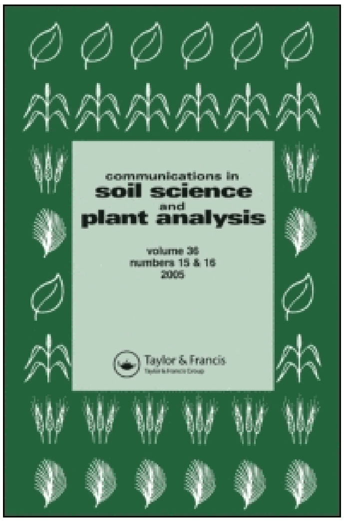

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INNOVATIVE MANAGEMENT OF AGRICULTURAL PHOSPHORUS TO PROTECT SOIL AND WATER RESOURCES

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ABSTRACT

Agriculture, particularly livestock agriculture, is receiving increasing public scrutiny due to non-point source phosphorus (P) pollution and eutrophication. Much of today's situation may be attributed to system level trends in specialization and intensification that result in excess P entering livestock farms. Balancing P at the farm gate represents a necessary step for long-term soil and water quality protection. Remedial P management combines source and transport control that confront critical areas of P export in surface and subsurface runoff from agricultural landscapes. Source management seeks to immobilize P in the environment through such strategies as reducing soluble P in manure, targeting P application to soils with high retention capacities, and managing soil P. Transport controls employ an understanding of loss or transfer mechanisms to avoid P application on areas with a high transport potential. Also, the potential for P transport can be reduced by implementation of conservation practices such as reduced tillage, terracing, and stream buffers. However, implementation of agricultural management strategies that minimize P export must consider the cost effectiveness of alternative measures, as low practice adoption may limit or impede water quality benefits.

INTRODUCTION

Phosphorus (P) is an essential element required for crop production and is the primary agent controlling freshwater eutrophication, the process of organic enrichment of water bodies that is the most ubiquitous water quality impairment in the U.S. today (EPA, 1996). Eutrophication restricts water use for fisheries, recreation, and industry due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their death and decomposition. Also, many drinking water supplies throughout the world experience periodic massive surface blooms of *cyanobacteria*, which contribute to summer fish kills, unpalatability of drinking water, and formation of carcinogens during water chlorination (Kotak et al., 1993; Palmstrom et al., 1988).

Although concern over eutrophication is not new, there has been a profound shift in our understanding of, and focus on, sources of P in U.S. water bodies. Since the late 1960s, the relative contributions of P to U.S. water bodies from point sources and non-point sources has changed dramatically. Great strides have been made in the control of point source discharges of P, such as the reduction of P in sewage treatment plant effluent. These improvements have been due, in part, to the ease in identifying point sources. Non-point sources of P have been primarily ignored, greatly due to the difficulty in their identification and control (Carpenter et al., 1998). Thus, control of non-point sources of P is a major hurdle to protecting fresh water bodies from eutrophication.

While a variety of non-point sources, ranging from suburban lawns to construction sites to golf courses, contribute P to U.S. water bodies, agriculture, particularly intensive livestock agriculture, is one of the most pervasive sources of P found in U.S. surface waters (USGS, 1999). Today's problem may be attributed to the evolution of agricultural systems from net sinks of P (i.e., deficits of P limit crop production) to net sources of P (i.e., soil P levels exceed crop requirements and are available to transport pathways such as surface runoff and erosion). Specifically, farming system changes have resulted in the export of P from some crop producing areas and the import of P into intensive livestock producing areas.

This paper examines factors affecting the potential for agricultural P loss and outlines management options that can be directed at controlling nonpoint sources of agricultural P. Best management practices that address the two factors affecting potential for agricultural P loss, source factors and transport factors, are presented.

THE EVOLUTION OF AGRICULTURE FROM P SINK TO P SOURCE

Before World War II, farming communities tended to be self-sufficient in that they produced enough feed locally to meet livestock requirements and could recycle the manure nutrients effectively to meet crop needs. As a result, sustainable nutrient cycles tended to exist in relatively localized areas. After World War II, farming systems became more specialized with crop and livestock operations in different regions of the country. This has resulted in a major one-way transfer of P from grain-producing areas to animal-producing areas (Lanyon, 2000; Sharpley et al., 1998b; Sims, 1997).

In many states, animal feeding operations (AFOs) are now the major source of agricultural income. Over the last 10 years, cattle, pig, and poultry numbers have increased 10 to 30%, while the number of farms has decreased 40 to 70% (Gardner, 1998). This intensification has been driven by an increased demand for animal products and an improved profitability associated with economies of scale. Intensification has also created regional and local imbalances in P inputs and outputs. On average, only 30% of the fertilizer and feed P input to farming systems is output in crops and livestock produce (National Research Council, 1993).

Most P entering intensive livestock operations is applied to soil. Animal manure can be a valuable resource for improving soil structure and increasing vegetative cover, thereby reducing surface runoff and erosion potential. The continual long-term application of manure at levels exceeding crop needs increases soil P levels. In many areas of intensive confined livestock production, manures are normally applied at rates designed to meet crop N requirements and to avoid groundwater quality problems created by leaching of excess N. This often results in a build up of soil test P above amounts sufficient for optimal crop yields, which can increase the potential for P loss in runoff as well as in leachate (Haygarth et al., 1998; Sharpley et al., 1996a; Heckrath et al., 1995).

PROCESSES AND PATHWAYS OF AGRICULTURAL P LOSS

Phosphorus is transferred from agricultural lands to water by surface runoff and leaching. The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms. Sediment P includes P associated with soil particles and organic material eroded during flow events and is the main form of P in surface runoff from most cultivated land (Sharpley et al., 1992). Surface runoff from grass, forest, or uncultivated soils carries little sediment and is, therefore, generally dominated by dissolved P. In most cases, the concentration of P in water percolating through the soil profile is small due to fixation of P by P-deficient subsoils. Exceptions occur in sandy, acid organic, or organic soils, with low P fixation or holding capacities and in soils where the preferential flow of water can occur rapidly through macropores and earthworm holes (Heckrath et al., 1995; Sharpley and Syers, 1979).

Phosphorus export is generally restricted to limited areas within a watershed. These "critical source areas" occur when source factors and transport factors converge to favor P loss. Source factors govern the availability of P to transport factors, which in turn control P transfer from land to water. Critical source areas vary rapidly in time, expanding and contracting quickly during a storm as a function of rainfall intensity and duration, antecedent moisture conditions, temperature, soils, topography, ground water, and moisture status over a watershed. Thus consideration of how much P is brought into a watershed and land applied, along with the dominant pathways of water movement, are critical to the development of effective and remedial measures.

REMEDIAL MEASURES

The overall goal of our efforts to reduce P losses from agriculture to water should be to increase P use-efficiency, by attempting to balance P inputs in feed and fertilizer into a watershed with outputs in crop and livestock produce, together with managing the level of P in the soil. Reducing P loss in agricultural runoff may be brought about by source and transport control strategies (Table 1). We have generally been able to reduce the transport of P from agricultural land in erosion. However, much less attention has been directed toward source management and the control of dissolved P losses in surface runoff. Strategies for source and transport management are described below, and an explanation is given of how strategies can be targeted to critical source areas.

Source Management

Source management attempts to minimize the buildup of P in the soil above levels sufficient for optimum crop growth, by regulating P at the farm gate, controlling the quantity of P in manure, and controlling the amount of P that is applied in a localized area.

Farm Gate P Management

Addressing farm gate imbalances of P is fundamental to reducing non-point source P loss. Manipulation of dietary P intake by animals may help reduced P inputs as feed; often the major cause of P surplus. Phosphorus intake above minimum dietary requirements established by National Research Council (1989) does not appear to confer any growth or health advantages and actually reduces profitability through increased feed costs (Knowlton and Kohn, 1999). Carefully matching dietary P inputs to livestock requirements can reduce the amounts of P excreted by animals (Morse et al., 1992) and hence the amount of P applied to land in manure.

At present, manure is rarely transported more than 10 miles from where it is produced, severely restricting disposal options. As a result, manure is often applied to soils with sufficient nutrients to support crop growth. Mechanisms need to be established to facilitate movement of manure from surplus to deficit areas. However, it must be shown that the recipient farms are more suitable for manure application than manure-rich farms. For instance, such transport may be a short-term alternative if N-based management is used to apply the transported manure. If this happens, soil P in areas receiving manure may eventually reach excessive levels.

A variety of programs currently exist to improve placement of manure across farm boundaries. In an increasing number of states, extension and local trade organizations have established "manure bank" networks that puts manure-needy farmers in contact with manure-rich growers. Even so, these networks are generally small. Large scale transportation of manure from producing to non-manure producing areas is not occurring, largely due to concern that avian diseases will be transferred from one farm (or region) to another. Thus, biosecurity must be ensured for any manure transportation network that is developed.

Composting may also be considered as a management tool to improve manure distribution. Although composting tends to increase the P concentration of manure, the volume is reduced and thus, transportation costs are reduced. Additional markets may also become available for composted materials. Composting makes manure more uniform in its physical and chemical properties and therefore able to be spread more evenly and at more accurate rates.

There is interest in using some manure as sources of "bioenergy." For example, dried poultry litter can be burned directly or converted by pyrolytic methods into oils suitable for use to generate electric power. Liquid wastes can be digested anaerobically to produce methane which can be used for heat and energy. As the value of clean water and cost of sustainable manure management is realized, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost-effective, and thus, create expanding markets.

Manure P Management

A significant amount of the P in grain is in phytate, a form of P that cannot be digested by monogastric animals such as pigs and chickens. As a result, it is common to supplement feed with mineral forms of P. This supplementation con-

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Table 1. Best Management Practices for Control of Nonpoint Sources of Agricultural P and N

Practice	Description	Impact on Loss†	
		P	N
Source Measures			
Feed additives	Enzymes increase nutrient utilization by animals	+ve	+ve
Crop hybrids	Low phytic-acid corn reduces P in manure	+ve	Neutral
Manure management	Compost, lagoons, pond storage; barnyard runoff control; transport excess out of watershed	+ve	+ve
Rate added	Match crop needs	+ve	+ve
Timing of application	Avoid autumn and winter application	+ve	+ve
Method of application	Incorporated, banded, or injected in soil	+ve	Neutral
Crop rotation	Sequence different rooting depths	Neutral	+ve
Manure amendment	Alum reduces NH_3 loss and P solubility	+ve	+ve
Soil amendment	Flyash, Fe oxides, gypsum reduce P solubility	+ve	Neutral
Cover crops/residues	If harvested can reduce residual soil nutrients	+ve TP −ve DP	+ve

Plowing stratified soils	Redistribution of surface P through profile	+ve	Neutral
Transport Measures			
Cultivation timing	Not having soil bare during winter	+ve	+ve
Conservation tillage	Reduced and no-till increases infiltration and reduces soil erosion	+ve TP −ve DP	+TN −ve NO_3
Grazing management	Stream exclusion, avoid overstocking	+ve	+ve
Buffer, riparian, wetland areas, grassed waterways	Removes sediment-bound nutrients, enhances denitrification	+ve TP Neutral DP	+ve
Soil drainage	Tiles and ditches enhance water removal and reduce erosion	+ve TP −ve DP	+ve TN −ve NO_3
Strip cropping, contour plowing, terraces	Reduces transport of sediment-bound nutrients	+ve Neutral DP	+ve Neutral NO_3
Sediment delivery structures	Stream bank protection and stabilization, sedimentation pond	+ve	+ve
Critical source area treatment	Target sources of nutrients in a watershed for remediation	+ve	+ve

† TN is total N, NO_3 is nitrate, TP is total P, and DP is dissolved P.
+ve is positive impact/−ve is negative impact.

tributes to P enrichment of manures and litters. Enzymes such as phytase, which break down phytate into forms available to monogastric animals, can be added to feed to increase the efficiency of grain P absorption by pigs and poultry. Such enzymes reduce the need for P supplements in feed and potentially reduce the P content of manure. Also, corn hybrids are available which contain low amounts of indigestible phytate P. Pigs and chickens fed "low-phytic acid" corn grain excreted less P in manure than those fed conventional corn varieties (Ertl et al., 1998).

Commercially available manure amendments, such as slaked lime or alum, are used to reduce ammonia (NH_3) volatilization, leading to improved animal health and weight gains. Coincidentally, these amendments can also reduce the solubility of P in poultry litter by several orders of magnitude, and decrease dissolved P concentrations in surface runoff (Moore et al., 2000; Shreve et al., 1995). Perhaps the most important benefit of manure amendments for both air and water quality would be an increase in the N:P ratio of manure, via reduced N loss because of NH_3 volatilization. An increased N:P ratio of manure would more closely match crop N and P requirements.

Managing P Applications to Soil

The rate, method, and timing of P application can be managed to minimize the potential for P loss in runoff (Sharpley et al., 1998b; Withers and Jarvis, 1998). As might be expected, P loss in runoff increases with greater applications of P as fertilizer or manure (Edwards and Daniel, 1993; McDowell and McGregor, 1984). Although rainfall intensity and duration influence the concentration and overall loss of manure N and P in runoff, the relationship between potential loss and application rate is critical to establishing environmentally-sound manure management guidelines, as discussed in a later section. Incorporation of manure into the soil profile either by tillage or subsurface placement, reduces the potential for P loss in runoff. Mueller et al. (1984) showed incorporation of dairy manure by chisel plowing reduced total P loss in runoff from corn 20-fold, compared to no-till areas receiving surface applications. In fact, P loss in runoff was decreased by a lower concentration of P at the soil surface and a reduction in runoff with incorporation of manure (Mueller et al., 1984; Pote et al., 1996).

As the major portion of annual P loss in runoff generally occurs during one or two intense storms (Edwards and Owens, 1991; Smith et al., 1991), avoiding P applications during periods of the year when intense storms are likely would reduce the potential for loss. Also, an increase in the length of time between applying manure and a rainfall/runoff event will reduce P transport in runoff (Sharpley, 1997; Westerman and Overcash, 1980). Although these measures may reduce the risk for P loss in runoff, they are often not practical for a farmer to implement. For example, subsurface injection or incorporation in rocky soils may be difficult, and without manure storage, farmers who contract out the cleaning of poultry houses will have little flexibility of when manure or litter is applied.

As we move from agronomic to environmental concerns with soils containing P levels in excess of crop requirements, soil P testing is beginning to be used to indicate when P enrichment of runoff may become unacceptable. As these and other P-based recommendations expand, much attention has focused on the paucity of soil-specific data linking soil P with the potential for P loss (Sharpley et al., 1999).

Given the absence of such data, a common approach has been to adopt agronomic soil P standards, following the rationale that soil P in excess of crop requirements is vulnerable to removal by surface runoff or leaching. Since agronomic standards already exist for soil test P, this approach requires little investment in research and can be readily implemented. However, we must be careful how we interpret soil test results for environmental purposes (Fig. 1). Interpretations given on soil test reports (i.e., low, medium, optimum, high, etc.) were estab-

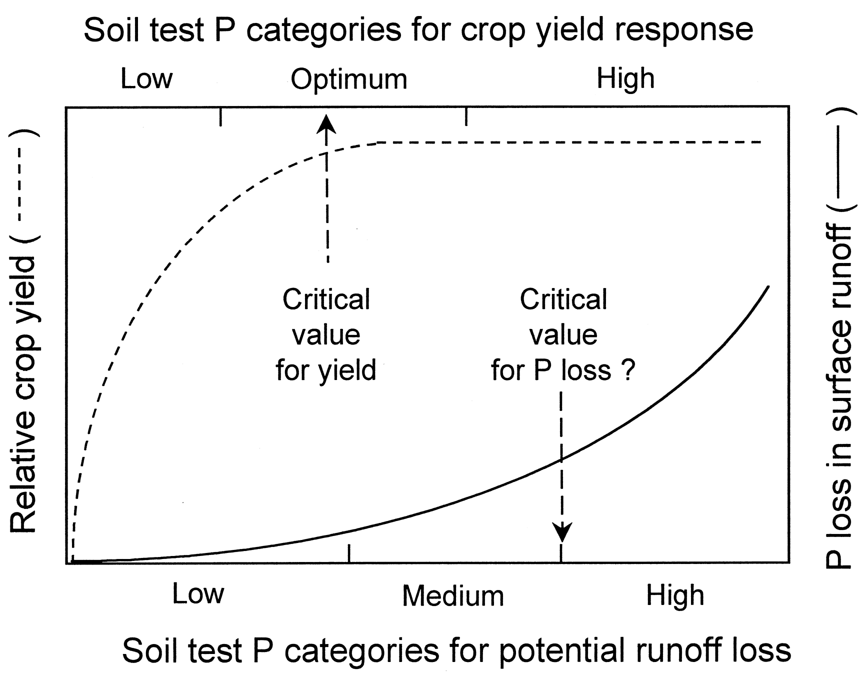

Figure 1. As soil P increases so does crop yield and the potential for P loss in surface runoff. The interval between the critical soil P value for yield and runoff P will be important for P management.

lished based on the expected response of a crop to P and not on soil P release to surface or subsurface runoff (Sharpley et al., 1996a). Some would simply extend the levels used for interpretation for crop response and say a soil test that is above the level where a crop response is expected is in excess of crop needs and therefore is potentially polluting (Fig. 1). But, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and runoff enrichment potential.

One environmental measure of soil P, developed in The Netherlands by Breeuwsma and Silva (1992) to assess P leaching potential, is soil P saturation (percent saturation = available P / P fixation maximum). The role of soil P saturation as an indicator of P loss potential derives from the observation that soil P saturation is strongly correlated to P desorption, such that P desorption increases at higher degrees of soil P saturation (Sibbeson and Sharpley, 1997). Indeed, many studies have correlated soil P saturation with P in runoff (Sharpley, 1995; Pote et al., 1996; 1999), as well as with P in leachate (Hesketh and Brookes, 2000). In The Netherlands, a threshold soil P saturation of 25% has been established above which the potential for P movement in surface and ground waters becomes unacceptable (Breeuwsma and Silva, 1992).

A variety of soil extracts have been evaluated as indicators of P loss potential by relating extract P to P in surface runoff or subsurface leachate. Ryden and Syers (1975) stated that to establish the relationship between P additions, fertilizer additions and P in particulate or aqueous phases of runoff, a desorption or "support medium should reflect the cation status as well as the ionic strength of the aqueous phase of the system." With the possible exception of macropore flow, the longer residence time of subsurface flow in soil, implies that a soil extractant of higher ionic strength is required than for surface runoff. Soil extractions with water and $0.01 M$ $CaCl_2$ have shown promise in estimating the dissolved P concentrations of surface runoff and subsurface leachate, respectively (Fig. 2) (McDowell and Sharpley, 1999; McDowell and Condron, 1999). Using these desorption approaches in conjunction with Fe-oxide strips and gels, we can determine the quantity of desorbable P in runoff or soils in the medium- and long-term (Sharpley, 1993; Freese et al., 1995).

Analysis of soil P data for environmental purposes represents an important step in the development of recommendations for farmers and policy makers. One innovative environmental approach to data analysis uses a split-line model to determine a soil P threshold or "change point," that separates the relationship between soil P and dissolved P in runoff into two sections, one with greater P loss per unit increase in soil P concentration or percent saturation than the other (Heckrath et al., 1995; Hesketh and Brookes, 2000; McDowell and Condron, 1999). McDowell and Sharpley (1999) showed that a similar change point occurred between soil test P (Mehlich-3 P) concentrations of the 0–5 cm soil layer and dissolved P in either surface or sub-surface runoff (Fig. 3). The change point

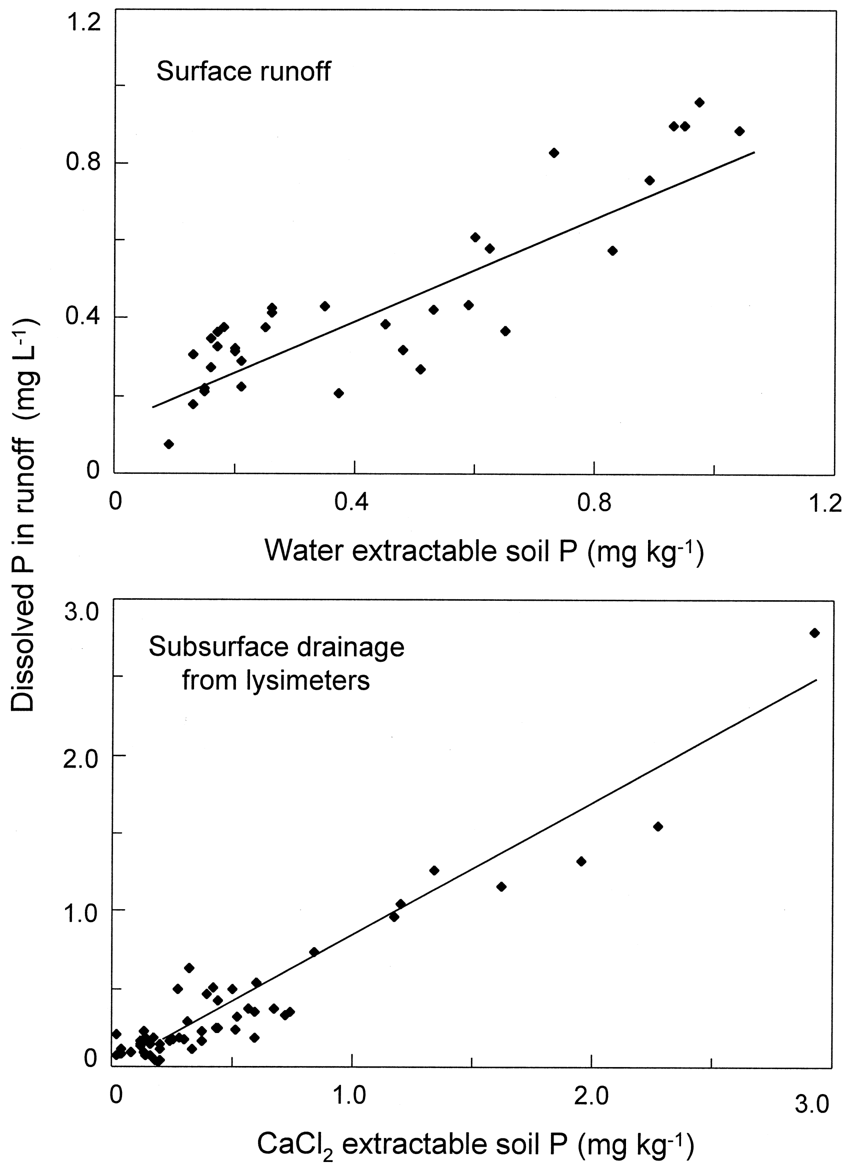

Figure 2. Relationship between the concentration of dissolved P in surface runoff and subsurface drainage from 30 cm deep lysimeters and the water and $CaCl_2$ extractable soil P concentration, respectively of surface soil (0–5 cm) from a central PA watershed (adapted from McDowell and Sharpley, 1999 and Sharpley et al., 1999).

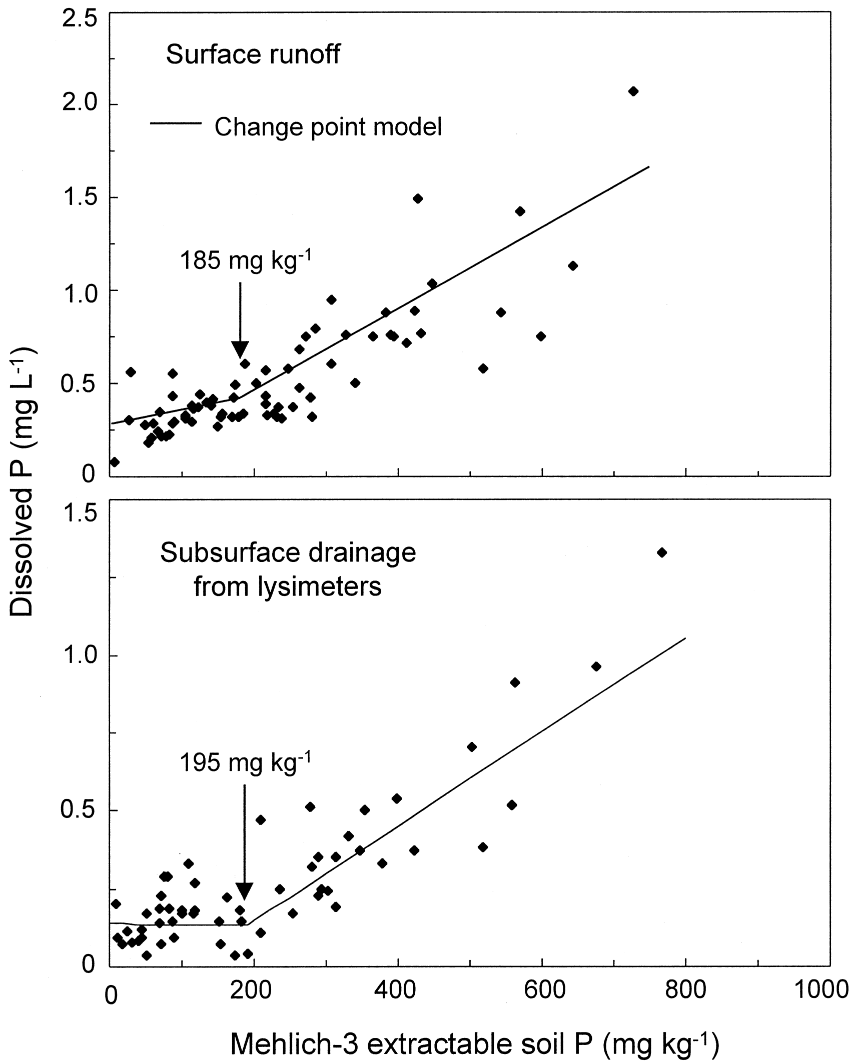

Figure 3. Relationship between the concentration of dissolved P in surface runoff and subsurface drainage from 30 cm deep lysimeters and the Mehlich-3 extractable soil P concentration of surface soil (0–5 cm) from a central PA watershed (adapted from McDowell and Sharpley, 1999 and Sharpley et al., 1999).

identifies a threshold soil P level above which the potential for P loss may be greater than below it.

Given the relationship between soil P and runoff/leachate P, a variety of management options that reduce either soil P or soluble P alone have been examined. Stout et al. (1998) determined that gypsum produced as a coal combustion by-product reduces P solubility in soil without significantly reducing plant-available P. Elsewhere, Sharpley (1999) determined that deep tillage can reduce soil test P by as much as 65%. While such options do address the proximate concern of excessive soil P levels, they should not be seen as solutions to the greater problem of over-application of P to soils. Furthermore, in the case of deep tillage, the trade-off between reduced soil test P levels and increased susceptibility to erosion must be considered.

Transport Management

Transport management refers to efforts to control the movement of P from soils to sensitive locations, such as bodies of fresh water. Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops, and impoundments (e.g., settling basins). Basically, these practices reduce rainfall impact on the soil surface, reduce runoff volume and velocity, and increase soil resistance to erosion. Conversion from furrow irrigation to sprinkler to drip irrigation significantly reduces irrigation erosion and runoff. Furrow treatments, such as straw mulching, and use of polyacrylamides will also reduce in-furrow soil movement (Lentz et al., 1998).

As well as reducing P export, riparian areas can increase wildlife diversity and numbers and aquatic habitat. In addition to acting as physical buffers to sediment-bound nutrients, plant uptake captures P, resulting in a short-term accumulation of nutrients in non-woody biomass as well as a long-term accumulation in woody biomass (Groffman et al., 1992; Lowrance et al., 1985; Peterjohn and Correll, 1984). However, the effectiveness of riparian areas as nutrient buffers can vary significantly. For instance, the route and depth of subsurface water flow paths though riparian areas can influence nutrient retention. Riparian zones are most efficient when sheet flow occurs, rather than channelized flow, which will bypass retention mechanism. Thus these areas must be carefully managed to realize their full retention and filtration capabilities.

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

Table 2a. The P Index. Phosphorus Loss Potential Due to Transport Characteristics

Characteristics	Phosphorus Loss Rating					Field value
Soil erosion (tons/acre)	**2** X (tons soil loss/acre/year)					
Soil runoff class†	Very low **0**	Low **2**	Medium **4**	High **8**	Very high **16**	
Subsurface drainage†	Very low **0**	Low **2**	Medium **4**	High **8**	Very high **16**	
Leaching potential†	Low **0**		Medium **2**	High **4**		
Distance from edge of field to surface water (feet)	>30 feet permanent vegetated buffer **0**	10–30 feet vegetated buffer AND >30 feet no P application zone **2**	10–30 feet vegetated buffer **4**	<10 feet vegetated buffer AND >30 feet no P application zone **8**	<10 feet from water **16**	
Priority of receiving water†	Very low **0**	Low **1**	Medium **2**	High **4**	Very high **8**	

Total Site Value: ______

Transport Potential for the Site (total site value /32)‡: ______

† Surface runoff is a function of runoff curse number, slope and soil permeability class for a field; subsurface drainage is a function of whether artificial drainage has been installed; leaching potential is a function of soil permeability; priority of receiving water body is a function of surface area, mean water residence time, and average depth of the water body.

‡ The total site value is divided by a high value (32), so that when a site's full transport potential is realized the value is 1. Transport factors <1 represent a lower than maximum potential and >1 a very high potential.

Table 2b. The P Index. Phosphorus Loss Potential Due to Site Management Practice

Site Characteristics	Phosphorus Loss: Site Source Factors: Very Low	Low	Medium	High	Very High	Field Value
Soil test P	Soil test P (ppm)					
Loss rating value	Soil test P * 0.2[†]					
Fertilizer P rate	Fertilizer rate (lbs P_2O_5 / acre)					
P fertilizer application method and timing	Placed with planter or injected more than 2″ deep **0.2**	Incorporated <1 week after application **0.4**	Incorporated >1 week or not incorporated >1 following application in May–October **0.6**	Incorporated >1 week or not incorporated following application in Nov–April **0.8**	Surface applied on frozen or snow covered soil **1.0**	
Loss rating value	Fertilizer P application rate * loss rating for fertilizer P application method and timing					
Manure P rate	Manure application (lbs P_2O_5 / acre)					
P fertilizer application method and timing	Placed with planter or injected more than 2″ deep **0.2**	Incorporated <1 week after application **0.4**	Incorporated >1 week or not incorporated >1 following application in May–October **0.6**	Incorporated >1 week or not incorporated following application in Nov–April **0.8**	Surface applied on frozen or snow covered soil **1.0**	
Loss rating value	Fertilizer P application rate * loss rating for fertilizer P application method and timing					
Total Management Value (Sum of soil, fertilizer, and manure P loss rating values):						______

[†] A correction factor of 0.2 for soil test P is based on the field data which showed a five-fold greater runoff P concentration with an increase in manure or fertilizer P addition compared to an equivalent increase in soil test P (as Mehlich-3 P) (Sharpley and Tunney, 2000).

Kirkland, 1986; Young and DePinto, 1982). As a result, the effect of remedial measures in the contributing watershed may be slow, emphasizing the need for immediate action to avoid prolonging water quality problems.

Targeting Management to Address Transport Potential

Critical soil P levels are being proposed to guide P management recommendations, examples of which are given by Sharpley and Tunney (2000). In most cases, agencies proposing these limits seek to uniformly apply them to areas and states under their jurisdiction. However, critical soil P levels, and for that matter, source values alone, provide an incomplete perspective of P loss potential and are therefore too limited to be the sole criterion to guide P management and P applications. For example, adjacent fields with similar soil test P levels but differing susceptibilities to surface runoff and erosion due to topographic and hydrologic variables will have different potentials for P loss and should not face similar restrictions on P use and management. The potential for such discrepancies is highlighted by the observation that most of the P exported ($>75\%$) from many agricultural watersheds comes from a small definable part of the landscape ($<20\%$ of land area), during a few storm events (Gburek and Sharpley, 1998). Therefore, critical soil P levels alone have little meaning vis a vis P loss potential unless they are used in conjunction with an estimate of potential surface runoff, erosion, and leaching.

Preventing P loss is now taking on the added dimension of defining, targeting, and remediating critical source-areas of P (i.e., areas where high soil P levels coincide with high surface runoff and erosion potentials). This approach enables P management to be conducted at multi-field or watershed scales, focusing on problem areas, and allowing for status quo management in areas of low P loss potential. Conventionally-applied remediations may not produce the desired results and may prove to be an inefficient and poor cost-effective approach to the problem if this source-area perspective to target application of P fertility, surface runoff, and erosion control technology is not used.

A simple site assessment index for P (the P index) was developed by USDA-NRCS, in cooperation with several research scientists, to rank the vulnerability of fields as sources of P loss in surface runoff (Gburek et al., 2000; Lemunyon and Gilbert, 1993; Sharpley et al., 1998a). The index accounts for and ranks transport and source factors controlling P loss in surface runoff and sites where the risk of P movement is expected to be higher than that of others (Table 2). Site vulnerability to P loss in surface runoff is assessed by selecting rating values for individual transport and source management factors from the P index (Table 2). A P index value, representing cumulative site vulnerability to P loss, is obtained by multiplying summed transport and source management factors (Table 3).

Table 3. Worksheet and Generalized Interpretation of the P Index

To solve for P loss rating—add all numbers on Part A and all numbers on Part B. Write these numbers on the worksheet. Multiply Part A × Part B. This is your final P loss rating.

Part A Value: ___________

Part B Value: ___________

Multiply A × B = ___________ = ___________ P Loss Rating

P Index	Generalized interpretation of the P index
<8	**LOW** potential for P loss. If current farming practices are maintained, there is a low probability of adverse impacts on surface waters.
8–14	**MEDIUM** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss.
15–32	**HIGH** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a P management plan are needed to minimize the probability of P loss.
>32	**VERY HIGH** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss.

The P index is intended to serve as a practical screening tool for use by extension agents, watershed planners, and farmers. The index can also be used to help identify agricultural areas or management practices that have the greatest potential to accelerate eutrophication. As such, the P index will identify alternative management options available to land users, providing flexibility in developing remedial strategies. Some general recommendations are given in Table 4; however, P management is very site-specific and requires a well-planned, coordinated effort between farmers, extension agronomists, and soil conservation specialists.

Integrating P and N Management

Farm N inputs are usually more easily balanced with plant uptake than are P inputs, particularly where confined livestock operations exist. In the past, separate strategies for either N or P have been developed and implemented at farm or watershed scales. Because of different critical sources, pathways, and sinks controlling P and N export from watersheds, remedial efforts directed at either P or N

Table 4. Management Options to Minimize Nonpoint Source Pollution of Surface Waters by Soil P

Phosphorus index	Management options to minimize nonpoint source pollution of surface waters by soil P
< 15 (LOW)	***Soil testing***: Have soils tested for P at least every three years to monitor build-up or decline in soil P.
	Soil conservation: Follow good soil conservation practices. Consider effects of changes in tillage practices or land use on potential for increased transport of P from site.
	Nutrient management: Consider effects of any major changes in agricultural practices on P losses *before* implementing them on the farm. Examples include increasing the number of animal units on a farm or changing to crops with a high demand for fertilizer P.
15–150 (MEDIUM)	***Soil testing***: Have soils tested for P at least every three years to monitor build-up or decline in soil P. Conduct a more comprehensive soil testing program in areas that have been identified by the P Index as being most sensitive to P loss by surface runoff, subsurface flow, and erosion.
	Soil conservation: Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management).
	Nutrient management: Any changes in agricultural practices may affect P loss; carefully consider the sensitivity of fields to P loss before implementing any activity that will increase soil P. Avoid broadcast applications of P fertilizers and apply manures only to fields with lower P Index values.

150–300 (HIGH)	***Soil testing***: A comprehensive soil testing program should be conducted on the entire farm to determine fields that are most suitable for further additions of P. For fields that are excessive in P, estimates of the time required to deplete soil P to optimum levels should be made for use in long range planning. ***Soil conservation***: Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management). Consider using crops with high P removal capacities in fields with high P Index values. ***Nutrient management***: In most situations fertilizer P, other than a small amount used in starter fertilizers, will not be needed. Manure may be in excess on the farm and should only be applied to fields with lower P Index values. A long-term P management plan should be considered.
> 300 (VERY HIGH)	***Soil testing***: For fields that are excessive in P, estimate the time required to deplete soil P to optimum levels for use in long range planning. Consider using new soil testing methods that provide more information on environmental impact of soil P. ***oil conservation***: Implement practices to reduce P losses by surface runoff, subsurface flow, and erosion in the most sensitive fields (i.e., reduced tillage, field borders, grassed waterways, and improved irrigation and drainage management). Consider using crops with high P removal capacities in fields with high P Index values. ***Nutrient management***: Fertilizer and manure P should not be applied for at least three years and perhaps longer. A comprehensive, long-term P management plan must be developed and implemented.

control can negatively impact the other nutrient (Table 1). For example, basing manure application on crop N requirements to minimize nitrate leaching to ground water can increase soil P and enhance potential P losses (Sharpley et al., 1998b; Sims, 1997). In contrast, reducing surface runoff losses of total P via conservation tillage can enhance N leaching and even increase algal available P transport (Sharpley and Smith, 1994).

These positive and negative impacts of conservation practices on N and P loss potential should be considered in the development of sound remedial measures. Clearly, a technically sound framework must be developed that recognizes critical sources of P and N export from agricultural watersheds so that optimal strategies at farm and watersheds scales can be implemented to best manage both P and N. One approach, explored by Heathwaite et al. (2000) and Sharpley et al. (1998a), is to employ the P index to target P management on critical source areas of P and assume N-based management on all other areas. With such an approach, however, careful consideration must be given to the potential long-term consequences of N management on P loss and vice versa.

IMPLEMENTING REMEDIAL MEASURES

Since the early 1980s, several studies have investigated the long-term (7 to 10 yr) effectiveness of BMPs to reduce P export from agricultural watersheds. These studies quantified nutrient loss prior to and after BMP implementation or attempted to use untreated watersheds as controls. Overall, these studies showed that BMPs reduced P export from a variety of watersheds. For example, water quality improvements have been demonstrated following BMP implementation in several areas of the USA (USDA-ASCS, 1992; Bottcher and Tremwell, 1995; Goldstein and Ritter, 1993; National Water Quality Evaluation Project, 1988; Richards and Baker, 1993). With this experience, however, it is evident that several factors are critical to effective BMP implementation. These factors include targeting watersheds that will respond most effectively to BMPs, identifying critical source areas of nutrient export, and accounting for both watershed and estuary response time and equilibration (capacity to buffer added P).

The time of watershed or estuary response to BMP implementation is particularly important for P, due to its long residence time in ecosystems, compared to N. Studies have shown that even where P applications are stopped, elevated soil P can take up to 20 years to decline to levels at which crops will respond to applications (McCollum, 1991). Also, internal recycling of P in estuarine sediments can supply sufficient P to maintain eutrophic conditions in P-sensitive waters.

Watershed Identification and Cost-Effectiveness

Marginal farm profits and cost share programs play an important role in BMP implementation. With limited resources, it is necessary to select watersheds that will either have the greatest impact on the water body of concern, or provide the greatest reduction in P loss following remediation. Model simulation and field studies have been used to determine the cost-effectiveness of several BMPs (Table 5). The cost-effectiveness of BMPs is not universal and can vary by site or region. When resources are limited, concerns for cost-effectiveness may outweigh the absolute efficacy of individual BMPs. For instance, although riparian areas and manure management (chemical amendments, storage, waste treatment, and barnyard runoff control) can reduce runoff P more than tillage management, conservation tillage is often a more cost-effective measure and may be preferable. Such an example emphasizes the need to determine the load reduction required for a given watershed and water body prior to selecting appropriate BMPs. Clearly, construction of terraces, which are initially expensive, may in some cases be a viable option, especially when motivated by an imperative to cut P loss. Ultimately, careful selection and integration of different practices is necessary to maximize beneficial impact and cost-effectiveness.

Analysis of cost-effectiveness can have important implications to formulating remediation strategies. For instance, Meals (1990) quantified the effect of several manure BMPs on P export from two watersheds in the LaPlatte River Basins, Vermont, draining into Lake Champlain. The BMPs included barnyard runoff control, milkhouse waste treatment, and construction and use of manure storage

Table 5. Cost-Effectiveness of BMPs on Reducing P Losses from Continuous Corn with a 5% Slope and 140 kg P ha^{-1} yr^{-1} Manure Broadcast (Data Adapted from USDA-ASCS, 1992 and Heathman et al., 1995)

Best Management Practice	P Loss kg ha^{-1} yr^{-1}	Cost-Effectiveness \$/kg P $saved^{-1}$
None	10.0	—
Contour cropping	6.3	1.7
Terraces	3.2	4.7
Conservation tillage	3.9	0.8
Vegetative buffer areas†	2.5	1.1
Manure management	2.8	3.3
All BMPs	1.8	4.9

†Cost-effectiveness includes the cost of land taken out of production.

Table 6. Cost-Effectiveness of Animal Waste Management BMPs in the LaPlatte River Basin Project, Vermont, for 1980 to 1989 (Data Adapted from Meals, 1990)

	Catchment 1		Catchment 2	
Management	P Reduction kg	Effectiveness $/kg P^{-1}	P Reduction kg	Effectiveness $/kg P^{-1}
Barnyard runoff control	311	4	78	14
Milkhouse waste treatment	34	12	11	32
Waste storage facility	154	269	14	1963
Total	567	77	103	282

facilities (Table 6). Post BMP losses of P were lower than before BMPs. For both watersheds, barnyard runoff control resulted in the greatest reduction in P export and was the most cost-effective BMP (Table 6). Furthermore, if a choice had to be made between which of the two watersheds in Table 6 were to be targeted, watershed 1 would have been selected given its better cost-effectiveness ratios.

Targeting Remedial Efforts Within a Watershed

Once an area has been selected for remediation, the next step is selection of appropriate BMPs. For the example of the two watersheds in Table 6, the most effective BMP installation priority would be barnyard runoff control, milkhouse waste treatment, and animal waste storage facilities. Without careful prioritizing and targeting of critical sources within a watershed, BMPs may not produce expected reductions in P export.

The importance of targeting BMPs within a watershed or basin is shown by several studies in the Little Washita River watershed (54,000 ha) in central Oklahoma (Sharpley and Smith, 1994). Nutrient export from two subwatersheds (2 and 5 ha) were measured from 1980 to 1994, while BMPs were installed on about 50% of the main watershed. Practices included construction of flood control impoundments, eroding gully treatment, and conservation tillage. Following conversion of conventional-till (moldboard and chisel plough) to no-till wheat in 1983, nitrogen export was reduced 14.5 kg ha^{-1} yr^{-1} (3 fold) and P loss 2.9 kg ha^{-1} yr^{-1} (10 fold; Fig. 4; Sharpley and Smith, 1994). A year later, eroding gullies were shaped and an impoundment constructed in the other subwatershed, and P loss decreased dramatically (5 and 13 fold, respectively; Sharpley et al., 1996b). There was no effect of BMP implementation, however, on P concentration in flow from the main Little Washita River watershed (Fig. 4). Thus, a lack of effective targeting of BMPs and control of major sources of P export in the Little Washita River watershed contributed to no consistent reduction in watershed export of P.

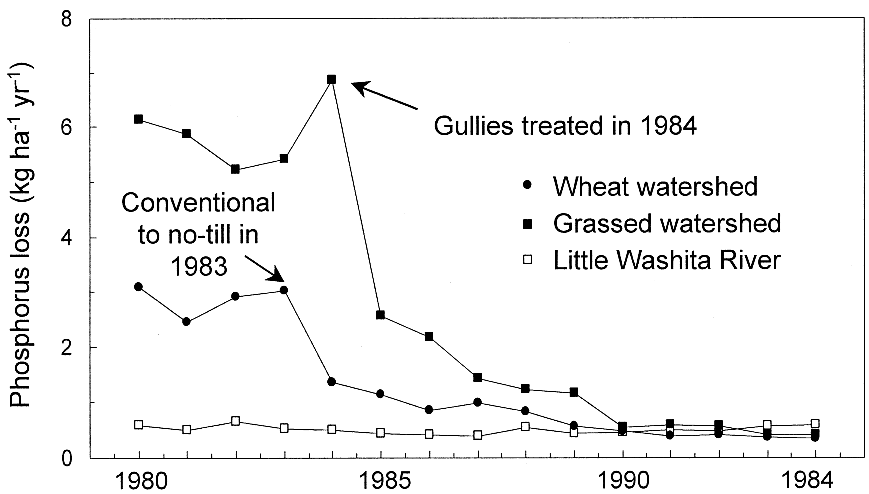

Figure 4. Annual P loss from the Little Washita River watershed and from two subwatersheds that were in grass with eroding gullies treated in 1984 and wheat converted from conventional to no-till in 1983 (adapted fro Sharpley and Smith, 1994; Sharpley et al., 1996b).

Incentives for BMP Adoption

In order to initiate real and lasting changes in agricultural production, emphasis must be placed on consumer-based programs and education rather than assuming that farmers will absorb the burden. Acceptance of BMPs will not be easy. Because farmers' decisions are generally shaped by regional and often global economic pressures and constraints, which they have little or no control over, there is often reluctance to adopt management practices that do not address these concerns. Clearly, new ways of using incentives to help farmers implement BMPs are needed. The challenge is to recognize how social policy and economic factors influence the nutrient-management agenda.

Equally important is that everyone is affected by and can contribute to a resolution of nutrient-related concerns. Rather than assume that inappropriate farm management is responsible for today's water quality problems, the underlying causes of the symptoms must be addressed. As shown above, much of today's problems result from system level changes. The cause of today's problems are related to marketplace pressures, the breakdown and imbalances in global P cycling, and economic survival of farms. Research is, thus, needed to develop programs that encourage farmer performance and stewardship to achieve previously agreed upon environmental goals. These programs should focus on public participation to resolve conflicts between economic production efficiency and water quality.

In the U.S., there are numerous sources of technical assistance and financial cost-share and loan programs to help defray the costs of constructing or implementing practices that safeguard soil and water resources. Some of these sources are Conservation Technical Assistance (CTA), Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), Special Water Quality Incentives (SWQI), Wetlands Reserve Program (WRP), and Wildlife Habitat Incentive Program (WHIP) (U.S. EPA, 1998). Elsewhere, watershed-based programs, such as the New York City Watershed Agriculture Program, have been established to provide technical assistance and financial support to farmers participating in water quality protection programs.

Stakeholder alliances encourage collaborative, rather than adversarial, relationships among concerned parties. Such alliances have been formed in response to recent public health issues related to the nutrient enrichment of waters in the eastern U.S. In the Chesapeake Bay, stakeholder alliances have developed among state, federal, and local groups and the public to work together to identify critical problems, focus resources, include watershed goals in planning, and implement effective strategies to safeguard soil and water resources (Chesapeake Bay Program, 1995; 1998). Similarly, in New York a Watershed Agriculture Council was formed of farmers, civic leaders, and representatives from the New York City Department of Environmental Protection to help guide management in the New York City Watershed.

Another way of making some environmental programs more affordable is to increase public awareness and involvement. In the northeast U.S. for example, a multi-agency collaborative venture, called the Dairy Network Partnership, has just released Chesapeake Milk in Fresh Fields Stores. For every half-gallon of Chesapeake Milk sold, 2.5 cents will be returned to the certified Pennsylvania dairy farmers to reward their high environmental standards. Another 2.5 cents will be deposited into an Environmental Quality Initiative (EQI) that will provide a cost-share for those farmers who want to install conservation practices to qualify for the EQI program.

SUMMARY

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

Future advisory programs should reinforce the fact that not all fields contribute equally to P export from watersheds. Most P export comes from only a

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small portion of the watershed as a result of relatively few storms. Although soil P content is important in determining the concentration of P in agricultural runoff, surface runoff and erosion potential will often override soil P levels in determining P export. If water or soil do not move from a field or below the root zone, then P will not move. Clearly, management systems will be most effective if targeted to the hydrologically active source areas in a watershed that operate during a few major storms.

Manure management recommendations will have to account for site vulnerability to surface runoff and erosion, as well as soil P content, because not all soils and fields have the same potential to transfer P to surface runoff and leaching. As a result, threshold soil P levels should be used in conjunction with site management and P transport potential.

Phosphorus applications at recommended rates can reduce P loss in agricultural runoff via increased crop uptake and cover. It is of vital importance that we implement management practices that minimize soil P buildup in excess of crop requirements, reduce surface runoff and erosion, and improve our capability to identify fields that are major sources of P loss to surface waters.

Overall;

- Management systems should attempt to balance P inputs and outputs at farm and watershed scales.
- Source and transport controls should be targeted to identified critical source areas of P export from watersheds.
- Threshold soil P levels that guide manure applications should be linked with site vulnerability to P loss.

Consideration of all these factors will be needed to develop extension and demonstration projects that educate farmers, the livestock industry, and the general public as to what is actually involved in ensuring clean water. Hopefully, this will help overcome the common misconception that diffuse or nonpoint sources are too difficult, costly, or variable to control or target substantial reductions.

Efforts to implement defensible remedial strategies that minimize P loss from agricultural land will require interdisciplinary research involving soil scientists, hydrologists, agronomists, limnologists, and animal scientists. Development of guidelines to implement such strategies will also require consideration of the socio-economic and political impacts of any management changes on both rural and urban communities and of the mechanisms by which change can be achieved in a diverse and dispersed community of land users.

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