ment a plan integrating any practices or BMPs that are appropriate. There would be no official list of standard BMPs but rather a wide range of activities conducted on individual farms in order to meet the expectations. Carefully established outcomes can promote solutions to meet the environmental challenges faced by farmers based on local conditions while stimulating innovation at the same time. Success of this approach is predicated on the ability to deliver appropriate technical support. Clearly defined, measurable outcomes are essential to this approach to nutrient management. Incentives for meeting the performance criteria would reinforce the approach to farming that is consistent with the strategic goals of society. If the incentives that are currently in place are not revised, promoting nutrient management to protect the environment is not likely to be accepted by those producers who need to make the greatest changes to meet environmental requirements. If the current incentives were adequate for environmental protection it is unlikely that we would have the environmental problems in the first place. Teaming performance criteria with incentives could entice those who might not otherwise participate to do so. ❑

Minimizing surface water eutrophication from agriculture by phosphorous management

T.C. Daniel, A.N. Sharpley, D.R. Edwards, R. Wedepohl, and J.L. Lemunyon

Runoff from agricultural land is one of the major sources of nonpoint source (NPS) pollution. In recent reports to Congress, USEPA identified agricultural NPS pollution as the major source of stream and lake contamination preventing attainment of the water quality goals identified in the Clean Water Act (*54*). Nutrients from agricultural nonpoint sources have been identified as the main cause of cultural eutrophication in freshwater inland lakes of the U.S. and an important source of nutrients to estuaries, affecting 57 and 18 percent of impaired lakes and estuaries, respectively (*57*). With increasing amounts of phosphorus (P) control being required of point source discharges, agricultural NPSs of P are an increasing national concern. In most cases, noxious aquatic weed growth results from the addition of excessive amounts of nitrogen (N) and P (*24*). Concentrations of 0.3 and 0.01 mg L^{-1} for inorganic N and P, respectively, have been identified as critical levels expected to promote noxious aquatic plant growth in lake water (*38, 59*). Phosphorus is the single most important nutrient to manage for controlling accelerated eutrophication in freshwater lakes (*55*). Although N may occasionally be limiting to algae during certain periods of the year, for example, when the total N to total P ratio is less than 15:1, P is still most often the nutrient of concern. Controlling P inputs to lakes is much easier than controlling N sources, as certain blue-green algae are capable of fixing atmospheric N. It is important to note that even when algal growth is limited by N, P load reduction can result in improved water quality if the load reduction is sufficiently large to drive the lake or reservoir to P limitation. In estuaries, both P and N are often limiting nutrients, with P being the limiting nutrient in the upper, freshwater dominated portions and N in the more marine dominated regions (*8*).

The relative importance of P and N to the productivity of free-flowing waters is less well understood. Bothwell (*4*) showed that although there was a relationship between peak areal biomass of periphyton communities in streams and P concentrations, P was not limiting when dissolved P (DP) concentrations exceeded 0.03 to 0.05 mg L^{-1}-levels exceeded in all but the most oligotrophic streams.

This paper will provide background information on the forms and sources of P, the importance of minimizing P in surface waters, procedures for identifying P-sensitive water bodies, and management approaches that limit P loss.

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Phosphorus chemistry of soil and runoff

Phosphorus occurs naturally in soil at levels between 300 and 1,200 mg kg^{-1}, although amounts can vary from 100 to 2,500 mg kg^{-1}. The wide variation in soil P content is a function of parent material, texture, and management factors such as the rate and type of P applied and soil cultivation. These factors also influence the amount of P in inorganic and

organic forms. In most soils, 50 to 90 percent of the P is inorganic, consisting of iron and aluminum phosphates in acidic soils and calcium phosphates in alkaline soils. Most inorganic P forms are so insoluble that only a small fraction (< 10 percent) is available at any one time for plant uptake.

The major portion of soil organic P is in stable fulvic and humic compounds. More labile organic P forms, such as glycerophosphates, phosphosugars, phospholipids, and nucleic acids can be mineralized by microbial activity. Although less than 5 percent of soil organic P is usually mineralized annually, in some cases this supplies sufficient P for plant growth.

Plants absorb inorganic P from soil solution, the level of which is determined by adsorption and desorption of labile iron, aluminum, and calcium phosphates; dissolution of more soluble mineral forms of recently applied P; and mineralization of organic P. Adsorption of P by soil occurs rapidly and because of the high binding energy between soil and P, adsorption tends to dominate desorption. Thus, a general decrease in plant-available P occurs after P is applied. As the labile form of P is depleted by plant uptake, it is slowly replenished by inorganic P desorption, organic P mineralization, crop residue decay, and applied fertilizer or manure.

The loss of soil P in runoff occurs in dissolved and sediment-bound or particulate forms (Figure 1). The standard procedure to separate dissolved and particulate forms in runoff is by filtration through a 0.45μm pore diameter membrane filter. Dissolved P is comprised mostly of orthophosphate which is immediately available for algal uptake (*33, 60*). However, variable amounts of organic and colloidal P less than 0.45μm may pass through the filter and be hydrolyzed or dissolved by the strong acidic medium of the molybdate-blue procedures used for P analysis. Amounts of dissolved organic P are normally small with 90 to 95 percent DP actually bioavailable (i.e., algal available) (*22, 50*).

Sediment P includes P sorbed by soil particles and organic matter eroded during runoff and constitutes the major portion of P transported from conventionally tilled land (75 to 95 percent). Runoff from grass or forest land carries little sediment and is dominated by dissolved P. Sediment P can provide a variable but long-term source of P to aquatic biota. Sharpley et al. (*46*) found that from 10 to 90 percent of P associated with sediment runoff was bioavailable and varied as a function of watershed management.

The first step in the movement of dissolved P in runoff is the desorption, dissolution, and extraction of P from soil crop residues, fertilizer, and manure (Figure 1). These processes occur as rainfall interacts with a thin layer of surface soil (< 2 cm) before leaving a field as runoff (*40*). Once in runoff water, dissolved P can be resorbed by runoff sediment. In runoff from no-till or pasture, the sediment load is generally so low that little dissolved P is adsorbed by suspended sediment. Under these conditions, losses of dissolved P can exceed losses in runoff from conventional tilled fields with higher erosion. Rainfall that does not run off percolates through the soil profile where sorption by P-deficient subsoils results in low dissolved P concentrations in subsurface flow.

As P is sorbed by soil material, erosion determines sediment P movement (Figure 1). Sources of sediment P in streams include eroding surface soil, plant material, stream banks, and channel beds. Where there is permanent vegetative cover, such as forest or pasture, the primary source of sediment is from stream bank erosion. This sediment will have characteristics similar to the subsoil material of the area which is often of low P content. During detachment and movement of sediment in runoff, the finer-sized fractions of source material are preferentially eroded. Thus, the P content and reactivity of eroded particulate material is usually greater than source soil (*41*).

As P moves to a lake by stream flow, there is generally a progressive decrease in P load by water dilution and sediment deposition. However, P often becomes more algal available as it moves from the edge of a field to a lake as a result of these chemical and physical processes.

P sources and management considerations

Phosphorus is supplied to crops through application of both commercial fertilizer and animal manure. For both P sources, runoff losses are generally greatest in the short-term (one to three runoff events) following application with the amount of fertilizer P lost in the runoff generally less that 5 percent of that applied.

Commercial fertilizer. Loss of P in the runoff from cropland is influenced by the rate, time, formulation, and method of fertilizer application. The severity of the runoff-producing event and amount of surface cover also influence P loss. A clear relationship exists between P application rate and method and amount of P transported in the runoff. In a field and laboratory study, Römkens and Nelson (*37*) demonstrated a linear relationship between the amount of P added as fertilizer and runoff P loss. Baker and Laflen (*2*), using simulated rainfall, confirmed this work and further demonstrated the effect of fertilizer placement on runoff P transport. Concentrations of DP in the runoff from areas receiving broadcast applications of P fertilizer averaged 100 times higher than the runoff from areas receiving similar rates of P that were point-injected below the soil surface. Time of P application also influences the amount ultimately transported in the runoff. Generally, one or two runoff events account for the majority of the P lost in the runoff (*62*). If these runoff events coincide with recent application of P, regardless of the form of P, then the amount of P transported in the runoff is expected to be higher than if P applications were made during times of low runoff probability (*15*). For example, Burwell et al. (*6*) in a watershed study demonstrated that P loss in Missouri was greatest during the planting season; a time consistent with the most intense rains, P application, and minimum crop cover.

There is no intrinsic reason for

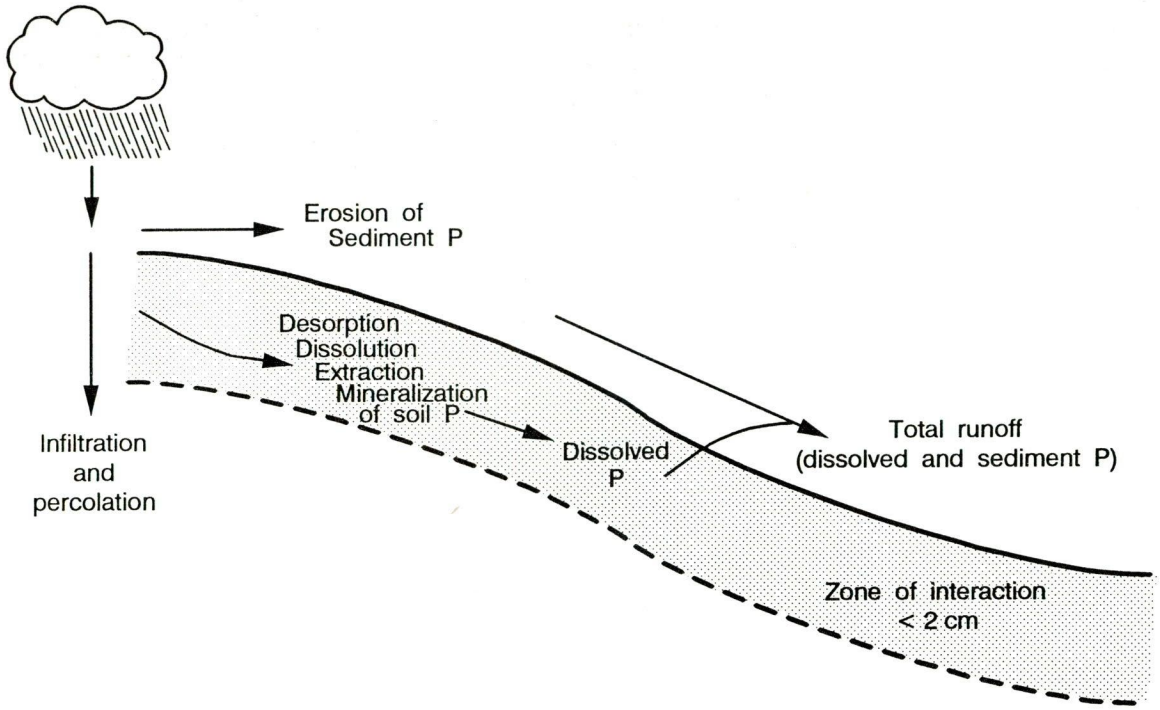

Figure 1. Processes involved in the transport of dissolved and sediment P in runoff.

long-term management of commercial fertilizers to lead to problems associated with accumulation of soil P. Commercial fertilizers allow producers the flexibility to tailor the fertilizer treatment to the specific needs of their crop, soil, and weather conditions. Application of P at rates consistent with crop needs will prevent over-application of P and subsequent accumulation and is in the economic interest of the producer. Poorly managed application of commercial fertilizers, however, has the potential for causing accumulation of soil P and thus for promoting increased P loss. Pierzynski et al. (*34*) examined several midwestern soils and attributed soil test P (STP) levels of 218 and 246 mg kg^{-1} in a Plainfield sand (Wisconsin) and Blount silt loam (Illinois), respectively, to addition of commercial fertilizer.

Animal manure. While row-crop production in the Corn Belt can result in contamination of surface waters with sediments, nutrients, and pesticides (*20*), Duda and Finan (*11*) showed that the greatest potential for accelerated eutrophication occurs in geographic regions of intense animal production. Regions that coincide with intense animal manure production are especially susceptible to eutrophication for several reasons. Efficiency of operation requires confinement of large numbers of animal units and ultimately the production of large volumes of manure. The nutrient value of fresh animal manures averages approximately 4.3 percent N, 1.4 percent P, and 2.2 percent K (*1*). The nutrient content of slurry or liquid manures will be diluted considerably. Losses of N can occur during storage and land application, further diminishing the nutrient content of manures.

Both long- and short-term P losses are of concern in the context of manure application. The greatest potential for short-term (the first one to three storms following application) P loss occurs when the manures are surface-applied, in which case P loss is directly proportional to P application rate (*12, 13, 14*). Runoff P concentrations during storms that occur soon after application can be quite high; Edwards and Daniel (*12, 13, 14*) measured total P (TP) concentrations of 22, 29, and 12 mg L^{-1} in the first storm following application of poultry litter, poultry manure, and swine manure, respectively. Large proportions of TP in runoff from areas receiving animal manures can be in the dissolved form and available for algal uptake (*12, 13, 14, 29*).

Generally manure is land applied with application rates based on N with no consideration given to the amount P in the manure. Animal manures are normally applied at rates sufficient to meet N needs of the receiving crop. Since animal manures have an average N:P ratio of 3:1 (*16*), and major grain and hay crops use N and P at a ratio of approximately 8:1 (*64*), excess P is supplied when manure is used to meet all the N needs of the crop. If application rates are adjusted for N losses via processes such as volatilization and denitrification, the excess P applied can be significantly greater. For example, if manure is used to meet the N needs for fescue production in northwest Arkansas, an excess of 40, 37, and 17 kg ha^{-1} of P will be applied using poultry, swine, or dairy manure, respectively (*1, 19, 53*).

Elevation of STP levels. Long-term application of fertilizer P at rates exceeding those of crop removal has resulted in elevated levels of STP, especially in areas where long-term land application of manure has been practiced. For example, in Wisconsin the average STP level for all soil tested was 48 mg kg^{-1} and for coarse textured soils used for intensive vegetable production the average STP level was 72 mg kg^{-1} (*7*). In Delaware, 65 percent of the soils tested were considered in the high range (*47*). Several midwestern soils were examined by Pierzynski et al. (*34*) and elevated STP levels were attributed to the addition of commercial fertilizer. Dairy manure application has contributed to 200 mg kg^{-1} STP levels in Wisconsin (*27*). Unfortunately, once high STP levels have been reached, considerable time is required for noticeable depletion. McCollum (*26*) estimated that without further additions of P, eight to 10 years of cropping corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] would be required to reduce P levels in a Portsmouth sand from 54 mg kg^{-1} STP (Mehlich-III) to 20 mg kg^{-1}.

Relationship between soil P and runoff P. The P content of surface soil directly influences the loss of P in runoff. In fact, a highly significant linear relationship was observed between the soil test P (STP as Bray - 1 P) content of surface soil (1 cm [0.4 in]) and the dissolved P concentration in runoff from cropped and grassed watersheds in Oklahoma (Figure 2) (*44*). A similar dependence of the dissolved P concentration in runoff on the level (Bray-1) of STP was found by Romkens and Nelson (*37*) for a Russel silt loam in Illinois (r^2 = 0.81), on a Tokomaru silt loam in New Zealand by Sharpley et al. (*45*) (r^2 = 0.98, 0.1 M NaCl extractable soil P), and on water extractable soil P (r^2 = 0.61) of 17 Mississippi watersheds by Schreiber (*39*).

Vaithiyanathan and Correll (*58*) observed that the loss of P in runoff from forested and cropped watersheds in the Atlantic coastal plains was closely related to soil P content (r^2 = 0.96). In fact, the high organic P content of the forest soils (331 mg kg^{-1}; 70 percent of total P) contributed to the high organic P loss in runoff, while the high inorganic P content of the cropped soils (486 mg kg^{-1}; 75 percent of total P) resulted in a higher inorganic P loss. Other studies have also demonstrated the close dependence of P loss in runoff upon surface soil P content (*3, 35, 36, 51*).

Other factors that affect the loss of P in runoff include depth of surface soil that interacts with runoff water, the concentration of sediment in runoff, and runoff volume. Few mechanistic models have been developed to quantify these factors, so simpler, empirical models have been proposed. Using simulated rainfall, Sharpley et al. (*43*) investigated the effect of these factors on P transport in runoff. Eventually, an equation describing the kinetics of soil P desorption was proposed to predict P transport in runoff (*42*). Using this equation, Sharpley and Smith (*42*) were able to demonstrate close agreement between predicted and measured soluble P concentration in the runoff from long-term watershed studies. Other researchers have recognized the essential role of soil P concentration in developing methods to estimate P losses. Storm et al. (*48*) used a modification of the equation of Sharpley and Smith (*42*) and described particulate P loss as directly proportional, within a particle size class, to soil P concentration in a combined soluble/particulate P transport model. Wendt and Alberts (*63*) used similar methods to estimate transport of P adsorbed to soil particles and incorporated isotherms to account for adsorption/desorption dynamics. Soil P concentration was an integral input to the physically-based P transport model developed by Novotny et al. (*31*). Comprehensive hydrologic/water quality models such as EPIC (*65*), CREAMS (*21*) and AGNPS (*67*) estimate losses of P as directly proportional to P concentration in the upper layer of soil.

Priority water body selection

Identification of P-sensitive water bodies. Recently there have been several management efforts involving federal, state, and local governments in cooperation with individual citizens to manage NPS problems (*61*). Of note was a recommendation to target limited financial and technical resources on the most valuable and impaired watersheds, with additional priority on projects having strong local support.

The development of clear water quality objectives is essential. Individual lakes or reservoirs will respond differently to the same phosphorus loads because of morphological differences related to depth, water residence time, and degree of stratification. Additionally the principal use desired of a particular water body will vary and will affect the "desired" inland lake phosphorus concentration and loadings. Lakes used principally for water supply, swimming, and multi-purpose recreation will benefit from low phosphorus loadings. Lakes principally used for fish production may benefit from a moderate degree of fertility (*32*).

Approaches to developing priorities vary from state to state. Wisconsin, which has an ongoing NPS priority lakes and watershed program, utilizes an iterative process to identify lakes needing nonpoint source controls. Lakes in Wisconsin are grouped into two classes based on their sensitivity to phosphorus. Of the 15,000 identified inland lakes in Wisconsin, approximately 1,400 were targeted for phosphorus control. The principle criteria used were (a) lakes had to be greater than 10 ha (25 acres) in size to be reflective of their relative value to the state's tourism and recreation base, (b) lakes had to have flushing rates fewer than six times per year to separate them from riverine systems in which phosphorus is of lesser concern, and (c) lakes had to be deep enough to stratify. This last criterion was used to identify lakes in which internal phosphorus cycling occurs and for which most of the commonly used empirical, Vollenweider-type models were developed.

To further screen lakes for possible selection as a NPS control project a point system is used to rank lakes. Included in this ranking are factors

which determine the degree to which (a) the lake's water quality is threatened; (b) the lake is able to respond or to be protected from threats if best management practices are implemented; and (c) the lake is valued as a resource. Finally, high ranking lakes are selected by a nomination process for inclusion into the NPS priority lakes and watershed program.

Once selected for a project, an iterative process is used to set achievable water quality goals for the individual lake. The most stringent best management practices (BMPs) are then implemented in the watersheds of those lakes considered exceptionally valuable and extremely sensitive to phosphorus loadings. Those less susceptible or those having designated uses more compatible with higher phosphorus loadings will have a lesser degree of critical sites or lands identified for implementation of NPS BMPs.

As Wisconsin's program has evolved it has become evident that there is a need to target and prioritize nutrient management actions within a watershed and focus on individual farms to be reflective of the needs of the receiving water bodies. As indicated earlier, application standards for animal manure have typically been N driven to be reflective of ground water contamination concerns. Similarly, control of sediment has been a priority resulting in the use of conservation tillage practices which then often require incorporation of manure or fertilizer to minimize runoff potential. Finally, individual farm management plans are then developed using sediment, N, and P as priorities.

Identification of critical areas in priority watersheds. Because P transport is controlled most effectively at the origin of the excess P, the next management step (after determining that a critical water body is P limited) should be to identify regions within the contributing watershed in which P transport reduction strategies will be most effective. These regions should subsequently be the primary focus of efforts to reduce P inputs to the P-sensitive water body by implementation of BMPs. Direct, indirect, and a combination of direct and indirect methods may be used to target regions for implementation of management options to reduce P losses from the point of origin.

Direct critical region identification refers to systematic monitoring of water body tributaries to determine relative P contributions from the various subbasins. With judicious selection of monitoring station locations, direct monitoring can identify subbasins contributing high P loads. The most apparent advantage of this approach is that subsequent decisions regarding where to focus remedial measures will be based on data rather than subjective considerations or surrogates to observed data. The disadvantages to direct critical region identification are the resources and time involved. Effective monitoring stations are expensive to establish and operate, and sample analysis costs can be quite high. Monitoring costs will increase directly with the size of the monitored watershed and the critical region resolution desired. In addition, several years' time can be required to obtain meaningful information due to the highly variable nature of NPS pollution occurrence. The resource requirements of direct monitoring for critical area identification are likely the main reason that this method is not widely used except in large watersheds.

Critical region identification is currently performed most often via indirect methods. The principle underlying indirect methods of critical region identification is to obtain a spatial representation of some index of P export; the operative assumption is that the P transport index selected is a reasonable surrogate for observed data. The criteria for critical area identification vary considerably in terms of complexity. Examples of relatively simple screening criteria include animal manure application rate, dilution, distance to nearest receiving water, and combinations of factors (*10, 28, 68*). Other reported screening criteria include factors such as existing facilities and attitude of the owner/operator (*52*). Heatwole and Shanholtz (*18*) reported on a procedure to rank the relative contributions of sites as a function of animal manure application rate and estimated delivery to nearest receiving water.

Advances in geographic information systems (GIS) technology have been extremely valuable in processing the multitude of data required to meaningfully characterize the P contribution potentials of subregions of watersheds. The latest advance in use of indirect methods to identify critical regions has been the linkage of spatial data on P transport factors with hydrologic/water quality simulation models (*9, 17, 30, 66*). Distributed parameter models can estimate P export at the field scale, and use of GIS technology to construct the model input database can help alleviate some of the practical difficulties inherent in distributed parameter models. Indirect methods of critical region identification can be less expensive and time-consuming than direct methods and will thus probably become increasingly common with advances in prediction accuracy of hydrologic/water quality models. The dependence of critical region identification on some degree of derived data is probably the largest limitation to indirect methods. Until indirect methods are shown to give results similar to what would be obtained from direct monitoring, healthy skepticism as to whether a particular region is indeed critical may be justified.

A combination of direct and indirect methods can combine the best attributes of the two approaches to critical area identification. Limited observed data can be used to calibrate a hydrologic/water quality simulation model, and the model can then be executed on the basis of GIS-assisted input to identify regions likely to have particularly high P export. Although an uncalibrated simulation model might adequately reflect relative differences in P export from various regions, calibration is essential to accurate estimation of amounts of P transport.

Once critical hydrologic areas have been identified, the landowner, producer, and field staff need to assess the soil, hydrology, and man-

agement of individual fields to determine specific fields that have the potential for P loss. A field level assessment tool has been developed (*23*) that uses easily attainable soil, hydrologic, and management information. Using this assessment of the soil, topography, soil test levels of P, and management practices, a relative ranking procedure can be used to identify those fields that have the highest potential for producing off-site movement of P. Through this procedure, a numerical value—or P index—is assigned to each field. The process also indicates potential problem areas such as excessive erosion or manure application rates.

Management options for reducing P losses

Where lakes, reservoirs, or estuaries are the primary water bodies of concern, programs minimizing eutrophication from agricultural NPS pollution should emphasize limiting P inputs to surface water. In Florida, water quality management programs dealing with NPS pollution have focused on P (*25*). In Holland, the national strategy for minimizing NPS pollution, especially eutrophication due to animal wastes, is to limit entry of P into both surface and ground water (*5*).

Because STP and runoff P concentrations are related, a critical level of STP exists that results in runoff which is, on average, sufficiently high in P to cause eutrophication. State and federal water quality management agencies are attempting to identify these "cut-off levels" of STP above which no additional P should be added. Cut-off levels for soil P, along with influential chemical properties such as clay and organic matter content, need to be identified for bench-mark soils. Once identified, these levels could be a valuable tool for identifying potential P related problems associated with excess applications of either animal manure or commercial fertilizer. Developing management practices that are sequentially enacted as the STP level increases toward the cut-off level would slow down the process of restricting P application.

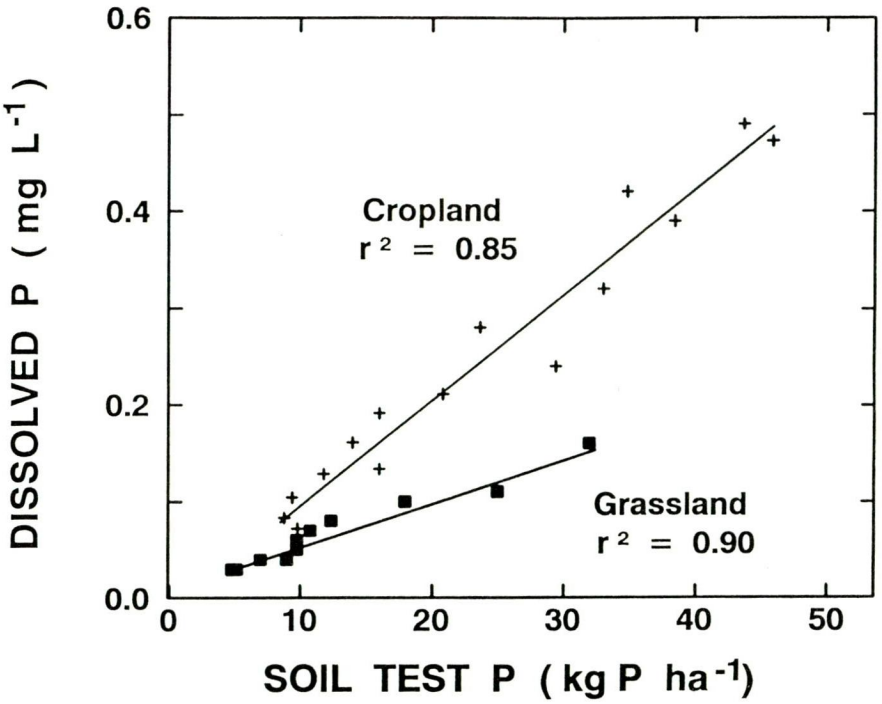

Figure 2. Effect of soil test P on the dissolved P concentration of runoff from several Southern Plains watersheds (44).

The first step in proper manure management is to view manure as a valuable resource that can be utilized to advantage. Alternative uses of manure should be pursued along with methods of increasing the bulk density and N content of the manure, encouraging the transport of manure from manure-rich to manure-deficient areas. However, until such methods are perfected and expanded, the predominant method of utilization will remain land application.

All fields do not contribute equally to the P load of a lake or reservoir. Therefore, if the same management practice is implemented on two different fields, the effectiveness in reducing the P load will differ. The P indexing procedure is designed to identify and rank fields for implementation of management practices. For fields with a low to moderate P index rating, flexibility exists and a wide range of management practices is available. Generally these practices are designed to reduce runoff, which is the major transport mechanism for P, and because of this they also control erosion in the process. For fields with a high P index, especially those with high STP levels, the same practices apply but less flexibility exists and more stringent approaches may be required.

Fields with low to moderate P indexes. Many management options are available for reducing P losses in the short-term following application, and all have been demonstrated to be effective under some circumstances. Options such as injection of P sources, when appropriate, can reduce the concentration of P near the soil surface. Other management options such as no-till farming, vegetative filter strips, terracing, winter cover crops, and contour farming can reduce transport of P in particulate form by reducing erosion. Strategies which reduce runoff from treated areas, such as tile drainage and impoundments, can be effective in reducing loss of DP as well as sediment P. Measures such as timing P application to avoid

occurrence of intense storms and application of chemical amendments to precipitate P may also be effective in reducing P losses shortly after application, but the effectiveness of such practices needs to be better defined.

Fields with high P indexes and STP levels. The best P management plan is to prevent surface soil accumulation of P in the first place. Soil testing should be an integral part of P management to ensure that soil P levels are high enough for adequate yields and that the manure or fertilizer is applied only to fields that are P deficient, avoiding those with excessive P or those that have the potential for excessive P. If commercial fertilizer is the predominant long-term method of supplying plant nutrients, then the composition of the fertilizer can be structured to supply only the necessary amount of N and P. This approach is flexible and cost-effective to the producer. When animal manures are used as a nutrient source, less flexibility exists and a combination of manure and commercial fertilizer should be used to supply the nutrients required by the crop. Manure can be used to supply all the P required and a portion of the N needs, with the remaining N requirement being supplied by commercial fertilizer. When STP levels are between high and the cut-off level, manure application rates should be P- rather than N-based.

Cost-effective practices. Large-scale implementation of management options to reduce P loss is best approached by first constructing a framework for assessing the relationship between implementation costs and water quality benefits. While it is relatively easy to define the costs of a management practice, it is difficult to quantify the benefits that will be derived. Assessment of management practice effectiveness is difficult because of dependence of effectiveness on site-specific variables, and an all-inclusive database is lacking. Rigorous mathematical simulation models can be used to estimate management option effectiveness, but issues regarding data input requirements and output accuracy should be resolved before depending solely on models. If the effectiveness of a practice for reducing P loss from application sites can be defined, then this edge-of-field effectiveness should be translated into effects on the P-sensitive water body. This translation is best accomplished using simulation models that address edge-of-field P transport dynamics, channel flow dynamics, and the dynamics of the P-sensitive water body. A notable example of this type of combined model was developed by Summer et al. (*49*). Assuming that the first two challenges can be surmounted, there must be a relationship established between quality of the P-sensitive water body and some measure of value, so that costs and benefits are defined on a common basis. This might be the most difficult component in a framework for assessing management plans, since the value associated with a given level of quality in the P-sensitive water body depends on the use of the water body. If the water body is used solely as a water supply, then assessing its value might be relatively straightforward. If the water body is used for multiple purposes such as fishing, boating, and other uses, then the concept of value depends on intangibles and can be very subjective.

Remediation of impacted water bodies is often accomplished with expenditures of limited cost-shared public monies. Plans to improve the quality of P-sensitive water bodies thus need to focus on obtaining maximum benefits from limited public resources. To accomplish this goal, implementation plans to reduce P loading to the P-sensitive water body should initially focus on regions identified as critical. Identification of an "optimal" plan can be rather laborious, depending on the size of the area in question and on the array of potential management practices under consideration. A systematic procedure for plan development, however, will ensure that only the most effective management practices are implemented and that these practices will be implemented in locations that are most appropriate. Use of public monies to implement management practices without regard to effectiveness or where little water quality improvement is likely is a questionable public policy and will not maintain or generate broad public support.

Summary

Transport of solutes in agricultural runoff is of increasing national concern. While several pollutants are carried in the runoff, P is deemed especially important because it is the nutrient limiting growth of aquatic vegetation in most surface waters. Runoff losses of P are generally less than 5 percent of that applied with the bulk of the loss occurring in one or two events following land application. Loss of P in runoff occurs in dissolved and sediment-bound or particulate forms. Sources of runoff P include commercial fertilizers and animal manures, and the amount contained in runoff is directly influenced by management practices such as rate, method, and time of application. Runoff losses from manure are a particular concern in regions where confined animal operations exist in proximity to surface water bodies sensitive to P inputs. Soil test P levels are increasing nationally and a relationship exists between the amount of P in the soil and that contained in the runoff. This relationship requires further definition and "cut-off STP levels" need to be identified.

Limited financial and technical resources should be targeted on those water bodies deemed valuable and most likely to respond to implementation of BMPs within the watershed. State water quality management agencies need to develop clear water quality objectives for lakes/reservoirs based on intended use. Methods for identifying and prioritizing P-sensitive water bodies must be perfected and demonstrated. Once P-sensitive water bodies are known, it is necessary to identify hydrologically active areas or "hot spots" in the watershed requiring BMPs. A variety of practices exist that, when implemented, can maintain high surface water quality especially for

traditional row-crop agriculture. Less flexibility exists with land application of manure, especially on fields with elevated STP levels. Soil testing should be an integral part of manure management. Land application strategies for manure should be based on N to protect the ground water with equal consideration given to P for protection of surface waters.

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