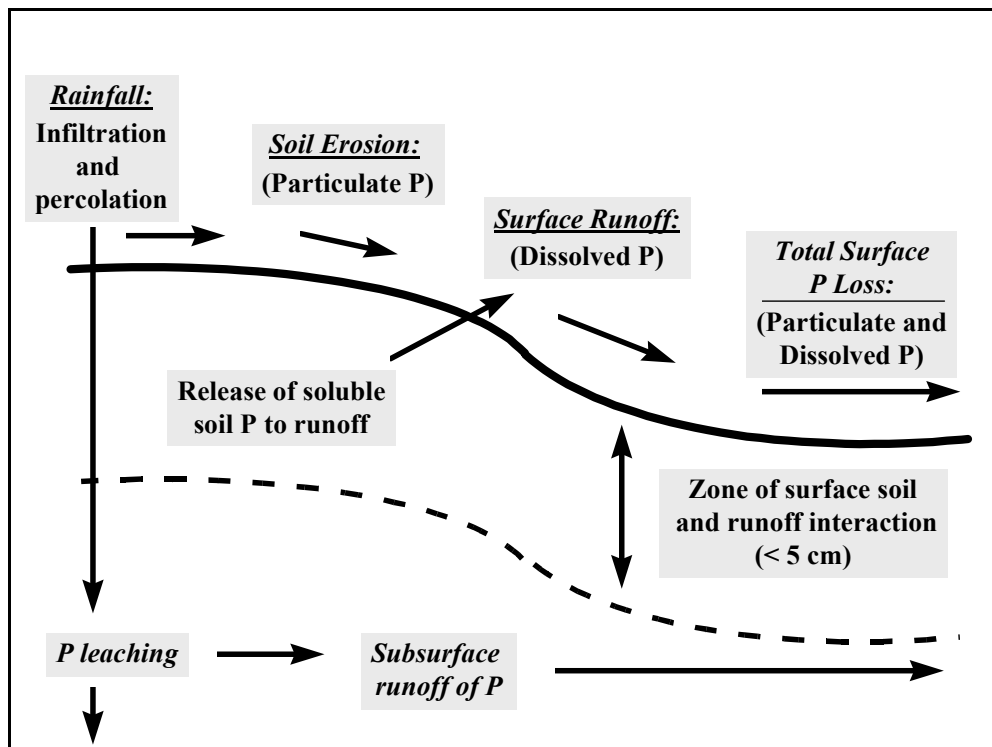


Figure 1-5. Transport processes for the movement of soil P to water.

MANAGING AGRICULTURAL PHOSPHORUS FOR WATER QUALITY: ROLE AND VALUE OF SOIL TESTING

Agronomic vs. Environmental Soil P Tests

Today, farmers, soil scientists and agronomists are faced with a dilemma over the coupling of agronomic and environmental concerns over soil P. That is, while soil P must be maintained at the “optimum” concentrations needed for good crop production, it is also vital to prevent escape of P to surface water bodies. Movement of P from soil to water is affected by a host of soil management practices (e.g., tillage method, cover crops, riparian zones, terracing, fertilizer and manure application rates and application practices, etc.). However, the soil P concentration that correlates with P

bioavailability is the greatest determinant of the balance between adequate soil P fertility and off-site P loss. In that regard, it can be argued that soil testing to assess the available P status of a soil is currently the best management tool available to ensure that crops are provided with adequate, but not excessive, supplies of P.

The importance of soil testing for P to agricultural profitability is unquestioned and the role of soil testing in protecting the environment is growing rapidly. Given this, the objectives of this bulletin are to inform the reader as to: (1) the current status of soil testing for P and its use in nutrient management programs; (2) improvements needed in environmental soil testing for P; and, (3) progress towards interpretation of soil test P results for environmental purposes.

LITERATURE CITED

- Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Environ. Qual.* 23: 139-147.
- Mozaffari, M., and J. T. Sims. 1994. Phosphorus availability and sorption in an Atlantic Coastal Plain watershed dominated by animal-based agriculture. *Soil Sci.* 157:97-107.
- Pierzynski, G.M., J.T. Sims, and G.F. Vance. 1994. *Soils and environmental quality*. Lewis Publ., Boca Raton, FL. 313 pp.
- PPI (Potash and Phosphate Institute). 1994. Soil test summaries: Phosphorus, potassium, and pH. *Better Crops Plant Food* 78:14-17.
- Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. *New England Water Works Assoc. J.* 61:109-127.
- Sharpley, A. N., T. C. Daniel, J. T. Sims, and D.H.Pote. 1996. Determining environmentally sound phosphorus levels. *J. Soil and Water Cons.* 51(2): 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. *J. Environ. Qual.* 13:211-215
- Terry, D.L., P.Z. Yu, and H.S. Spencer. 1996. *Commercial Fertilizers 1995*. Assoc. Amer. Plant Con. Off., Lexington, KY. 41 pp.
- USA vs South Florida Water Management District. 1994. U.S. District Court / Southern District, Case number 88-1880-CIV.
- USEPA. 1986. Quality criteria for water. Office of Water Regulation and Standards. EPA-440/5-86-001. May 1986.
- Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus. Pub. No. DAS/SAI/68.27. Organization for Economic Cooperation and Development, Directorate for Scientific Affairs, Paris, France.

Chapter 2: ***Soil Testing for Phosphorus: Current Status and Uses in Nutrient Management Programs***

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PRINCIPLES OF SOIL TESTING FOR PHOSPHORUS

Soil testing to determine the nutrient requirements for optimum plant growth began in the 19th century. Initial efforts used total soil analysis, until Daubeny (1845) developed the concept of *active* (readily available) and *dormant* (unavailable or slowly available) forms of plant nutrients in soils. This became the foundation for later soil testing efforts to develop chemical solutions (“*extractants*”) that could accurately measure plant available P in soils. Throughout the 20th century soil scientists and agronomists have conducted countless experiments to develop soil P tests for differing crops and soils. The fundamental objective of this research has been to identify the “*optimum*” soil P levels required for plant growth. The need for additional fertilization or manuring, and the economic return on an investment in fertilizer P, could then be predicted. Other objectives of soil testing have been to “*index*” the P supplying capacity of soils thus estimating the time before

fertilization would again be required, and to group soils, in terms of the likelihood of an economic response to P, based on their physical and chemical properties. Bray (1948) recognized the value of a systematic approach to soil testing and identified the following characteristics of a successful soil test extractant for P:

- The soil test should extract all or a proportionate amount of the plant available P from soils with differing chemical and mineralogical properties.
- The soil test should be accurate and rapid.
- The P extracted by the soil test should be well correlated with plant P concentration, plant growth and the response of the plant to added P in fertilizers or manures.
- The soil test should accurately detect differences in soil P concentrations caused by previous fertilization or manuring.

The major steps involved in a soil P testing program are outlined in Table 2-1. From an agronomic perspective, if these steps are followed, soil P management will be successful and economically beneficial.

However, as discussed below, and later in this publication, soil P testing for environmental purposes requires a thorough re-analysis of each step in the soil testing process, from sample collection to interpretation of results.

Table 2-1. Basic components in a soil testing program.

Soil Testing Component	Definition and General Considerations
Soil Sampling	<i>Collection of a sample that accurately represents the area of interest is the first step in an effective soil testing program. Soil samples are normally collected from the “topsoil” or “plow layer” (0-20 cm depth) although this may vary with type of crop and intent of the test. In most cases ~20-25 individual soil cores are collected from a field that is no larger than 10-15 hectares. These cores are then composited to produce one sample that is submitted to the laboratory for analysis. Soil sampling patterns should reflect natural differences in soils (e.g. soil series) and any management practices or historical activities likely to affect soil test results (e.g. crop rotation, manuring, tillage practice).</i>
Soil Sample Handling and Preparation	<i>Care should be taken during soil sample handling to avoid contamination from sampling and mixing devices. After collection, soil samples should be submitted to the laboratory as soon as possible where they are normally air-dried and ground prior to analysis. Providing as much information as possible with the sample (e.g. previous fertilizer use, intended management plans, soil series) helps to ensure receipt of an accurate recommendation.</i>
Soil Sample Analysis	<i>From an agronomic perspective, the purpose of soil analysis is to chemically “extract” the amount of nutrient from the soil that is proportional to that which will be available to the crop during the growing season. Since many different soil testing methods exist (see Table 2-2 for an overview of soil testing methods for P), it is vital that the analytical procedures selected are appropriate to the geographic region of interest and for the intended use of the soil.</i>
Interpretation of Analytical Results	<i>The ultimate goal of soil testing is to provide the user with a recommendation as to the likelihood that the application of nutrients in fertilizers or manures will provide a profitable increase in crop response. Recommendations based on soil testing results are developed using crop response data that has been obtained within a state or region with similar soils, cropping systems, and climatic conditions. Therefore, it is important to submit samples to a laboratory that is familiar with the crops to be grown and the soils and management practices that will be used.</i>

Phosphorus Soil Testing: New Questions

Soil scientists and agronomists have responded well to the challenge of identifying soils that need P fertilization. Today, however, new questions are emerging about soil P testing. In many crop production systems, particularly those dominated by intensive animal operations, soil P values are well beyond those required for plant growth, and are increasing due to the continued use of animal manures. Other agricultural systems, (e.g. intensive vegetable production, soils amended with sewage sludges, and specialty crops such as tobacco) have seen the same increases in soil test P. Using our current soil testing practices we can identify soils that are well above the “optimum” P concentrations needed for plant growth. We can even predict the length of time required to deplete these soils back to the optimum range should fertilization and organic waste use cease. Whether we can predict the environmental impact on water quality of soils with extremely high P values is another matter. It is, however, a difficult question now being addressed to the soil testing community by many in the U.S.

CURRENT STATUS OF PHOSPHORUS SOIL TESTING IN THE U.S.

Soil Testing Methods

Soil testing methods for P have always been based on the chemical reactions that control P availability in soils. Because these reactions can vary between soils in different physiographic regions, several distinctly different soil tests for P are now used in the

U.S. (Table 2-2). This is essential because the forms of plant available P vary with soil properties, particularly soil pH. For acid to neutral soils, aluminum (Al) and iron (Fe) bound P are the main sources of plant available P. The primary sources of P in calcareous soils are calcium phosphates and P adsorbed to the surface of calcium carbonates. As shown in Table 2-2, Kamprath and Watson (1980) classified soil tests for P into four general categories: (1) dilute concentrations of strong acids, (2) dilute concentrations of strong acids plus a complexing ion, (3) dilute concentrations of weak acids, and (4) buffered alkaline solutions.

Soil Test Interpretation

The purpose of soil test interpretation is to predict, based on the amount of P that can be chemically extracted from a soil, the likelihood that crop yield or quality will be sufficiently improved by the application of P to justify the costs involved. Most laboratories in the U.S. use the “*sufficiency level*” philosophy of soil test interpretation which states that the probability of a profitable response to additions of P can be accurately predicted from soil test P. Crops grown on soils testing below an established “critical value” for soil test P are more likely to respond than those testing above this value. Calibration studies are used to provide a quantitative relationship between soil test P and the statistical probability of an economic response to additions of P. A detailed discussion of the principles used to interpret soil test results for P is provided in Chapter 4 of this publication.

Table 2-2. Soil test extractants now used for phosphorus in the United States.

Soil Test Category	Common Soil Tests	Regions in the U.S. Where Commonly Used
<u>Dilute concentrations of strong acids:</u> Solvent nature of acids primarily extracts Al and Fe bound P, plus some Ca-P. Most appropriate for soils with pH < 7.0	Mehlich 1	Southeast and Mid-Atlantic .
<u>Dilute concentrations of strong acids plus a complexing ion:</u> These extractants remove P by both the solvent action of the acids and the complexing ability of the flouride ion for Al-P. Most effective on acidic soils.	Bray P1 Mehlich 3	<u>Bray:</u> North Central and Midwest <u>Mehlich 3:</u> Widespread use in the U.S.
<u>Dilute concentrations of weak acids:</u> Anion replacement	Morgan and Modified Morgan	Northeast
<u>Buffered Alkaline Solutions:</u> Extract P by hydrolysis of cations binding P. Also precipitate CaCO ₃ from calcareous, alkaline, and neutral soils, which reduces Ca concentration in solution, thus increasing P concentration in solution, so that it can be more easily and accurately measured	Olsen AB-DTPA	West and Northwest

USES OF PHOSPHORUS SOIL TESTING IN NUTRIENT MANAGEMENT PLANNING

Soil testing has become the primary source for data used in the site specific application and monitoring of nutrient management principles for the relatively non-mobile nutrients P, K, Mn, Cu and Zn. Advances in instrumentation and computerization of soil testing laboratories today allow for rapid summarization of soil testing results. It is now possible to readily track long-term trends in soil testing in a state or region and to determine if certain cropping systems or soil management practices are influencing soil chemical properties and thus crop growth and/or the environment. For planning purposes soil testing is used to identify the location and extent of P deficiency in both individual sampling units and broader geographic areas. Soil testing

also can help to identify management factors which result in P deficiency or excess accumulation. This critical information helps in the development of a nutrient management plan which considers source characteristics, placement and timing as well as rates to ensure adequate uptake by the crop without accumulation of nutrients to excessive levels in soils.

Identifying Extent and Location of P Deficiency or Excess

Farmers have always had to deal with nutrient management, but prior to widespread adoption of soil testing methods in the 1950's there was no quantitative data on which to base lime and nutrient recommendations for a specific site. Crop specific "recipes" were developed which essentially assumed all soils were equal in their requirements, and that variability between soils of different physical

and chemical properties could not be managed. Field calibration proved that soil testing methods were indeed reliable indicators of variability, and that site specific differences could be economically managed to produce higher crop yields and quality. With a knowledge of fertility status and the appropriate application rates required to produce economically justified yields, planning for a specific field or management unit became possible. Depending on the extent of soil test calibration available, interpretation (See Chapter 4) of soil test results and associated recommendations today usually vary with crop, soil, management factors (such as tillage) and climatic region.

Armed with soil test results, farmers could choose to strategically build nutrient status on fields with less than optimal amounts, and reduce or suspend application to fields with optimal or higher nutrient status in line with their economic criteria or other considerations. Many farmers now have their own micro-computer based nutrient management plans, a key component of which is long-term soil testing records. This approach is being further refined through use of global positioning satellite technology (GPS) to accurately locate smaller sampling units than previously possible. Through use of an intensive grid sampling pattern (often requiring 10 or more times as many sampling units) and geostatistical computer programs, growers are better able to capture the variability of fertility status within fields. By being able to accurately return to the same spot with fertilizer spreaders capable of varying rates on demand, nutrient applications can be matched more precisely to areas of needs and excess. For crops such as corn, small grains and soybeans, yield monitors can also be used to document yield variability by position in the field. Although much research remains to be done before these applications

prove themselves economically sound, they will no doubt result in further refinement of soil testing methods as they improve our ability to document the complex interactions between soil properties, soil test levels and crop yields. Eventually it may be possible to integrate soil testing data with other information (e.g. soils, topography, cropping systems, hydrology, and climate) through the use of geographic information systems (GIS) to identify areas where environmental problems associated with high P soils are most likely to occur.

Soil Test Summaries

Adoption of modern computer-based information processing by most soil testing laboratories allows rapid summarization of soil test results. Traditionally, the data necessary to link soil test results with a specific sampling unit has remained solely in the hands of the farmer or his crop advisor. While new regulations may require more detailed reporting, most soil testing facilities can accurately identify only the county in which a sampling unit is located. But even at a state or national level, soil test summaries can be very useful for needs assessment, problem recognition, planning, and evaluation. An example of the use of soil test summaries to provide a national perspective on the P status of agricultural soils was shown earlier in Figure 1-3. Using soil test information such as this, or more detailed summaries at regional or state scales can help to identify areas where high P soils predominate, a vital first step in determining what management practices are producing excess soil P, the likelihood that environmental problems from high P soils may occur, and the potential solutions available to prevent excess soil P from impacting water quality. Such information

allows tracking of trends in soil P status over time, and coupled with information on cropping systems, can provide relative impacts of various cropping and fertilization systems on soil nutrient status and potential water quality impacts.

At a county level, soil test results can lead to the discovery of problem areas. For example, in Georgia counties with large areas of Greenville sandy loam (a Typic Rhodudult of the Coastal Plain), soil test P results were consistently lower than in adjacent counties. Subsequent research confirmed that less P was extracted from these soils, which are high in colloidal iron, even though plant growth was optimal. This resulted in a lowering of the interpreted optimal level for this soil series. Similar information has been used to target county educational efforts for lime promotions based on the observed pH and lime sales figures in a county or state.

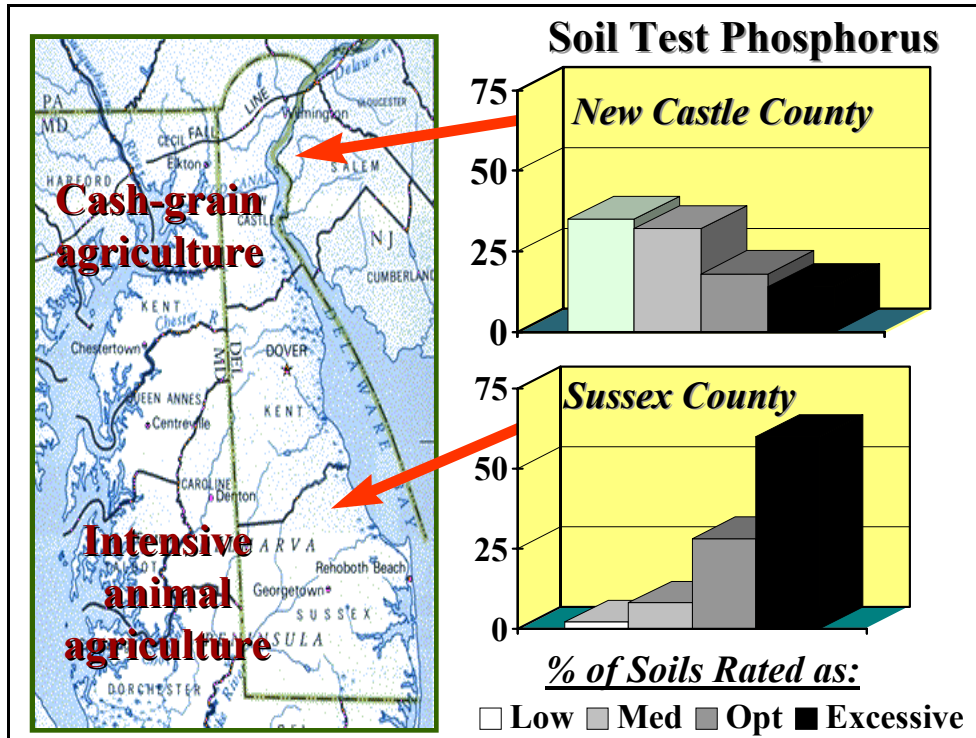
Above-optimum plant nutrient levels are frequently observed in counties with significant acreage of high value cash crops such as vegetables or tobacco. Tobacco was traditionally grown at low pH to reduce disease, resulting in reduced P availability. Over-compensation for this high value cash crop, especially after use of crop protection chemicals became widespread, has resulted in large accumulations of P in soils used for tobacco production.

With the growth of animal industries in recent years, soil test summaries have also been used to identify areas of potential environmental problems. The influence of animal based agriculture on soil test P levels in Delaware, site of one of the most concentrated areas of poultry production in the U.S can be demonstrated using county

level soil test results (Figure 2-1a). In New Castle County, where farmers rely on purchased P fertilizer for crop production, few soils are considered “excessive” in P. However, the intensive animal based agriculture in Sussex County, where poultry litter applications continuously add more P than is removed by crops, has created an agricultural setting that is dominated by soils in the optimum or excessive ranges.

In a similar situation in North Carolina Barker and Zublena (1995) used a combination of soil test results, agricultural statistics, and existing databases on manure generation and nutrient content to calculate average plant N, P, and K requirements and plant available nutrients produced in collectible manure for each county of North Carolina. The assumptions they used were conservative in that they tended to overestimate plant nutrient requirements and underestimate plant available manure. Crop requirements for flue cured tobacco, vegetables, soybean, and silviculture were not included. The crop nutrient requirements were compared with manure nutrient production in each county (Figure 2-1b). Statewide they found that 20% of the crop N and 66% of the P needs could be met by manure applications. Three counties had enough manure to exceed N demands, and 18 counties produced more P than required by the crops identified. This manure nutrient assessment has been an important tool in redirecting educational efforts and staffing needs within the North Carolina counties, and to increase awareness of nutrient accumulation in counties with concentrated animal production.

(a)



(b)

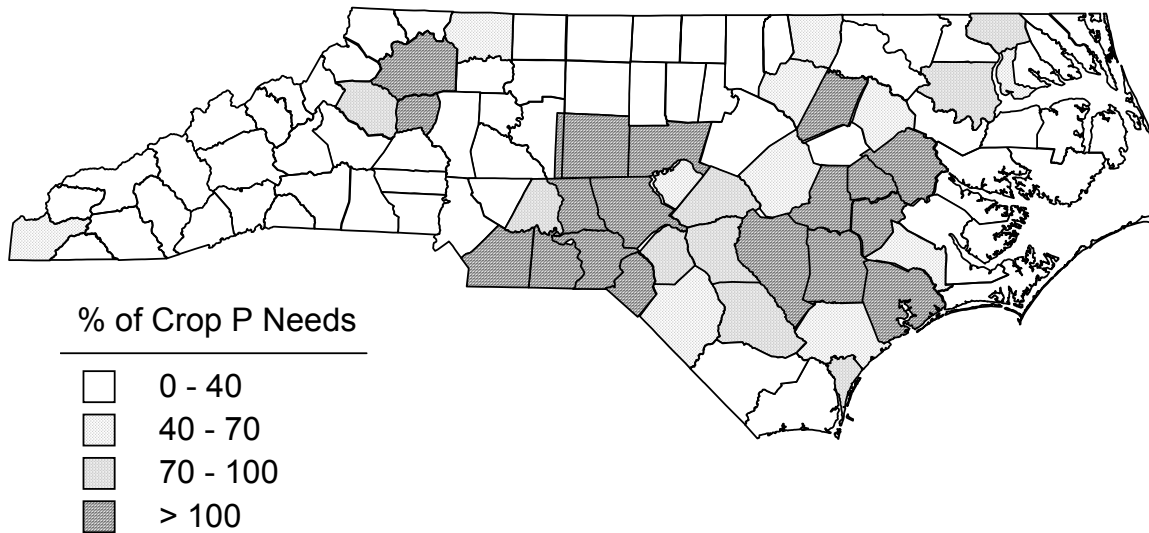


Figure 2-1. Soil test summaries for (a) Delaware, illustrating the difference in soil test P ratings between a county with few animals (New Castle County) and one with highly intensive poultry production (Sussex County) (Sims, 1997) and (b) Percentage of the crop P requirements in North Carolina counties that can be met by the plant available P provided by animal manures (Barker and Zublena, 1995).

National and Regional Soil Testing Efforts

Soil testing programs have many common goals and problems. Because of this individual laboratories, both public and private, have often joined together in regional or national committees and workgroups. Examples include the Soil and Plant Analysis Council (national organization affiliated with the American Society of Agronomy), NEC-67 (Northeast Coordinating Committee on Soil Testing), MASTPAWG (Mid-Atlantic Soil Testing and Plant Analysis Work Group), NCR-13 (North Central Soil Testing Committee), SERA-6 (Southeast Regional Committee on Soil Testing), and the Western States Soil Testing Proficiency Program. These organizations provide an excellent resource capable not only of providing current information and addressing soil testing issues, but of acting as a conduit by which advances in soil management research can be transferred to the agricultural community, advisory and regulatory agencies, and the public as a whole.

LITERATURE CITED

- Barker, J. C. and J. P. Zublena. 1995. Livestock manure nutrient assessment in North Carolina. Proc. 7th Intl. Symp. Agric. and Food Processing Wastes. June 18-20, Chicago, IL. Am. Soc. Agric. Eng. p. 98-106.
- Bray, R.H. 1948. Correlation of soil tests with crop response to fertilizers and with fertilizer requirement. p. 53-86 *In* H.B. Kitchen (ed.) Diagnostic techniques for soils and crops. Am. Potash Inst., Washington, D.C.
- Daubeny, C.G.B. 1845. Memoirs on the rotation of crops and on the quantity of inorganic matters abstracted from the soil by various plants under different circumstances. Roy. Soc. (London) Phil. Trans. 135:179-253.
- Kamprath, E. J. and M. E. Watson. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils. p. 433-469 *In* F. E. Khasawneh (ed.) The role of phosphorus in agriculture. American Society of Agronomy; Madison, WI.
- Sims, J. T. 1997. Agricultural and environmental issues in the management of poultry wastes: Recent innovations and long-term challenges. *In* J. Rechcigl (ed.) Uses of By-Products and Wastes in Agriculture. Am. Chem. Soc., Washington, D. C.

Chapter 3: *Improvements Needed in Environmental Soil Testing for Phosphorus*

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ENVIRONMENTAL SOIL TESTING FOR PHOSPHORUS

More than a century ago, Dyer (1894) stated that knowledge of the total amount of phosphorus (P) in soils was of limited practical value for agricultural production, whereas *readily available* P, extracted by a chemical solution could better predict if a soil needed P fertilization. Since that time, as discussed in Chapter 2, many chemical extractants have been used to assess plant available P in soils (Bray and Kurtz, 1945; Mehlich 1953; Mehlich, 1984; Morgan, 1941; Olsen et al., 1954).

More recently, given the concerns about the environmental impacts of agricultural P discussed in Chapter 1, there has been increased interest in using existing soil tests, or new soil testing methods, for environmental as well as agronomic purposes (Sims, 1993; Sharpley et al., 1994). A major reason for the increased interest in “*environmental soil testing*” for P has been that a considerable body of research now shows that the extractable P content of soils influences the amount of P in runoff water and subsurface drainage (Heckrath et al., 1996; Pote et al., 1996; Sharpley et al., 1977;

Sharpley et al., 1978; Sharpley et al., 1985; Sharpley et al., 1996; Sims et al., 1997), particularly if soil test P values exceed those needed for optimum crop growth. This has pointed to the need for soil testing methods that not only predict the probability of crop response to inputs of P, but that also can accurately quantify the likelihood that environmental problems will be caused by agricultural P (Figure 3-1).

The basic requirements for an environmental soil P test are the same as those for agronomic P tests. An environmental soil test for P should reproducibly extract all or a proportional amount of the P fraction in soils that is susceptible to surface runoff, leaching, or dissolution from eroded sediments. It should be fairly rapid and inexpensive but accuracy cannot be sacrificed for speed of analysis. There are some differences, however, between agronomic and environmental soil P tests and there are improvements needed in the environmental P tests that have been developed or proposed to date. This chapter addresses these points, focusing on the improvements needed in the methodology of environmental soil P testing.

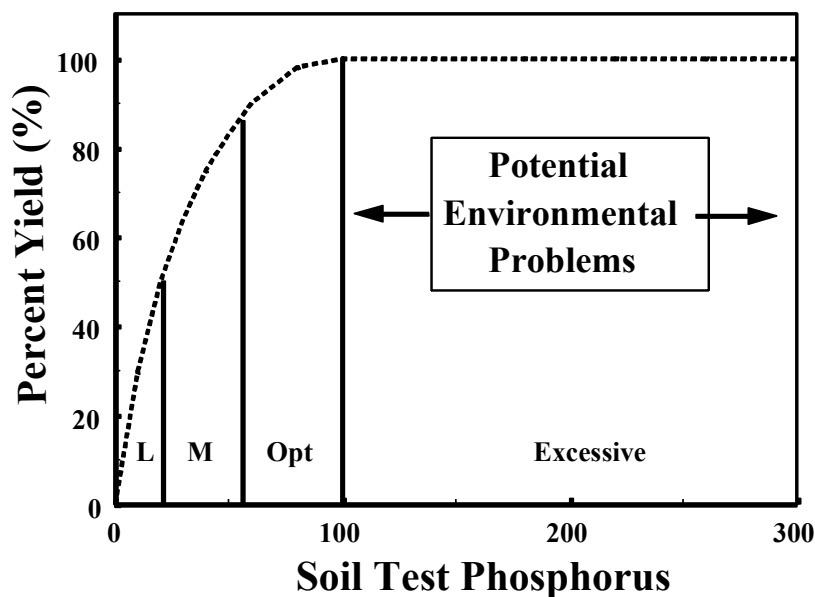


Figure 3-1. Relationship between soil test P (L=low, M=medium, Opt=optimum), crop response, and potential environmental impacts of P. Note that scale is in relative units.

**ENVIRONMENTAL SOIL TESTING
METHODS FOR PHOSPHORUS:
SAMPLING AND HANDLING**

When to Sample

To make an informed decision about the need for fertilizer or manure P in a given field, or the potential of a field to be a significant source of P loss from soil to water, we must first know the soil P status. Therefore, samples should be taken far enough in advance of application (2 to 3 months) to allow time for soil sample analysis, data interpretation, and the development of an optimum application strategy for P. It is also important to avoid sampling soils shortly after fertilizer or manure have been applied, particularly in reduced or no-tillage situations

where these materials are not incorporated thoroughly with the soil. Allowing time to pass between the application of P to a soil and sample collection permits soil chemical and biological P transformations to attenuate any recently added P and thus to more accurately characterize the environmentally important forms of soil P. The most reliable interpretations of soil P test results are also obtained if soil samples are collected at the same time each year (e.g. the fall).

Sampling Depth

Traditionally, soil samples have been taken to a depth of 15 to 20 cm, since this is the soil depth mixed by most tillage implements and also where most plant roots are found. However, for an environmental soil

P test the sampling depth may have to be much shallower or much deeper, depending on the information required. For example, if erosion or surface runoff of P is a primary concern, then the best depth of soil to sample may be very shallow (< 5 cm; Sharpley et al., 1978; Pote et al., 1996), since this is the zone of greatest interaction between soil and runoff water (see Figure 1-5). It may also be desirable to collect another sample at the normal sampling depth to determine the feasibility of reducing soil P concentrations in the shallow, runoff prone depths by deep tillage. Alternatively, if P leaching to ground water or loss in subsurface runoff through field drains and ditches is the primary concern, soil samples should be taken from greater depths to determine the extent of downward P movement in the soil. For example, in some European countries (Belgium, the Netherlands) the soil P status to a depth of 1 meter or to the depth of the mean high water table is used to determine the environmental risk of P loss via leaching and subsurface runoff.

Sample Handling and Storage

Soil samples used to determine plant nutrient availability are normally air-dried or oven-dried, ground, and sieved prior to analysis. This method of sample handling minimizes changes in nutrient availability from chemical and microbial activity that could occur after a sample has been collected. Drying may have a large influence on the results of an environmental soil P test if the method utilized is very sensitive. For example, Miller et al. (1993) showed that water soluble P extracted from dried soils was greater than that extracted from moist soils. They attributed the higher water soluble P levels in dried soils to P released from biological sources (microorganisms, plant roots) during the drying process. There is a

need to investigate this point further as most routine soil testing laboratories may find it difficult to reproducibly analyze moist soils. In general, there is a lack of research on the effects of sample handling (drying, grinding, and sieving) on the extractability of P from soil fractions that are believed to be of environmental importance.

ENVIRONMENTAL SOIL P TESTS: CURRENT OPTIONS

Using Agronomic Soil P Tests

The major soil P tests now used in the U.S. were described in Chapter 2 and include the Bray P₁, Mehlich 1, Mehlich 3, Morgan, and Olsen extractants. Each soil test was designed to estimate the amount of P available to plants in a given physiographic region. Because of the widespread use of these soil tests and the large data base they provide on soil P, interest has grown in using them for other purposes, such as to estimate the potential for P loss to surface waters. It is important to note, however, that these tests were developed to predict the likelihood of plant response to fertilizer P, hence other soil testing procedures may be more effective or appropriate for environmental purposes.

Encouragingly, initial research has shown that traditional agronomic soil tests for P are often well correlated with dissolved P and/or bioavailable P in runoff waters and subsurface drainage. For example, Wolf et al., (1985) reported that the equilibrium P concentration at zero sorption (EPC₀, a measure of desorbable P in most soils) and algal-available P (extracted by a 0.1M NaOH + 1 N NaCl solution) could be accurately predicted in a wide range of U.S. soils by the Bray P₁, Mehlich 1, and Olsen soil P tests (Figure 3-2).

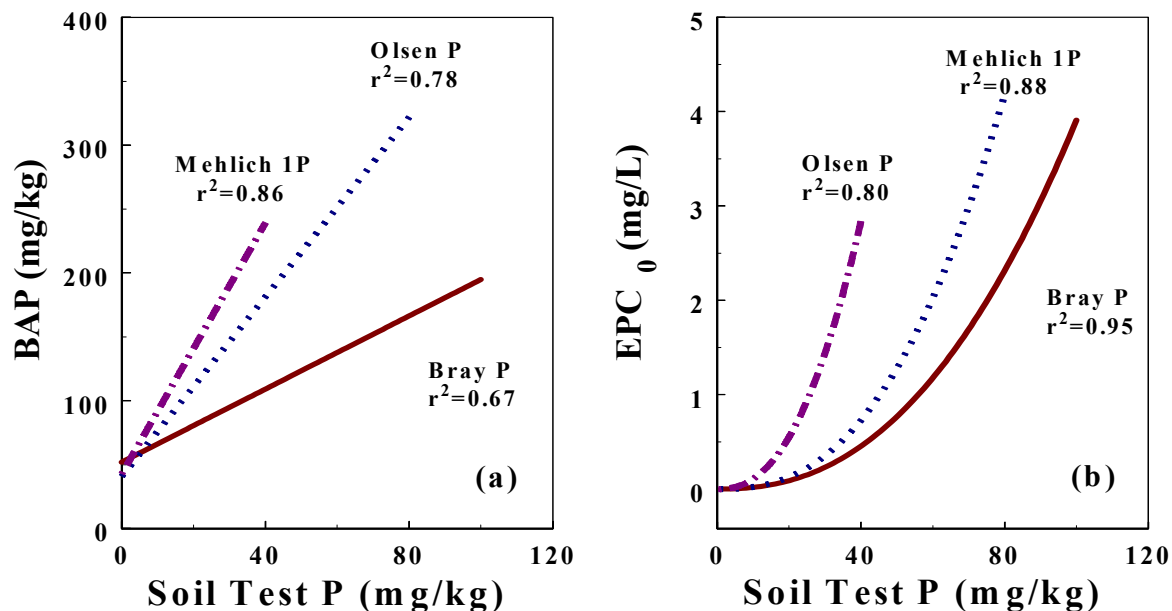


Figure 3-2. Relationship between soil test P and (a) biologically available P (BAP) and (b) the equilibrium P concentration at zero sorption (EPC₀). Adapted from Wolf et al., 1985.

Many other field and laboratory studies subsequently supported the results of these researchers and showed that traditional soil tests for P are positively correlated with dissolved P and/or bioavailable P in soils and/or in surface and subsurface runoff (Daniel et al., 1993; Heckrath et al., 1995; Pote et al. 1996; Provin, 1996; Sharpley, 1995; Sharpley et al., 1996; Simard et al., 1995; Sims et al., 1997; Smith et al., 1995). This is extremely encouraging as it clearly suggests that private and public soil testing laboratories can play an active role in environmental soil testing programs for P.

RECENT INNOVATIONS IN ENVIRONMENTAL SOIL TESTING FOR PHOSPHORUS

In addition to the use of agronomic soil tests, several new soil P test methods have been developed and tested to determine if they can accurately predict bioavailable P in runoff and/or P loss in leaching and subsurface runoff. Some of the most promising new methods are: (1) a method developed by Dutch scientists to determine the degree of P saturation in soils (Breeuswma et al., 1995), (2) a method that uses an iron oxide coated filter paper strip as an “infinite sink” to measure desorbable soil P (Chardon et al., 1996), and (3) a method that uses distilled water to extract readily desorbable soil P (Pote et al., 1996).

Degree of P Saturation

The amount of P that can be held by soils, referred to as the phosphate sorption capacity (PSC), is determined to a large degree by the amount of iron and aluminum oxides and hydroxides in acid soils and the amount of soluble Ca and calcium carbonate in alkaline soils. While the PSC of most soils is relatively high compared to the rates of P added in fertilizers and manures, a soil's PSC can become saturated if heavy applications of P fertilizers are applied year after year. In the Netherlands, where P leaching is a major problem, a new P soil test method has been developed, referred to as the degree of P saturation (*DPS*; Breeuwsma and Silva, 1992; Van der Zee and Van Riemsdijk, 1988). In this method, the P sorption capacity (PSC) of the soil is determined, along with the percent P saturation, as follows:

$$DPS (\%) = \frac{\text{Extractable P}}{\text{P Sorption Capacity}} \times 100$$

Where extractable soil P is determined by extraction with 0.2M ammonium oxalate, buffered to pH 3.0 with oxalic acid. The total PSC can be determined using standard P adsorption isotherms in combination with some measure of previously sorbed P, or estimated from the quantity of oxalate-extractable Al and Fe (Breeuwsma and Silva (1992). Estimating PSC by oxalate extraction is quicker, easier and less expensive than determining the P sorption capacity of each soil using adsorption isotherms. The Dutch consider a soil P saturated when 25% or more of PSC has been used. This level of P sorption saturation will likely result in ground water P concentrations above the 0.1 mg P L⁻¹ standard used in the Netherlands (Breeuwsma et al., 1995).

Recent work by Pote et al. (1996) showed that P concentrations in surface runoff from tall fescue plots with relatively high soil test P levels were highly correlated with the DS. Sharpley (1995) found a better relationship between dissolved and bioavailable P concentrations in runoff and DPS among different soil types than was found with Mehlich 3 P (Figure 3-3a and 3-3b). He concluded that the DPS approach integrates the effect of soil type with soil P content and better estimates P that may be lost from a soil than soil test P alone. It should be noted that this method would be very easy to adapt by modern soil testing facilities, since, with the widespread use of ICPs most laboratories are equipped for rapid multi-element analysis of a single solution (e.g. oxalate P, Al, Fe).

Iron Oxide “Strip” P (the *Pi* Soil Test)

Another method which shows promise as a means to assess the amount of P in soils that is subject to runoff or leaching is the iron oxide filter paper method, sometimes referred to as “strip P” or the “*Pi* soil test” (Chardon et al., 1996; Menon et al., 1997; Pote et al., 1996; Sharpley, 1991; Sharpley, 1993). In this method, a strip of filter paper is coated with Fe-oxide (a strong adsorbent for P), and placed with a soil sample in a centrifuge tube, followed by the addition of a dilute salt solution (e.g. 0.01M CaCl₂). The soil suspension is then shaken with the Fe-oxide strip for 16 h at which time the strip is removed, any soil adhering to the filter paper is washed off with deionized water, and the P sorbed by the Fe-oxide on the filter paper is extracted by dissolving the Fe-oxide with an acidic solution, and the desorbed P is measured, usually colorimetrically. In principle, the Fe-oxide strip acts as a “infinite sink” for the P that can be desorbed from a soil and thus measures the potential of a soil

to continue to release P during a runoff or leaching event. The mechanism of P recovery is essentially the same as that of anion exchange resins but the process is easier and less time consuming. Pote et al. (1996) found that this method accurately predicted the

quantity of P susceptible to runoff, better than most agronomic soil P tests. Sharpley (1993) also reported that Fe-oxide “strip P” was a good indicator of the biological availability of P in runoff waters to algae.

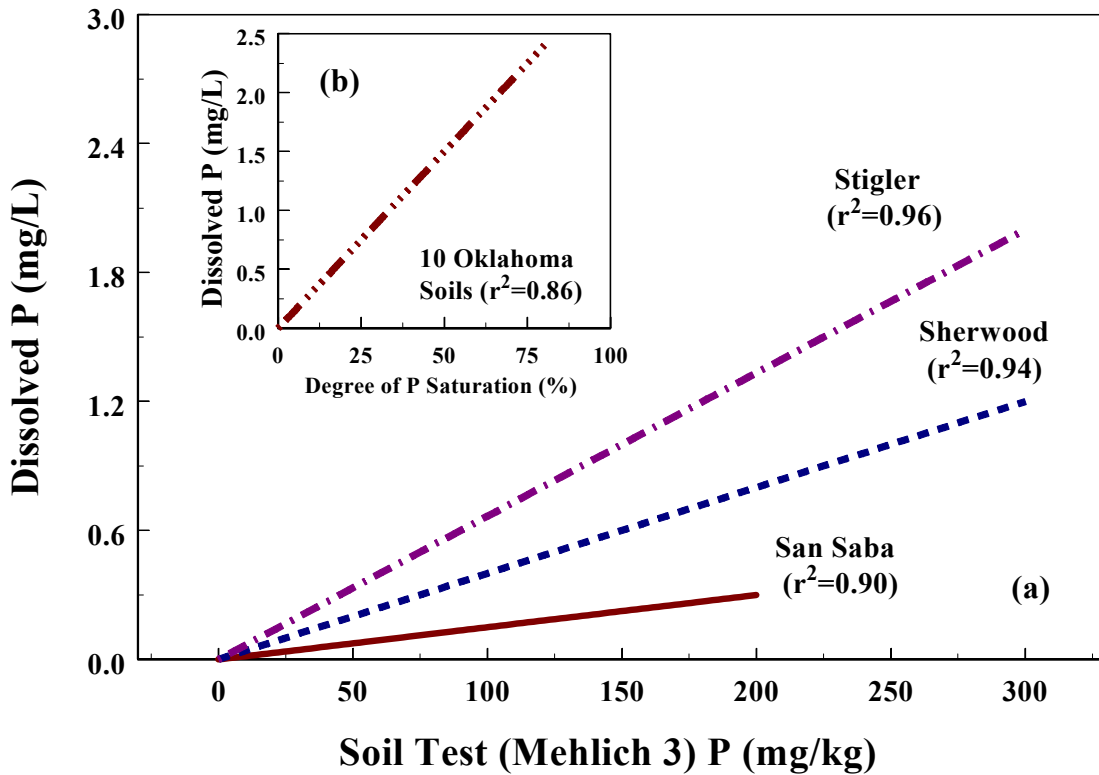


Figure 3-3. Relationship between dissolved P and (a) Mehlich 3 or (b) DPS. Adapted from Sharpley (1995).

Water Soluble P

Phosphorus can also be extracted from soils using distilled or deionized water which would be expected to simulate the rapid release of P to runoff water better than stronger chemical extractants (e.g. agronomic soil P tests), since rainfall is very similar to distilled water. Other advantages of this method are the low cost, and relatively quick

extraction time (usually 1 h, compared to 16 h for “strip P”). This extraction should also maintain the soil pH within one unit of its original value, also a desirable attribute since P solubility is highly dependent upon soil pH (Golterman, 1988; Sharpley, 1993). Pote et al., (1996) showed, in a field study with tall fescue that water soluble P was well correlated with runoff P (Figure 3-4).

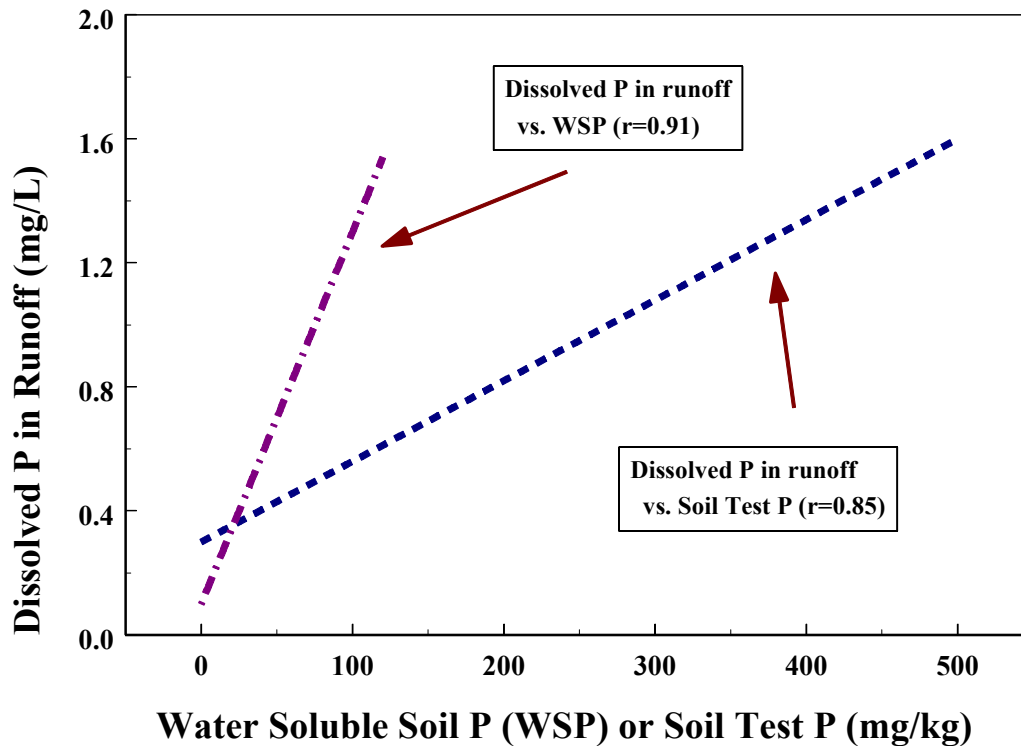


Figure 3-4. Relationship between dissolved P in runoff from tall fescue pastures in Arkansas and either water soluble P (WSP) or soil test P. Adapted from Pote et al., (1996).

LITERATURE CITED

- Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 59:39-45.
- Breeuwsma, A. and S. Silva. 1992. Phosphorus fertilisation and environmental effects in The Netherlands and the Po region (Italy). Report 57. DLO The Winand Staring Centre, Wageningen, The Netherlands.
- Breeuwsma, A., J.G.A. Reijerink, and O.F. Schoumans. 1995. Impact of manure on accumulation and leaching of phosphate in areas of intensive livestock farming. p. 239-251. *In* K. Steele (ed.) *Animal waste and the land-water interface*. Lewis Publishers-CRC, New York, NY.
- Chardon, W. J., R. G. Menon, and S. H. Chien. 1996. Iron oxide impregnated filter paper (Pi test): A review of its development and methodological research. *Nutr. Cycl. Agroecosystems* 46:41-51.
- Daniel, T.C., D.R. Edwards, and A.N. Sharpley. 1993. Effect of extractable soil surface phosphorus on runoff water quality. *Trans. ASAE* 36:1079-1085.
- Golterman, H.L. 1988. Reflections on fractionation and bioavailability of sediment bound phosphate. *Arch. Hydrobiol.* 30:1-4.
- Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. *J. Environ. Qual.* 24:904-910.
- Mehlich, A. 1953. Determination of P, Ca, M, K, Na, and NH₄. North Carolina Soil Test Division (Mimeo 1953).
- Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* 15:1409-1416.
- Menon, R. G., S. H. Chien, and W. J. Chardon. 1997. Iron oxide impregnated filter paper (Pi test): II. A review of its application. *Nutr. Cycl. Agroecosystems* 47:7-18.
- Miller, D.M., P.A. Moore, Jr., D.R. Edwards, D.S. Stephen, and E.E. Gbur. 1993. Determination of water soluble phosphorus in soil. *Arkansas Farm Research* 42:10-11.
- Morgan, M.F. 1941. Chemical soil diagnosis by the universal testing system. *Conn. Agric. Exp. Stn. Bull.* 450.
- Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extracting with sodium bicarbonate. *USDA Circ.* 939. U.S. Gov. Print. Office, Washington, D.C.
- Olsen, S.R., and F.E. Khasawneh. 1980. Use and limitations of physical-chemical criteria for assessing the status of phosphorus in soils. pp. 361-410. *In* F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds) *The Role of Phosphorus in Agriculture*. American Society of Agronomy, Madison, WI.
- Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. *Soil Sci. Soc. Am. J.* 60:855-859.

- Provin, T.L. 1996. Phosphorus retention in Indiana soils. Ph.D. Dissertation. Purdue University, West Lafayette, IN.
- Sharpley, A.N. 1985. Depth of surface soil-runoff interaction as affected by rainfall, soil slope and management. *Soil Sci. Soc. Am. J.* 49:1527-1534.
- Sharpley, A.N. 1991. Soil phosphorus extracted by Fe-Al-oxide-impregnated filter paper. *Soil Sci. Soc. Am. J.* 55:1038-1041.
- Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff by Fe oxide-impregnated paper. *J. Environ. Qual.* 22:597-601.
- Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. *J. Environ. Qual.* 24:920-9926.
- 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. *J. Environ. Qual.* 23:437-471.
- Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. *J. Soil and Water Conserv.* 51:160-166.
- Sharpley, A.N., S.J. Smith, W.A. Berg, and J.R. Williams. 1985. Nutrient runoff losses as predicted by annual and monthly soil sampling. *J. Environ. Qual.* 14:354-360.
- Sharpley, A.N., J.K. Syers, and R.W. Tillman. 1978. An improved soil-sampling procedure for the prediction of dissolved inorganic phosphate concentrations in surface runoff from pasture. *J. Environ. Qual.* 7:455-456.
- Sharpley, A.N., R.W. Tillman and J.K. Syers. 1977. Use of laboratory extraction data to predict losses of dissolved inorganic phosphate in surface runoff and tile drainage. *J. Environ. Qual.* 6:33-36.
- Simard, R.R., D. Cluis, G. Gangbazo, and S. Beauchemin. 1995. Phosphorus status of forest and agricultural soils from a watershed of high animal density. *J. Environ. Qual.* 24:1010-1017
- Sims, J. T. 1993. Environmental soil testing for phosphorus. *J. Prod. Agric.* 6:501-507.
- Sims, J. T., R. R. Simard, and B. C. Joern. 1997. Phosphorus losses in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* *In Press.*
- Smith, R.V., S.D. Lennox, C. Jordan, R.H. Foy, and E. McHale. 1995. Increase in soluble phosphorus transported in drainflow from a grassland catchment in response to soil phosphorus accumulation. *Soil Use Mgmt.* 11:204-209.
- Van der Zee, S. E. A. T. M. and W. H. van Riemsdijk. 1988. Model for long-term phosphate reactions in soil. *J. Environ. Qual.* 17:35-41.
- Wolf, A.M., D.E. Baker, H.B. Pionke, and H.M. Kunishi. 1985. Soil tests for estimating labile, soluble, and algae-available phosphorus in agricultural soils. *J. Environ. Qual.* 14:341-348.

Chapter 4: ***Interpreting Soil Test Phosphorus for Environmental Purposes***

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INTERPRETING SOIL TEST PHOSPHORUS FOR ENVIRONMENTAL PURPOSES: ISSUES AND OBSTACLES

The ultimate objective of soil testing today, for any land management situation, is to provide recommendations that are profitable and environmentally sound. Soil test *interpretation* refers to the process by which analytical results are translated into field scale recommendations for nutrient management. Recently, several critical issues have arisen as the emphasis on soil test interpretation for phosphorus (P) has begun to focus on environmental as well as agronomic concerns. These include:

C How do we revise our definition and interpretation of “critical values” for soil test P when our concern is surface water quality and not crop yield response? Simply attaching an environmental meaning to interpretations originally based on crop yield responses to inputs of P certainly overlooks many important

factors that contribute to the potential for agricultural P to have an environmental impact. It seems unlikely that the soil test P values shown to be “low”, “optimum” or “excessive” for crop production will be our best indication of the potential for agricultural runoff to cause surface water eutrophication. The site specific nature of the land and water factors that control P movement from soil to water in runoff and erosion will very likely result in the need for flexible critical values for soil test P that are more carefully linked to site management, hydrology, and surface water response.

C Can we achieve an acceptable balance between agronomic and environmental interpretations for soil test P? Will the soil P values needed to ensure optimum economic yields conflict with those required to minimize the enrichment of surface waters by agricultural P?

- C How do we decide what soil P tests will best provide us with the data that address our concerns with surface water quality? Beyond this how can we ensure that soil testing laboratories adopt these tests and interpret them correctly?

While these questions are admittedly complex, there have been advances in soil test interpretation, discussed in detail below, that can help to resolve some of these issues.

***INTERPRETING SOIL TEST
PHOSPHORUS FOR
ENVIRONMENTAL PURPOSES:
TRADITIONAL CROP RESPONSE
INTERPRETATIONS***

From an agronomic perspective it has long been known that the amount of a nutrient extracted by recommended soil test method correlates with the availability of that nutrient to a crop. The strength of this correlation is the basis for selecting a particular soil test extractant for a given combination of soil, crop, and growing conditions. To interpret a soil test we must know the quantitative nature of the relationship between the amount of a nutrient extracted by a given soil test and the expected crop response for each crop of interest. The process of determining the degree of limitation to crop growth or the probability of getting growth response to an applied nutrient at a given soil test level is referred to as *soil test calibration*. The most effective procedure for calibrating a soil test is to conduct multi-year, multi-site field studies where the crop of interest is grown on soils representative of those where the test will be used that cover the range of extractable nutrients likely to be encountered. This must be done for each crop with which the soil test

will be used. From these experiments, either the yield or the relative yield of the crop can be related to the amount of nutrient extracted by the soil test, as illustrated in Figure 4-1.

While the exact relationship between soil test level and yield or relative yield will vary considerably among crops and soil tests, the general nature of this relationship is relatively consistent (Figure 4-1). At low levels of extractable nutrients the yield is limited by lack of the nutrient. As the soil test level increases, yield increases until a point is reached where the nutrient no longer limits yield and thus the response to the nutrient diminishes and eventually ceases to occur. Above this level there is no longer a relationship between the extractable amount of the nutrient and yield. At very high soil test levels the yield may actually decline. The point where the curve initially plateaus is called the *critical level*. This is the soil test value that produces the best separation between responsive soils (where a profitable crop yield response to nutrient inputs will occur) from those where the nutrient no longer limits yield. The soil test response curve is often used to further divide the range in soil test values commonly found in an area into several categories, such as *below optimum*, *optimum*, and *above optimum* (Figures 3-1 and 4-2). Each category has both a qualitative meaning (i.e. indicates probability of economic response to nutrient inputs) and a quantitative use (i.e. determines rate of nutrient that will be recommended). The general definitions now used to interpret soil tests, based on the likelihood of an economic crop response, are given in Table 4-1. These definitions were developed by several regional soil test committees and work groups to standardize the terminology of soil test interpretation.

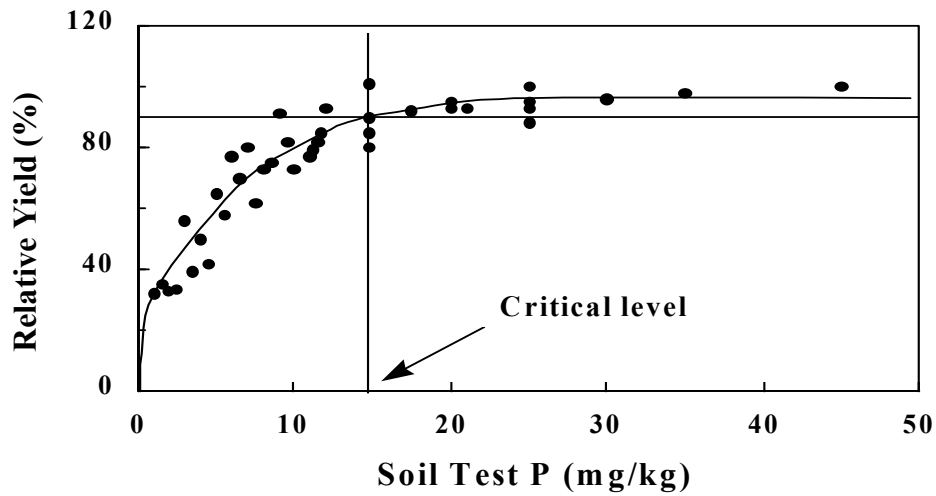


Figure 4-1. Relative yield vs. soil test P showing the response curve and graphical separation of the data into responsive and non-responsive populations.

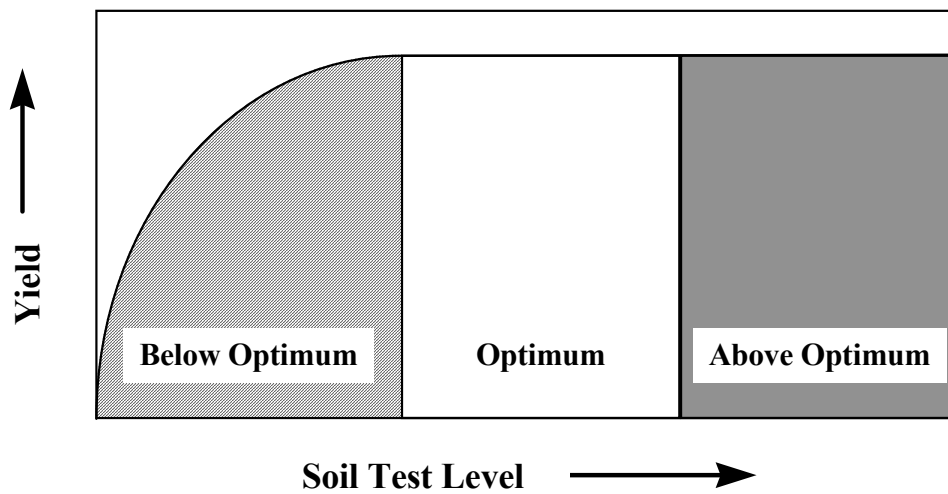


Figure 4-2. Response curve used to divide soil test values into categories related to the probability of an economic response to fertilization.

The preceding description of soil test calibration and interpretation process has been simplified to illustrate major concepts. In the real world there are many issues that must be addressed to understand the full implications of interpreting the results of a soil test. It is clear that there is a relationship between soil nutrient levels and crop production, as described above, but there are

also other factors that influence crop growth. These other factors may act independently or they may interact with soil nutrient levels to influence crop growth and yield (e.g. soil temperature may affect soil P availability to plants). A thorough understanding of crop response to nutrients and the effects of these other factors on this response is necessary to completely interpret a soil test result.

Table 4-1. Definitions of proposed soil test categories for crop response.

Category Name (Commonly used terms)	Category Definition	Recommendations
A. Crop Response		
Below Optimum (Very Low, Low, Medium)	The nutrient is considered deficient and will probably limit crop yield. There is a high to moderate probability of an economic yield response to adding the nutrient.	Recommendations are based on crop response and should build the soil into the optimum range over time. Starter fertilizer is recommended as appropriate.
Optimum, (Sufficient, Adequate)	The nutrient is considered adequate and will probably not limit crop growth. There is a low probability of an economic yield response to adding the nutrient.	If soils are tested annually no nutrient additions are needed for the current crop. For other than annual soil testing nutrient applications are often recommended to maintain the soil in the optimum range. Starter fertilizer may be recommended as appropriate.
Above Optimum (High, Very High, Excessive)	The nutrient is considered more than adequate and will not limit crop yield. There is a very low probability of an economic yield response to adding the nutrient. At very high levels there is the possibility of a negative impact on the crop if nutrients are added.	No nutrient additions are recommended. At very high levels remedial action may be required.
B. Environmental Response		
Potential negative environmental impact	There is the possibility that soils testing above this level may result in environmental degradation. This soil test level is independent of the crop response categories in part (A) of this table and may be above or even below the optimum level based on crop response. This level may vary depending on several other site specific characteristics (e.g. slope, hydrology).	If other site factors minimize environmental impact, nutrient additions may be recommended under crop response guidelines. If other site factors indicate a potential environmental impact, no nutrient additions including starter fertilizer are recommended. Remedial action to protect the environment may be required.

**INTERPRETING SOIL TEST
PHOSPHORUS FOR
ENVIRONMENTAL PURPOSES:
ENVIRONMENTAL
INTERPRETATIONS**

Defining “environmental impact”, as in Table 4-1, may seem fairly straightforward, but in fact it is very difficult and often controversial to define such a soil test category, for several reasons. First we need to ask whether routine soil test extractants, designed to assess plant availability of P, measure the forms of soil P that are most important to eutrophication, or other negative environmental impacts on water quality? If the soil test is appropriate, what should be the quantitative basis for interpreting the results for environmental purposes? Some would simply extend soil test P values used to predict crop response to environmental interpretations. In this case it is argued that soil test P values above the level where crop response is expected have a greater potential to cause surface water pollution and thus should be evaluated from an environmental, not an agronomic perspective. However, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to nutrients and nutrient pollution potential. The critical soil test level for pollution may be above or even below the critical level for crop response. If soil tests are to be properly interpreted for predicting the probability of nutrient pollution, calibrations that specifically relate the soil test to some measure of environmental response, such as P loss in runoff, will be necessary.

Unfortunately, the calibration of soil P with regard to the potential for an “environmental impact” on surface water quality is more difficult than for crop yield response. There are several reasons for this.

First, there can often be differences of opinion (scientific and political) on how to define an acceptable or unacceptable “environmental impact”. Second, there is an inadequate data base in most geographic areas to define the relationship between soil test P and P concentrations in erosion and runoff (surface and subsurface). Finally, at present there is no readily usable means to clearly integrate soil P with other site characteristics (slope, drainage, hydrology, soil type) that affect overall P loss to surface waters.

Relating Soil P and P Losses to Water

As discussed in previous chapters, the trophic state (degree of biological productivity) of most surface waters usually increases as the total P concentration in a water body increases. Establishment of unacceptable P concentrations in agricultural runoff (surface and subsurface) that will contribute to eutrophication is an important first step in the development of environmental interpretations for soil P. However, it is important to note that the P concentrations in runoff that are environmentally unacceptable will vary depending on factors such as the proximity of a P-sensitive water body, intended uses of the water (e.g. recreation, fishing, drinking water), and many socio-economic factors associated with land use.

Once an unacceptable P concentration in runoff waters has been established for a given physiographic region the critical soil test P value that has the potential to cause this concentration can be determined (Figure 4-3). The data in Figure 4-3 are from several studies that found P losses in runoff became greater as soil test P values in the upper two inches of the soil increased. Note that this environmental critical level for soil test P is likely to be site-specific and may be above or below agronomic critical values for soil test P.

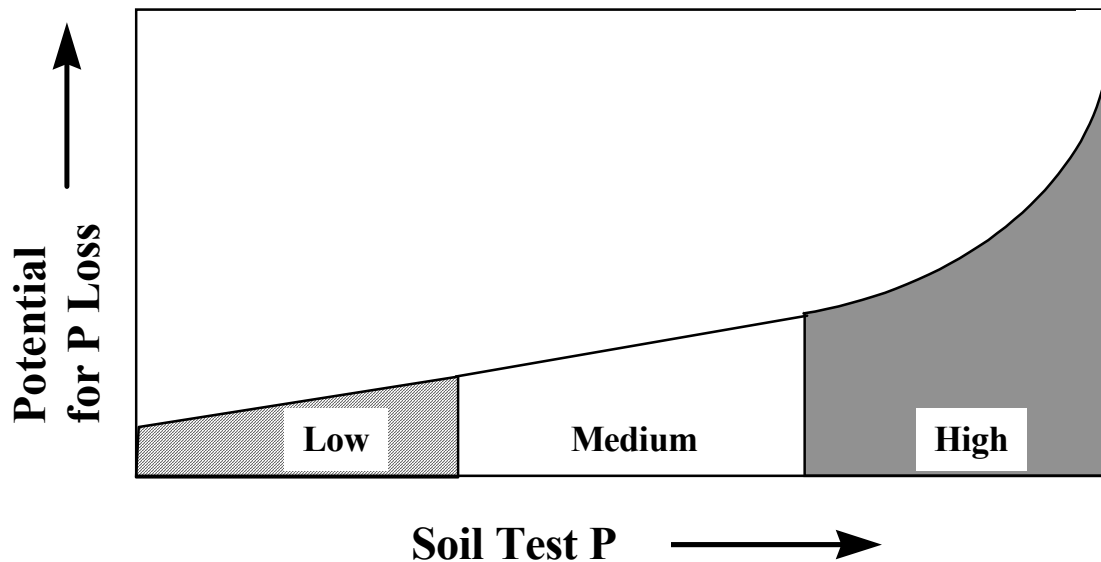


Figure 4-3. The potential for P loss in runoff increases as soil test P (0-5 cm depth) increases.

While the process of establishing upper critical limits for soil test P may seem logical and rather straightforward, it can often become highly controversial, for several reasons. First, the data base relating soil test P to runoff P is limited to a few soils and crops and local scientists or advisory agencies are often reluctant to rely too heavily upon soil test P - runoff P data generated in other states or regions. However, it is extremely time-consuming and costly to obtain data on P loss in runoff and unrealistic to expect that a large data base relating soil test P to runoff P, will be available in the near future. Because of this, one role soil testing laboratories could play in improved soil P management would be to provide predictions of “readily desorbed P”, based on soil test P and other routinely measured soil properties (e.g., pH or buffer pH, organic matter content). These data could then be integrated with other site specific information related to runoff volume to rate the potential of individual fields to be

significant sources of P to nearby surface waters. Second, the economic implications of establishing soil test P levels which limit the applications of animal manures, or other “biosolids” to agricultural lands are far-reaching. In many areas dominated by animal-based agriculture, there is simply no economically viable alternative to land application. Because of this, it is essential for long-term sustainable management of agricultural P that workable water quality criteria be proposed initially. The phasing-in of environmental controls to meet these criteria, such as changes in fertilizer or animal manure management, should promote wider acceptance and compliance of these practices by farmers without creating severe economic hardships within rural communities. Establishing interim goals for soil and runoff P allows time to develop the more comprehensive solutions to the problems of P management common to animal-based agriculture.

Site Characteristics

Surface transport processes (erosion, runoff) are normally the main mechanisms by which P is exported from watersheds. In some cases, however, the subsurface transport of P can be significant as well (e.g. loss in tile or ditch drainage). In the absence of a significant transport process, P loss can be expected to be negligible. Thus, consideration of the methods to control P transport by runoff, erosion and drainage is critical to a more detailed understanding of P loss from watersheds and ultimately to the development of an acceptable environmental soil P test. Runoff (surface and subsurface), and erosion, are dynamic and highly variable processes both temporally and spatially. As a result, about 90% of the P lost from watersheds annually, generally occurs from

less than 10% of the watershed during one or two storms.

While soil test P is related to P concentrations of runoff, different amounts of P can be lost from sites with similar surface soil test P contents (Figure 4-4). Several studies have shown that site characteristics such as slope and vegetative cover can have an overriding effect on P loss in runoff and erosion. Thus, P loss from fields with similar soil test P values can vary greatly as a function of soil management practices and any climatic, topographic, and agronomic factors that affect runoff and erosion (Figure 4-4). Thus, a more comprehensive approach than just a soil P test will ultimately be needed for reliable, yet flexible recommendations of the environmental impact of P management.

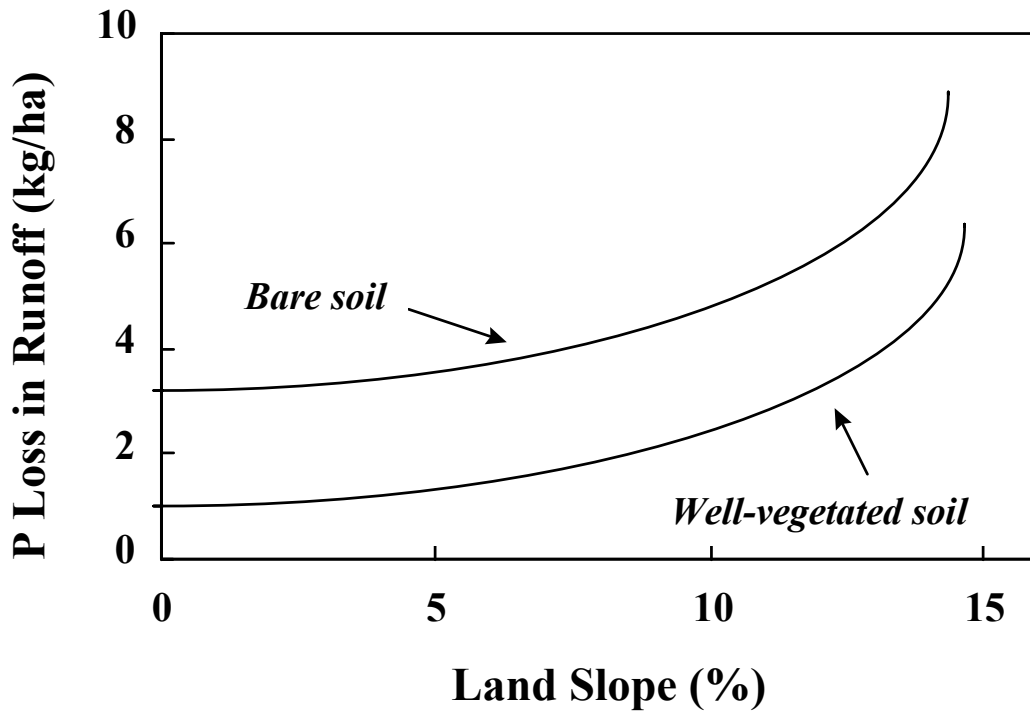


Figure 4-4. The loss of P in runoff from fields with similar soil test P values will vary with site characteristics such as slope and vegetative cover.

Given this, any quantitative assessment of the potential for an agricultural field to have an environmental impact on surface waters must integrate soil test P with factors describing site vulnerability to P loss based on runoff and erosion potential and site management (Figure 4-5). For example, adjacent fields having similar soil test P levels but differing susceptibilities to runoff and erosion, due to contrasting topography and management, should not have similar P recommendations. Indeed any environmental soil P test need not be conducted on all soils but could be

selectively directed towards samples from areas with high potential for P losses in runoff or erosion. Fields for more intensive sampling and testing could be identified based on data available in routine agronomic soil tests and supplemental information related to the potential for runoff and erosion such as field estimates of slope degree, length, and extent of vegetative cover. Once high-risk areas are known, more specific tests (e.g., readily desorbable P, Fe-oxide strip P, biologically available P, and DPS - see Chapter 3) can be conducted on the most erosion or runoff prone areas.

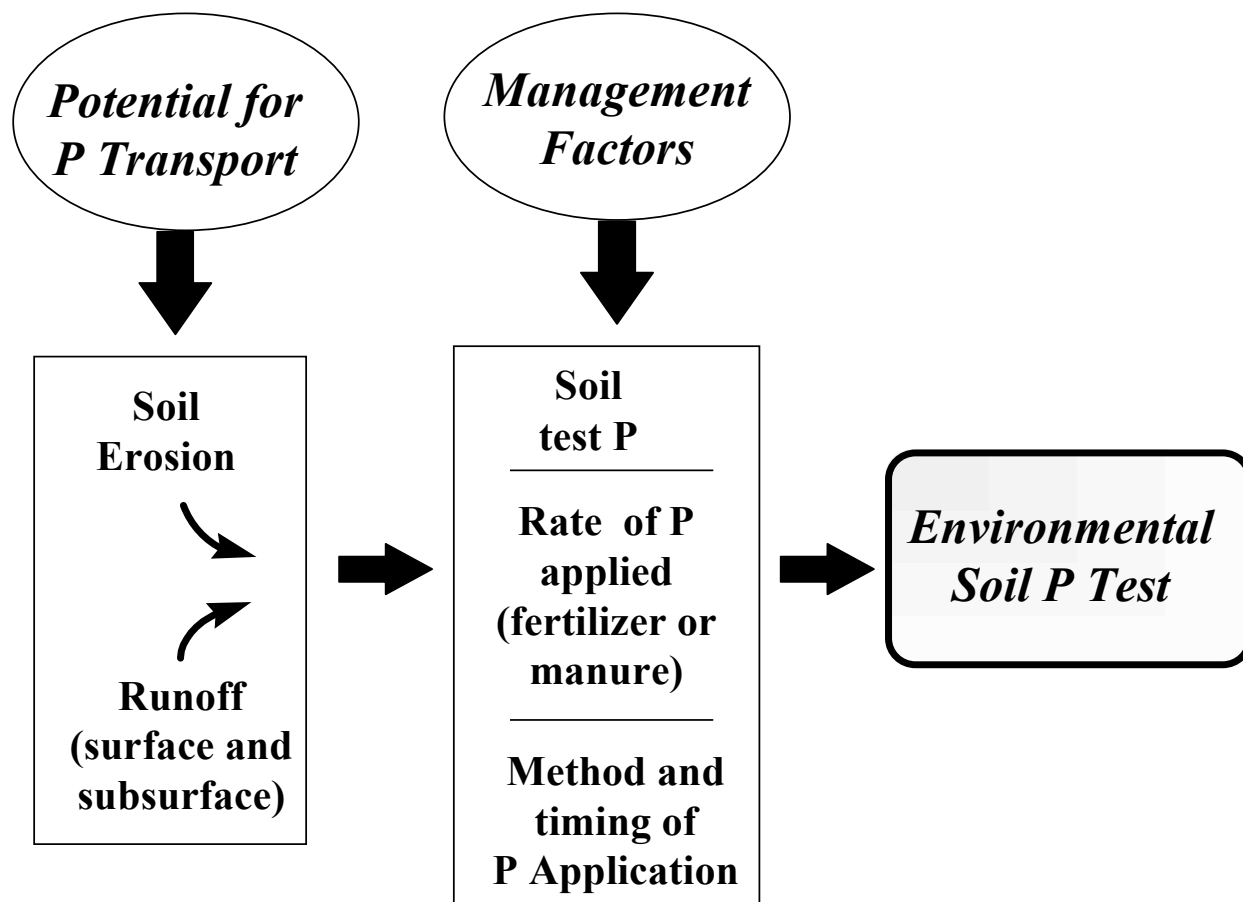


Figure 4-5. Development of an environmental soil P test must integrate soil management factors with those that affect P transport from soil to water.

The Phosphorus Index

As discussed in the Preface of this publication the USDA Natural Resources Conservation Service (USDA-NRCS) formed a national work group in 1990 of scientists from Universities, Cooperative Extension, and the USDA Agricultural Research Service to develop a P indexing procedure that could identify soils, landforms, and management practices with the potential for unfavorable impacts on water bodies because of P losses from agricultural soils. This indexing system integrates soil test P with many of the factors described above that affect P transport from soils to water. It is a practical example of the concepts illustrated in Figure 4-5, one that has been used in several states in the U.S. to improve soil P management for surface water protection. A description of this field rating system, referred to as the *Phosphorus Index*, is provided below and in Table 4-2. More detailed information is available in some of the references given at the end of this chapter (Lemunyon and Gilbert, 1993; Sharpley, 1995; Sims, 1996).

Using the Phosphorus Index

The *P Index* uses eight characteristics to obtain an overall rating for a site (Table 4-2). Each characteristic is assigned an interpretive *rating* with a corresponding numerical *value*: LOW (1), MEDIUM (2), HIGH (4), or VERY HIGH (8), based on the relationship between the characteristic and the potential for P loss from a site. Suggested ranges appropriate to each rating for a site characteristic are then assigned. Each of the characteristics in the *P Index* has also been given a *weighting factor* which reflects its relative importance to P loss. For instance, erosion (*weighting factor*=1.5) is generally more important to P loss than P fertilizer application method (*weighting factor*=0.5). At present, the weighting factors used are based on the professional judgment of the scientists that developed the *P Index*; they are not derived directly from field research with the *P Index*. Individual states or regions should modify the weighting factors as appropriate, based on local soil properties, hydrologic conditions and agricultural management practices.

LITERATURE CITED

Lemunyon, J. L., and R. G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. *J. Prod. Agric.* 6:483-486.

Sharpley, A.N. 1995. Identifying sites vulnerable to phosphorus loss on agricultural runoff. *J. Environ. Qual.* 24:947-951

Sims, J. T. 1996. The Phosphorus Index: A phosphorus management strategy for Delaware's agricultural soils. Soil Testing Fact Sheet ST-05, Univ. of Delaware College Agric. Sci., Newark, DE

SITE CHARACTERISTIC (Weighting Factor)	PHOSPHORUS LOSS RATING (Value)				
	NONE (0)	LOW (1)	MEDIUM (2)	HIGH (4)	VERY HIGH (8)
Soil Erosion (1.5)	N/A	< 5 T/A	5-10 T/A	10-15 T/A	> 15 T/A
Irrigation Erosion (1.5)	N/A	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes < 5%	Frequent irrigation on soils with slopes of 2-5%	Frequent irrigation on soils with slopes > 5%
Soil Runoff Class (0.5)	N/A	Very Low or Low	Medium	High	Very High
Soil Test P (1.0)	N/A	Low	Medium	High	Excessive
P Fertilizer Rate (kg P/ha) (0.75)	None Applied	< 15	15-45	46-75	> 75
P Fertilizer Application Method (0.5)	None Applied	Placed with planter deeper than 5 cm	Incorporate immediately before crop	Incorporate > 3 months before crop or surface applied > 3 months before crop	Surface applied > 3 months before crop
Organic P Source Application Rate (kg P/ha) (1.0)	None Applied	< 15	15-45	46-75	> 75
Organic P Source Application Method (1.0)	None	Injected deeper than 5 cm	Incorporate immediately before crop	Incorporate > 3 months before crop or surface applied < 3 months before crop	Surface applied to pasture or > 3 months before crop

Phosphorus Index for Site	Generalized Interpretation of Phosphorus Index for Site
< 8	LOW potential for P movement from the site. If farming practices are maintained at the current level there is a low probability of an adverse impact to surface waters from P losses at this site.
8 - 14	MEDIUM potential for P movement from the site. The chance for an adverse impact to surface waters exists. Some remedial action should be taken to lessen the probability of P loss.
15 - 32	HIGH potential for P movement from the site and for an adverse impact on surface waters to occur unless remedial action is taken. Soil and water conservation as well as P management practices are necessary to reduce the risk of P movement and water quality degradation.
> 32	VERY HIGH potential for P movement from the site and for an adverse impact on surface waters. Remedial action is required to reduce the risk of P loss. All necessary soil and water conservation practices, plus a P management plan must be put in place to avoid the potential for water quality degradation.

Table 4-2. The Phosphorus Index (Adapted from Sims, 1996).

Chapter 5: ***Managing Agricultural Phosphorus for Water Quality Protection: Future Challenges***

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AGRICULTURAL PHOSPHORUS AND WATER QUALITY

Managing soil phosphorus (P) to prevent surface water pollution is emerging as one of the more significant challenges facing agriculture today. As discussed in detail in this publication soil testing can be an effective tool to identify watersheds where water quality protection efforts should be prioritized. Most U.S. soil testing laboratories still focus on soil fertility-productivity decisions and, unfortunately, do not have proactive soil testing programs focusing on environmental protection, hence many of the advances in soil testing for P described in this bulletin have not received widespread use. Integrating environmental soil testing practices for P into private and public sector soil testing programs is one of several challenges that must be overcome to minimize the impact of agricultural P on surface water quality. If we are to meet these challenges and develop improved management practices for P that are not only profitable, but protective of our surface waters, we need to attain a consensus on what is known now about this problem and the most effective steps we can take today.

Agricultural Phosphorus and Water Quality: What do we know?

- Phosphorus is the nutrient that limits eutrophication in most U.S. surface freshwaters and in some estuaries (Sharpley et al., 1994). In most cases P is transported to surface waters by soil erosion and surface runoff except in very sandy soils or soils that are high in organic matter where P leaching and subsurface runoff can be an environmental concern (Sims et al., 1997).
- Agricultural P management is a national issue and is particularly acute in watersheds dominated by intensive animal agriculture. In these watersheds inputs of P in fertilizer and feed often exceed outputs in crops and animal products which usually leads to soils becoming highly enriched, even saturated with P. As soils are not infinite sinks for P, this can threaten water quality (Daniel et al., 1994; Sharpley et al., 1997).

- Only a few states have established threshold soil test P values (“upper critical limits”) based on water quality protection; in most cases these threshold values are voluntary and are applied to all soils. Since recent research has shown that properly identified threshold values will vary with soil series and landscape position, there is need for a systematic analysis of the process to be used to set upper critical limits for soil test P. (Gartley and Sims, 1994; Sharpley et al., 1996; Sims, 1993; Sims, 1997).
- Best management practices that reduce soil erosion are not the permanent solution to the movement of agricultural P from soil to water. Reducing erosion is highly desirable but soils that are extremely high in P can also have environmentally significant losses of soluble P in surface or subsurface runoff. The only permanent solution is balancing P inputs and outputs at a field, farm, or watershed scale (Beegle and Lanyon, 1994; Sharpley et al., 1996).
- New best management practices (BMPs) for P, based on recent research, are needed and several key issues need resolution. How can we identify the soils and landscapes that cause the highest risk for nonpoint source pollution of surface waters? What are reasonable threshold values for P that protect profitability and the environment; and what soil tests should be used to establish these upper critical limits? When should animal waste applications be based on P, and not nitrogen to prevent further, unnecessary accumulation of P in soils? How do recent advances in animal nutrition, such as phytase enzymes, low phytate corn or dietary P reductions, help resolve the issue of P excess in watershed with high animal densities? What interim BMPs are available now to mitigate the transport of P from soil to water while we seek permanent solutions to the broader problem?

Solving the complex problem of the impact of agricultural P on water quality will not be easy. Deliberate, thoughtful leadership is needed to identify cost-effective solutions, prioritize areas where they will be of greatest benefit, and educate those that will implement any new practices. Since the long-term sustainability of agriculture is linked more than ever to the quality of our environment, it is important to address these problems in a straightforward and timely manner. Information in this bulletin represents an effort by experts from a range of soil testing disciplines to initiate changes in soil testing programs for P to focus on environmental issues as well as on agricultural productivity.

Agricultural Phosphorus and Water Quality: What is needed today?

- Leadership and direction from all stakeholders in this issue - the agricultural sector, the animal and fertilizer industries, federal and state advisory and regulatory agencies, and university and governmental research organizations. Partnerships among these groups are needed to form a consensus on the most effective and economically viable means to reduce P impacts on water quality while still maintaining agricultural profitability.

LITERATURE CITED

- Beegle, D. B. and L. E. Lanyon. 1994. Understanding the nutrient management process. *J. Soil Water Cons.* 49:23-30.
- Daniel, T. C., A. N. Sharpley, D. R. Edwards, R. Wedepohl, and J. Lemunyon. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. *J. Soil Water Cons.* 49:30-38.
- Gartley, K. L. and J. T. Sims. 1994. Soil testing for phosphorus: Environmental uses and implications. *Commun. Soil Sci. Plant Anal.* 25:1656-1582.
- 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. *J. Environ. Qual.* 23:437-451.
- Sharpley, A. N., T. C. Daniel, J. T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. *J. Soil Water Cons.* 51:160-166.
- Sharpley, A. N., J. J. Meisinger, A. Breeuswma, J. T. Sims, T. C. Daniel, and J. S. Schepers. 1997. Impacts of animal manure management on ground and surface water quality. p. 173-242. *In* J. Hatfield (ed.) *Effective management of animal wastes as a soil resource.* Lewis Publishers, Boca Raton, FL.
- Sims, J. T. 1993. Environmental soil testing for phosphorus. *J. Prod. Agric.* 6:501-507.
- Sims, J. T. 1997. Phosphorus soil testing: Innovations for water quality protection. p. 47-63.. *Proc. 5th Intl. Symp. Soil and Plant Anal., Minneapolis, MN.*
- Sims, J. T., R. R. Simard, and B. C. Joern. 1998. Phosphorus losses in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* *In Press.*