Agricultural Phosphorus and Eutrophication: A Symposium Overview

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ABSTRACT

Phosphorus in runoff from agricultural land is an important component of nonpoint-source pollution and can accelerate eutrophication of lakes and streams. Long-term land application of P as fertilizer and animal wastes has resulted in elevated levels of soil P in many locations in the USA. Problems with soils high in P are often aggravated by the proximity of many of these areas to P-sensitive water bodies, such as the Great Lakes, Chesapeake and Delaware Bays, Lake Okeechobee, and the Everglades. This paper provides a brief overview of the issues and options related to management of agricultural P that were discussed at a special symposium titled, "Agricultural Phosphorus and Eutrophication," held at the November 1996 American Society of Agronomy annual meetings. Topics discussed at the symposium and reviewed here included the role of P in eutrophication; identification of P-sensitive water bodies; P transport mechanisms; chemical forms and fate of P; identification of P source areas; modeling of P transport; water quality criteria; and management of soil and manure P, off-farm P inputs, and P transport processes.

POINT-SOURCE POLLUTION from discrete defined sources has been greatly reduced by pollution control standards, regulatory enforcement, and capital investment and management in our industrial and municipal infrastructure. The success in reducing point-source pollution now draws attention to the diffuse and nondiscrete forms of pollution, the nonpoint sources.

Runoff from agricultural land is one of the major sources of nonpoint-source pollution. In reports to Congress, the USEPA has identified agricultural nonpoint-source pollution as the major source of stream and lake contamination that prevents attainment of the water quality goals identified in the Clean Water Act (Parry, 1998; USEPA, 1988). Specifically, eutrophication has been identified as the critical problem in those surface waters having impaired water quality in the USA, with agriculture the major source of nutrients in these lakes (50%) and rivers (60%) (Parry, 1998; USEPA, 1996). The input of P in agricultural runoff can accelerate the eutrophication of P-sensitive surface waters. In an increasing number of areas, the potential for P loss in runoff has been increased by the continual land application of fertilizer and/or manure from intensive livestock operations (Edwards and Daniel, 1992; McFarland and Hauck, 1995; Sharpley et al., 1996b). The continued input of P at levels greater than output in farm produce has created a P imbalance that has increased soil P to levels that are of environmental rather than agronomic concern in an increasing number of geographical areas (Sharpley et al., 1996a). However, this is an issue that manifests itself locally because, within states and regions, distinct areas of general P deficit and surplus exist. Unfortunately, problems associated with high soil P are aggravated by the fact that many are located near sensitive water bodies such as the Great Lakes, Chesapeake and Delaware Bays, Lake Okeechobee, and the Everglades.

As a result, states are developing management recommendations for P that attempt to balance system inputs and outputs (Natural Resources Conservation Service, 1995), leading to the need for:

1. Identification of P-sensitive water resources
2. Criteria to target critical sources of P for cost-effective remediation
3. Identification of threshold levels of soil P above which the potential enrichment of P in runoff exceeds agronomic benefits
4. Strategies to balance system inputs and outputs of P

From these we seek to develop management strategies that can minimize agricultural nonpoint-source pollution of our surface waters. Reducing system inputs of P and ultimately P loss in runoff to fresh waters will not be accomplished easily, particularly in manure-producing areas with limited acreage and P removal by crops. Thus, we must develop remediation strategies that are physicochemically as well as economically based. This will be achieved only through application of existing knowledge of P in agriculture and the environment, prioritization of innovative interdisciplinary research to reduce P imbalances, and consideration of the role of the producer (farm and integrator levels) in rural socioeconomic infrastructures.

This paper provides a brief overview of agricultural P management issues and options discussed at a special symposium, "Agricultural Phosphorus and Eutrophication," held during the American Society of Agronomy annual meetings in November 1996. The purpose of the symposium was to identify the role of agricultural P in eutrophication of lakes and streams and provide management directions. The interdisciplinary symposium included input from limnology, stream ecology, hydrol-

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Abbreviations: GIS, Geographical Information Systems; PAM, polyacrylamide.

ogy, watershed management, soil science, plant and animal nutrition, engineering, and policy makers. Topics discussed by the symposium papers will be presented to provide overall themes and common linkages.

PHOSPHORUS AND EUTROPHICATION

The Role of Phosphorus

Phosphorus is an essential element for plant growth, and its input has long been recognized as necessary to maintain profitable crop production. Phosphorus inputs can also increase the biological productivity of surface waters. Although N and C are essential to the growth of aquatic biota, most attention has focused on P inputs, because of the difficulty in controlling the exchange of N and C between the atmosphere and water, and fixation of atmospheric N by some blue-green algae. Thus, P is often the limiting element, and its control is of prime importance in reducing the accelerated eutrophication of fresh waters. As we move from fresh waters to saline oceans, through transition zones of brackish waters and estuaries, N generally becomes the element controlling aquatic productivity (Correll, 1998).

Surface water concentrations of inorganic P and total P between 0.01 and 0.02 mg L^{-1} are considered critical values above which eutrophication is accelerated (Sawyer, 1947; Vollenweider, 1968). These values are an order of magnitude lower than P concentrations in soil solution critical for plant growth (0.2–0.3 mg L^{-1}) emphasizing the disparity between critical lake and soil P concentrations and the importance of controlling P losses to limit eutrophication (Tisdale et al., 1985).

Advanced or accelerated eutrophication of surface water leads to problems with its use for fisheries, recreation, industry, or drinking, due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their senescence and decomposition. Also, many drinking water supplies throughout the world experience periodic massive surface blooms of cyanobacteria (Kotak et al., 1993). These blooms contribute to a wide range of water-related problems including summer fish kills, unpalatability of drinking water, and formation of trihalomethane during water chlorination (Kotak et al., 1994; Palmstrom et al., 1988). Consumption of cyanobacterial blooms, or water-soluble neuro- and hepatoxins released when these blooms die, can kill livestock, and may pose a serious health hazard to humans (Lawton and Codd, 1991; Martin and Cooke, 1994). Any of these impairments can have a serious effect on local or regional economies.

How the lake or stream is to be used will greatly influence the desired water quality goals and how it is to be managed. Watershed management rapidly becomes more complex when multiple demands and conflicting water quality goals are imposed on lakes and streams. For example, while a reservoir may have been built primarily for water supply, hydropower, and/or flood control, recreational value may increase and become a major economic consideration.

Targeting Phosphorus-Sensitive Waters

There have been several management efforts involving federal, state, and local governments, in cooperation with local citizens, to manage nonpoint-source pollution problems caused by excessive P. However, due to limited resources of time, expertise, and money, federal and state agencies need a means to prioritize the degree to which surface waters in a watershed are impaired by nutrients. New field-scale assessments and evaluation tools are becoming available to assess the status of many natural resource conditions and management impacts. For example, Wisconsin, which has an ongoing state sponsored nonpoint-source pollution watersheds program, utilizes an iterative process to identify and prioritize lakes needing nonpoint-source controls (Wisconsin Dep. of Natural Resour., 1986). Lakes are grouped into two classes based on their sensitivity to P and then ranked, using a point system that considers factors such as the degree to which:

1. The lake's water quality is threatened
2. The lake is able to respond or be protected from contamination
3. The lake is valued as a resource

Once an aquatic system and its accompanying watershed is identified as potentially benefiting from P management, the next step is to identify those fields within the watershed that are potential sources of P.

CRITICAL CONTROLS OF PHOSPHORUS EXPORT

The potential loss of P from agricultural land is dependent on several factors, including the relative importance of surface and subsurface runoff in a watershed area, land management, and the amount, form, and availability of P in soil.

Transport Mechanisms

Several decades of research have provided an understanding of the mechanisms controlling soil P dynamics and release to runoff. However, the hydrologic controls linking spatially variable P sources, sinks, temporary storages, and transport processes within a watershed are less well understood (Gburek and Sharpley, 1998). This information is critical to the development of effective management programs addressing the reduction of P export from agricultural watersheds.

Annual runoff is usually generated only from limited source areas within a watershed. These source areas vary rapidly in time, expanding and contracting rapidly during a storm as a function of rainfall intensity and duration, antecedent soil moisture conditions, water storage, temperature, soils, topography, groundwater, and moisture status over a watershed (Gburek and Sharpley, 1998). In the Northeast, surface runoff (unfrozen soil) is determined by soil water storage rather than infiltration capacity, generally due to high water tables or soil moisture contents in near-stream areas.

In watersheds where surface runoff is limited by infiltration rate rather than soil water storage capacity, areas of the watershed can alternate between sources and sinks of surface flow. This again will be a function of soil properties, rainfall intensity and duration, and antecedent soil moisture conditions. As surface runoff is the main mechanism by which P is exported from most watersheds, it is clear that if surface runoff does not occur P export is negligible. Thus, consideration of hydrologic controls and variable source areas is critical to a more detailed understanding of P export from agricultural watersheds. However, hydrologic and chemical controls must be integrated to understand and define processes that delineate P export from agricultural watersheds.

Chemical Forms and Fate

The export of P in runoff occurs in particulate and dissolved forms. Particulate P includes P associated with soil particles and organic matter eroded during flow events and constitutes the major proportion of P transported from most cultivated land (60–90%; Sharpley et al., 1992). Runoff from grass or forest land or nonerosive soils carries little sediment and is, therefore, generally dominated by the dissolved form. While dissolved P is, for the most part, immediately available for biological uptake (Nurnberg and Peters, 1984), sediment P can be a long-term source of P for aquatic biota (Carignan and Kalff, 1980). The bioavailability of particulate P can vary from 10 to 90% depending on the nature of the eroding soil and nature of the receiving lake.

Amounts of P exported from watersheds, except for wind-eroded particulates, are tied to watershed hydrology in terms of when and where surface runoff occurs, soil P content, and amount of P added as fertilizer or manure. This assumes in most cases that P export from watersheds occurs in surface rather than subsurface runoff, although it is recognized that in some regions—notably the Coastal Plains, organic soils of the northern Midwest, and Florida—P can be transported in drainage waters. Generally the P concentration in water percolating through the soil profile is small due to sorption of P by P-deficient subsoils. Exceptions occur in acid organic or peaty soils where the adsorption affinity and capacity for P are low due to the predominantly negatively charged surfaces and the complexing of Al and Fe by organic matter (Sims et al., 1998). Similarly, P is more susceptible to movement through sandy soils with low P sorption capacities; in soils that have become waterlogged, leading to conversion of insoluble Fe(III) to soluble Fe(II) and the mineralization of organic P; and in soils with preferential flow through macropores and earthworm holes (Bengston et al., 1992; Sharpley and Syers, 1979).

Because of the variable path and time of water flow through a soil with subsurface drainage, factors controlling dissolved P in subsurface waters are more complex than for surface runoff. Subsurface runoff includes tile drainage and natural subsurface flow, where tile drainage is percolating water intercepted by artificial systems, such as mole and tile drains. In general, the greater contact time between subsoil and natural subsurface flow results in lower losses of dissolved P than through tile flow (Sims et al., 1998). These losses are related to the degree of P saturation of soils, which is being used to estimate the potential for P export via leaching and drainage (Breeuwsma and Silva, 1992; Brookes et al., 1997; Sims et al., 1998).

As soil P content increases, the potential for particulate and dissolved P transport in runoff increases. Sources of sediment P in streams include eroding surface soil, streambanks, and channel beds. Thus, processes controlling soil erosion also control particulate P transport. In general, the P content and adsorption capacity of eroded particulate material is greater than that of source soil, due to preferential transport of clay-sized material. The transport of dissolved P in runoff is initiated by the release of P from soil and plant material. These processes occur when rainfall interacts with a thin layer of surface soil (1–5 cm) before leaving the field as runoff (Sharpley, 1985). Although the proportion of rainfall and depth of soil involved are difficult to quantify in the field, they will be highly dynamic due to variations in rainfall intensity, soil tilth, and vegetative cover.

Several studies have reported that the loss of dissolved P in runoff is dependent on the soil P content of surface soil. For example, a highly significant linear relationship was obtained between the dissolved P concentration of runoff and soil P content (Mehlich 3) of surface soil (5 cm) from cropped and grassed watersheds in Arkansas and Oklahoma (Pote et al., 1996; Sharpley, 1996a). These and similar studies related runoff dissolved P to soil P, determined by traditional soil test methods that estimate plant availability of soil P. While they show promise in describing the relationship between the level of soil and runoff dissolved P, they are limited for several reasons. First, while dissolved P is an important water quality parameter, it only represents the dissolved portion of runoff P readily available for aquatic plant growth. It does not represent particulate-bound P that can become available. Secondly, the Mehlich 3 extractant was developed to estimate the plant availability of soil P and may not accurately reflect runoff dissolved and desorbable P concentrations. While traditional chemical extractants have potential and should be evaluated, other approaches are being developed (water extraction, resin impregnated membranes, and Fe-oxide paper strips) which may provide a sounder estimate of the amount of soil P (dissolved/desorbable) subject to runoff and amount of algal-available P in runoff (dissolved/desorbable) (Sharpley et al., 1996a).

TARGETING SOURCE AREAS

The Use of Simulation Models

To make regional assessments to identify critical source areas within large geographical areas, experimental results from plots or fields as well as model estimates have to be scaled up. There is growing consensus that the water quality problems now facing society can best be solved by following a basin-wide or watershed protection approach. In most cases, watershed-level assessment and management involve a combination of water quality monitoring, spatial data collection, and modeling activities.

The accuracy of regional estimates depends on how good our experimental results or models are and how reliable available regional data are on the factors governing P transport. Keeping this important concept in mind, resource managers should use every opportunity to evaluate model predictions in real-world situations. The most important data are land use, soil texture, topography, and management practices. Once these data are in digital form, Geographical Information Systems (GIS) techniques can be used to combine them with experimental or model results (Cassell et al., 1998). In addition to regional assessments, this approach can be used to make comparative studies on the effectiveness of different remedial measures at the complex watershed scale. Using dynamic simulation models to calculate typical P transport values over a wide range of soil textures, slopes, and crops can serve as a quick and inexpensive method to make these watershed assessments (Cassell et al., 1998).

To focus the program there is often a need to prioritize management options in those watersheds providing inputs to P-sensitive waters. Management agencies are also often required to further target limited financial and human resources to those P-sensitive waters having the highest public or ecosystem value. Several regions are adopting a watershed approach to target priority water bodies and watersheds by considering the threat to the water quality and the practicability of alleviating the threat; the likelihood of achieving a significant reduction in P inputs; water use; and unique or endangered environmental resources. Recent modeling efforts have attempted to address temporal and spatial variations in P dynamics at watershed scales and to include these uncertainties (along with measurement, parameter, and model error) in watershed-level assessment and management, thereby promoting decision making based on probability of occurrence and the level of risk acceptable to resource managers (Hession et al., 1996; Cassell et al., 1998).

Water Quality Criteria

Water quality criteria for P have been established (USEPA, 1986). For example, to control eutrophication, total P should not exceed 0.05 mg L^{-1} in streams entering lakes/reservoirs, nor 0.025 mg L^{-1} within lakes/reservoirs. For the prevention of plant nuisances in streams or other flowing waters not discharging directly to lakes/impoundments the concentration of total P should not exceed 0.10 mg L^{-1}. These criteria are based on the early research of Sawyer (1947) and Vollenweider (1968), who proposed critical dissolved P and total P concentrations of 0.01 and 0.02 mg L^{-1}, respectively, which, if exceeded, may accelerate the eutrophication of surface waters. To determine the threshold level of soil P accumulation, Dutch regulators have set a critical limit of 0.10 mg L^{-1} as dissolved P tolerated in groundwater at a given soil depth (mean highest water level) (Breeuwsma and Silva, 1992).

These water quality criteria should not be used as the sole determinant to guide nutrient amendments where P loss in runoff and drainage water is of concern. In some cases background concentrations of P in runoff from undisturbed areas may exceed the quality thresholds. For example, the mean annual dissolved P concentration of runoff from several wheat (*Triticum aestivum* L.) watersheds in Oklahoma and Texas receiving no fertilizer P was 0.15 to 0.22 mg L^{-1} (Smith et al., 1991) and from grassed (*Cynodon dactylon* L.) watersheds receiving various types of manure was 1.40 to 1.80 mg L^{-1} (Heathman et al., 1995; Jones et al., 1995). Unfortunately, the 0.10 mg L^{-1} total P concentration considered eutrophic for streams not draining into lakes/reservoirs was exceeded in each case. Thus, it is unlikely that any form of nutrient management would reduce P in runoff below the critical concentrations of 0.10 mg L^{-1} total P, particularly where large applications of manure P are regularly made.

A more flexible approach considers the complex relationships between P loadings and physical characteristics of affected watersheds (leaching, runoff, and erosion potential) and water bodies (mean depth and hydraulic residence time) on a site-specific and recognized water-use basis. Also, water use will influence *desired or tolerable* nutrient loadings. For example, lakes used principally for water supply, swimming, and multipurpose recreation will benefit from low P loadings. However, lakes mainly used for fish production benefit from a moderate degree of biological productivity and thus tolerate higher P inputs.

Clearly, realistic water quality criteria that guide nutrient management within watersheds should encompass more factors than just P concentrations in runoff, such as proximity of P-sensitive waters, runoff potential, and land use. Unrealistic or unattainable criteria will not be adopted. Thus, it is essential for long-term sustainable management of nutrients that workable water quality criteria are proposed initially. The phasing in of environmental controls should then receive wider acceptance and compliance by farmers without creating severe economic hardships within rural communities.

BALANCING PHOSPHORUS IN AGRICULTURAL SYSTEMS

The overall goal of our efforts to reduce P losses from agriculture should aim to balance inputs of P in feed and fertilizer with outputs in crop and animal produce together with managing soils to maintain soil P resources at adequate levels. Increasing the use-efficiency of P in agricultural systems may be brought about by source and transport control strategies. Although we know how and have generally been able to reduce the transport of P from agricultural land in runoff and erosion, less attention has been directed toward source management.

Source Management

Reducing Off-Farm Inputs of Phosphorus in Feed

In many regions where P has been designated a management priority due to eutrophication concerns, P inputs in feed and fertilizer exceed production outputs in crop and animal produce leaving the farm or watershed. This situation exists in several areas of the USA, especially where livestock farming plays a major role in the agricultural economics of the region. In the northeastern

USA, several farms are reducing the amount of P imported in dairy feed by intensive grazing (Ford, 1994). Use of intensive pasture management has the potential to increase dairy-farm profits, provide labor savings, and as environmental concerns become greater, reduce off-farm inputs of P because less feed is imported.

Manipulation of dietary P intake by livestock is receiving increasing attention. In the Netherlands, the concentration of P in manure decreased temporarily during World War II when concentrates and fertilizers were less available. Reductions in concentrated P contents are now being similarly implemented to help reduce the amounts of P excreted to land (Wadman et al., 1987). Balancing supplemental P to dietary intake requirements of the animal would reduce P use by 15% (Mahan and Howes, 1995).

Also, enzyme additives to nonruminant (swine/poultry) animal feed may increase the efficiency of P uptake during digestion. One example is the use of phytase, an enzyme that enhances the efficiency of P recovery from phytin in grain feed. While the phytase enzyme has been shown to decrease the need for mineral P additions, the economics of its use as a routine feed additive are being evaluated. Another example is the isolation of chemically induced mutants of corn (*Zea mays* L.) with reduced levels of phytic acid P in the grain (Ertl et al., 1998). In a preliminary chicken feeding trial, the low phytic acid corn resulted in greater P availability and reduced P content in the manure (Ertl et al., 1998). As a result, genetically altering the phytic acid content in corn has the potential to improve feeding efficiencies and reduce the P content of subsequent manure.

Soil Phosphorus Management

Management of P on soil susceptible to P loss involves the use of environmental soil tests in combination with agronomic considerations to determine P application rates and methods. Environmental concern has forced many states in the USA to consider the development of recommendations for P applications and watershed management based on the potential for P loss in runoff. A major difficulty in their development has been the identification of a threshold soil test P level that can estimate P enrichment of runoff. Examples from several states in the USA are in Table 1. Establishing these levels is often a highly controversial process for two reasons. First, the data base relating soil test P to runoff P is limited to a few soils and crops, and there is an understandable reluctance to generalize the data to other regions. Second, there are major economic implications in establishing soil test P levels that may limit manure applications. In many areas dominated by animal-based agriculture, there simply is no economically viable alternative to land application. Because of these factors, those most affected by P limits based on soil tests are vigorously challenging their scientific basis. Clearly, there is a need to assess the validity of the use of soil test P values as indicators of P loss in runoff.

Efficient management of P amendments on soils susceptible to P loss involves the subsurface placement of fertilizer and manure and the periodic inversion of P stratified soils to redistribute surface P accumulations throughout the root zone. Both practices may indirectly reduce the loss of P by decreasing its exposure to surface runoff and by increasing crop uptake of P and yield. However, these practices are temporary, not permanent, solutions because of the risk of erosion.

Table 1. Threshold soil test P levels developed by several states (from Sharpley et al., 1996a).

State	Method	Threshold value
		mg kg^{-1}
Arkansas	Mehlich 3	150
Delaware	Mehlich 1	120
Ohio	Bray 1	150
Oklahoma	Mehlich 3	130
Michigan	Bray 1	75
Texas	Bray 1, TAMU†	200
Wisconsin	Bray 1	75

† Texas A&M University extractant.

Manure Management

Farm advisors and extension personnel now recommend that the P content of both manure and soil be determined by soil testing laboratories before land application of manure. This is important because there is a tendency among farmers to underestimate the nutritive value of manure. Thus, manure analyses are a constructive educational tool showing farmers that manure represents a valuable source of P. Manure analyses, in combination with soil testing, can also demonstrate the positive and negative long-term effects of manure use and the time required to build-up or deplete soil nutrients. For instance, soil analyses can help a farmer identify the soils in need of P fertilization, those containing excess P that should not be manured, and those where moderate manure applications may be of some value.

Additions of amendments to manure can potentially increase its nutrient value while reducing off-site damages to water quality. For example, commercially available manure amendments such as slaked lime or alum can reduce NH_3 volatilization and P solubility of poultry litter by several orders of magnitude (Moore and Miller, 1994). Also, the dissolved P concentration of runoff from fescue treated with alum-amended litter (11 mg L^{-1}) was much lower than from fescue treated with unamended litter (83 mg L^{-1}; Shreve et al., 1995). Perhaps the most important benefit of manure amendments (for both air and water quality), however, will be an increase in the N/P ratio of manure, via reduced N loss from manure by NH_3 volatilization. An increased N/P ratio of manure would approach crop N and P requirements closer to 3:1 vs. nearly 1:1 for some manure types. Thus, additions of manure based on crop N requirements would reduce the P excess added, thereby minimizing potential soil P accumulations.

The cost of transporting low-density manure more than short distances from the site of its production often exceeds its nutrient value. This has limited the area of land available for application of manure with most manure applied in the immediate vicinity of production. Thus, the dominant geology, soils, and topography of the local area often cannot be adequately taken into account before application. However, innovative measures are being used by some farmers to transport manure from the area of production. For example, following delivery of grain or feed, trucks and railcars are transporting dry manure instead of returning empty (Collins et al., 1988). In Delaware, the local poultry trade organization has established a *manure bank* network that puts farmers in need of manures in contact with small poultry growers who need more land to use all the manure generated by their operation. Cost-share monies are also made available to subsidize the use of newer and more efficient manure storage and application equipment. Even so, large-scale transportation of manure from producing to nonmanure producing areas is generally not occurring.

Transport Management

Phosphorus loss via erosion and runoff may be reduced by conservation tillage, crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops, and impoundments or small reservoirs. However, these practices are generally more efficient at reducing sediment P load than dissolved P load. Under conservation tillage, the accumulation of crop residues and added P at the soil surface provide a source of P to runoff that would be decreased during tillage. Also, NO_3^- movement to groundwater may increase under conservation compared with conventional tillage. To reduce P losses from surface-irrigated fields via runoff, Lentz et al. (1998) have shown the application of the high molecular weight anionic polyacrylamide (PAM) to initial irrigation inflows reduced tailwater volume twofold (by increasing infiltration), soil loss ninefold, and P loss five- to sevenfold.

Several studies have indicated little decrease in lake productivity with reduced P inputs following implementation of conservation measures (Meals, 1992, 1993). The lack of biological response was attributed to an increased bioavailability of P entering the lakes as well as internal recycling. Such water quality tradeoffs must be weighed against the potential benefits of conservation measures in assessing their effectiveness.

Critical Source Area Management

Any of the above strategies to minimize P loss in runoff will be most effective if sensitive or source areas within a watershed are identified, rather than spreading implementation over the entire watershed. Fields for more intensive sampling and testing could be identified based on data available in routine soil tests and supplemental information on site vulnerability to P loss. Lemunyon and Gilbert (1993) recently developed an indexing procedure to rank site vulnerability to P loss based on source (soil P and fertilizer and manure P inputs) and transport factors (runoff and erosion potential). 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 applications.

Once high-risk areas are known, advisory agencies could conduct more intensive sampling of the upper 0 to 5 cm of the soil surface, focusing on the most erosion or runoff prone areas. Together this data would not only identify fields where additional P should not be applied, but also specific sites where more intensive soil conservation practices would be needed because of topographical and hydrologic considerations.

CONCLUSIONS

Generally, the loss of agricultural P in runoff is not of economic importance to a farmer. However, it can lead to significant off-site economic impacts, in some cases occurring many miles from the P source. By the time these impacts are manifest, remedial strategies are often difficult and expensive to implement; they cross political and regional boundaries; and it can be several years or decades before an improvement in water quality occurs. Thus, a greater understanding is needed of what land management systems are primary sources of P, how much P in soil and water is too much, how and where can we reduce P inputs and losses, and what will be the efficiency of remediation needed to develop agricultural systems that sustain production as well as environmental quality. These challenges will require innovative, interdisciplinary, and applied research that is directed toward existing problems. The following papers were presented in 1996 at the ASA Symposium "Agricultural Phosphorus and Eutrophication" in Indianapolis, IN. They provide insights as to how we might meet and overcome these challenges.

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