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A.N. Sharpley, T. Daniel, G. Gibson, L. Bundy, M. Cabrera, T. Sims, R. Stevens, J. Lemunyon, P. Kleinman, and R. Parry

Sharpley is a soil scientist with the USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA; Daniel is a professor with the Department of Crop Soil and Environmental Sciences, University of Arkansas, Fayetteville, AR; Gibson is a senior scientist with the U.S. Environmental Protection Agency, Office of Science and Technology, Washington, DC; Bundy is a professor with the Department of Soil Sciences, University of Wisconsin, Madison, WI; Cabrera is a professor with the Department of Crop and Soil Sciences, Plant Sciences Building, University of Georgia, Athens, GA; Sims is a professor with the Department of Plant Science, University of Delaware, Newark, DE; Stevens is an extension soil scientist with the Crop and Soil Sciences Department, Washington State University, Prosser, WA; Lemunyon is an agronomist with the USDA-Natural Resources Conservation Service, Resource Assessment Division, South Regional Center, Fort Worth, TX; Kleinman is a soil scientist with the USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA; and Parry is an agriculture policy specialist with the U.S. Environmental Protection Agency, Washington, DC.

Abstract

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While phosphorus (P) is essential for profitable crop and livestock agriculture, its loss in watershed runoff accelerates eutrophication of receiving surface waters. The best management practices (BMPs) to mitigate P transfers to surface water include soil and water conservation practices, other management techniques, and social actions appropriate for specific agronomic, environmental, and socioeconomic conditions. Source BMPs are designed to minimize P available to runoff and reduce farm P imports by changing animal feed rations or adding feed additives that increase livestock P-use efficiency. Source BMPs also involve treating manure to lower its soluble P content, managing soil P levels, moving manure from surplus to deficit areas, and finding alternative uses for it other than land application. Transport BMPs are designed to limit runoff, erosion, and leaching as important pathways of P loss. These include such practices as conservation tillage, terracing, and stream buffers. When implementing BMPs, it is critical that the most appropriate BMP, or suite of BMPs, be selected, targeted, and implemented in a watershed, while following recommended installation and maintenance guidelines. Because source and transport BMPs do not address the main problem of farm and regional P surpluses, long-term solutions must extend beyond the farm gate. Advances in crop and livestock breeding, feed processing, and manure utilization hold promise. Also, since many BMPs involve costs and management changes, which will most likely have negative impacts on farm income, fair and equitable financial support and technical assistance through cost-share programs will improve BMP adoption.

Keywords: best management practice (BMP), conservation management, eutrophication, livestock, manure, nonpoint source pollution, phosphorus (P), P loss, runoff, soil conservation.

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Introduction

Phosphorus (P), an essential nutrient for crop and animal production, can accelerate freshwater eutrophication (Carpenter et al. 1998, Sharpley 2000). Recently, the U.S. Environmental Protection Agency (EPA) (1996a) and the U.S. Geological Survey (1999) identified eutrophication as the most ubiquitous water-quality impairment in the United States. 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, an increasing number of surface waters and public drinking water supplies have experienced periodic and massive harmful algal blooms (for example, *cyanobacteria* and *Pfiesteria piscicida*), which contribute to summer fish kills, unpalatability of drinking water, formation of carcinogens during water chlorination, and links to neurological impairment in humans (Kotak et al. 1993, Burkholder and Glasgow 1997).

Though concern over eutrophication is not new, there has been a profound shift in our understanding of, and focus on, sources of P in water bodies. Since the late 1960s, the relative contributions of P to water bodies from point and nonpoint sources have changed dramatically. On one hand, 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 of identifying point sources. On the other hand, less attention has been directed to controlling nonpoint sources of P (table 1), due mainly to the difficulty in their identification and control (Sharpley and Rekolainen 1997). Thus, control of nonpoint sources of P is a major hurdle to protecting fresh waters from accelerated eutrophication (Sharpley et al. 1999, Sharpley and Tunney 2000, Withers et al. 2000).

The Evolution of Agriculture From P Sink to P Source

While a variety of nonpoint sources, ranging from suburban lawns to construction sites to golf courses, contributes P to water bodies, agriculture, particularly intensive animal agriculture, is receiving increasing attention (Lander et al. 1998, Sharpley 2000). This may be attributed to the evolution of agricultural systems from net sinks of P, where deficits of P limit crop production to net sources of P, and where P inputs in feed and mineral fertilizer can exceed outputs in farm produce. Over the last 50 years, for example, more than 600 tonnes of P were applied to agricultural land worldwide compared with about 250 tonnes of P removed as produce. The trend of increased fertilizer use in crop production has divided farming systems over the last 50 years, creating specialized crop and animal feeding operations (AFOs) that efficiently coexist in different regions within and among countries. During the last 10 years in the United States, cattle, pig, and poultry numbers increased from 10 percent to 30 percent, while the number of farms on which they were reared decreased from 40 percent to 70 percent (Gardner 1998). This intensity was caused by a greater demand for animal products and an improved profitability associated with economies of scale and has resulted in a major one-way transfer of P from grain-producing areas to animal-producing areas (Sims 1997, Sharpley et al. 1998b, Lanyon 2000).

Since animals do not utilize P in feed efficiently, most of the P entering animal operations ends up in manure, which is usually land applied within 10 miles of where it was produced. Animal manure can be a valuable nutrient resource for improving soil structure and increasing vegetative cover, thereby reducing surface runoff and erosion potential (Barthès et al. 1999, Gilley and Risse 2000). However, in geographic regions of the United States where dense concentrations of concentrated animal feeding operations (CAFOs) exist, adequate land area for proper disposal of manure is usually in short supply. Because of this and improper manure management, long-term monitoring studies have shown that the greatest potential for accelerated eutrophication of nearby surface waters occurs in watersheds with high populations of CAFOs (Kellogg and Lander 1999, McFarland and Hauck 1999). Not only can surface waters be impaired but ground water can also be threatened. Researchers have confirmed movement of P to subsurface waters in heavily manured areas of the Delmarva Peninsula

Table 1. Sources and factors influencing P loss*

Factors	Description
Application method	P loss increases in this order: subsurface injection, plowed under, and surface broadcast with no incorporation
Application rate	The more P (fertilizer or manure) applied, the greater the risk of P loss
Application source	The P in some fertilizers and manures is more soluble than in others and, thus, more susceptible to runoff
Application timing	The sooner it rains after P is applied, the greater the risk for P loss
Connectivity to stream	The closer the field to the stream, the greater the chance of P reaching it
Erosion	Total P loss is strongly related to erosion
Irrigation runoff	Improper irrigation management can increase P loss by increasing surface runoff and erosion
Proximity of P-sensitive water	Some watersheds are closer to P-sensitive waters than others (that is, point of impact)
Sensitivity to P inputs	Shallow lakes with large surface areas tend to be more vulnerable to eutrophication
Soil P	As soil P increases, P loss in sediment, surface runoff, and subsurface flow increase
Soil texture	Soil texture influences relative volumes of surface and subsurface flow
Subsurface flow	In sandy, organic, and P-saturated soils or soils with preferential pathways, P can leach through the soil
Surface runoff	Water serves as the transport mechanism for P either off or through the soil

* Factors listed alphabetically.

and through soil to tile drains in major regions of the Midwest and Southeast (Sims et al. 1998).

Does this mean that the Nation is destined for poor water quality? Is it impossible to reap the efficient protein production benefits of the CAFO system while maintaining good water quality? Absolutely not! Why? Because there is a long history of researching, developing, implementing, and demonstrating management practices that can greatly minimize water-quality impacts to both surface and ground water. Traditional erosion control practices central to farm management plans for maintaining high water quality represent the products of research that began in the 1930s. When these traditional conservation practices were implemented in earlier U.S. Department of Agriculture watershed studies, dramatic differences in water quality occurred between watersheds with conservation practices and those without (Dragoon and Miller 1966, Schuman et al. 1973, Spomer et al. 1973). These practices, when implemented on a watershed basis, were shown to reduce sediment yield and concentration by altering watershed hydrology. Today, an arsenal of traditional and cutting-edge technology exists to address nutrient pollution from farms.

What Are Best Management Practices (BMPs)?

Best management practices include soil and water conservation practices, other management techniques, and social actions that are developed for a particular region as effective and practical tools for environmental protection. Rarely does one single practice or action solve the pollutant concern, but often it is a combination of measures that is used. Individual producers must decide which combination of BMPs is best suited to their farm enterprise, taking into account the specific soils, climate, and management factors.

BMPs range from measures that involve a change in farming operations, like conservation tillage and crop rotation, to simple actions such as not applying manure before forecasted rainfall. The cost of implementing some BMPs can be high, such as structural measures like manure storage systems. Other BMPs carry no apparent cost, as in the case of delayed manure application. A heightened level of total farm enterprise management is required with animal manures and nutrients. Certainly more time is required for planning and decisionmaking when soil and manure testing, crop rotations, yield goal recommendations, and application timing and methods have to be considered.

The list of BMPs for P management includes traditional as well as new evolving technology, such as feed management now being demonstrated in the field (table 2). While a comprehensive list may exist, what works in one geographic region may not work in another because of variation in climate, soils, geology, and so forth. Even so, do they really work and how well? The purpose of this publication is to answer these and other questions relating to BMPs that are designed to minimize potentially negative impacts on water quality associated with the management of P in agricultural production systems.

Controlling Phosphorus at the Source

It is generally less expensive to treat the cause of eutrophication than to treat its effects. For example, in the early 1990s, New York City decided that it was more cost effective to identify the sources of P in its water supply watersheds and target them for remediation, rather than build new water filtration facilities. Since then, a variety of farm-specific management plans and BMPs have been implemented to reduce nonpoint sources of P in the New York City watershed (Scott et al. 1998, National Research Council 2000). Similarly, there is increasing awareness within Europe that installing expensive P-stripping facilities at wastewater treatment plants, as required under the European Community Urban Waste Water Directive (Council of the European Communities 1991), will not provide the desired improvement in water quality without management of diffuse sources (nonpoint sources) from agriculture in sensitive watersheds (Kronvang et al. 1993, Withers et al. 2000).

Any approach to controlling P losses from agriculture must begin with the long-term objective

Table 2. Phosphorus best management practices

Source BMPs—practices that minimize P loss at the origin

1. Balance P inputs with outputs at farm or watershed scale
2. Minimize P in livestock feed
3. Test soil and manure to maximize P management
4. Physically treat manure to separate solids from liquid
5. Chemically treat manure to reduce P solubility, that is, alum, flyash, and water treatment residuals
6. Biologically treat manure, that is, microbial enhancement
7. Calibrate fertilizer and manure spreaders
8. Apply proper application rates of P
9. Use proper method for P application, that is, broadcast, plowed in, injected, subsurface placement, or banding
10. Carefully time P application to avoid imminent heavy rainfalls
11. Implement remedial management of excess P areas (spray fields and disposal sites)
12. Compost or pellitize manures and waste products to provide alternate use
13. Mine P from high-P soils with certain crops and grasses
14. Manage urban P use (lawns and gardens)

Transport BMPs—practices that minimize the transport of P

15. Minimize erosion, runoff, and leaching
16. Use cover crops to protect soil surface from erosion
17. Terrace to minimize runoff and erosion
18. Practice strip cropping to minimize runoff and erosion
19. Practice contour farming to minimize runoff and erosion
20. Manage irrigation to minimize runoff and erosion
21. Practice furrow management to minimize runoff and erosion
22. Install filter strips and other conservation buffers to trap eroded P and disperse runoff
23. Manage riparian zones to trap eroded P and disperse runoff
24. Install grass waterways to trap eroded P and disperse runoff
25. Manage wetlands to trap eroded P and disperse runoff

Table 2. Phosphorus best management practices (continued)

Transport BMPs—practices that minimize the transport of P

26. Manage drainage ditch to minimize erosion
27. Stabilize streambank to minimize erosion
28. Fence streambank to keep livestock out of water course
29. Protect wellhead to minimize bypass flow to ground water
30. Install and maintain impoundments to trap sediment and P

Source and transport BMPs—systems approach that minimize P loss

31. Retain crop residues to minimize erosion and runoff
32. Consider reduced tillage systems to minimize erosion and runoff
33. Manage grazing (pasture and range) to minimize erosion and runoff
34. Restrict animals from certain sites
35. Install and maintain manure handling systems (houses and lagoons)
36. Manage barnyard storm water
37. Install and maintain milkhouse waste filtering systems
38. Practice comprehensive nutrient management planning (CNMP)
39. Install and maintain tailwater return flow ponds

Water body treatment BMPs—practices designed to correct problems associated with excess P in water

40. Remove sediment from water bodies
41. Inactivate sedimentary P (alum and straw)
42. Stimulate aerobic conditions
43. Enhance vegetative growth in littoral zones to decrease water-column mixing
44. Practice vegetative mining of sedimentary P
45. Harvest aquatic vegetation

of increasing P-use efficiency by attempting to balance P inputs within a watershed with P outputs, while simultaneously improving the management of soil, manure, and mineral fertilizer P at farmgate, watershed, or regional scales. Reducing P loss in agricultural runoff may be brought about by BMPs that control the source and transport of P, such as those listed in table 2. An initial part in the BMP implementation process is designating where and to what extent water quality is impaired.

Setting Regional Water Quality Standards

The National Regional Nutrient Criteria Program in the U.S. Environmental Protection Agency, Office of Water sets regional water quality standards for nutrients. To do this, reference conditions or background levels found in pristine streams, lakes, reservoirs, and other surface waters in a given geographical area are identified (figure 1). Waters are monitored for total P, total N, chlorophyll-*a,* and clarity where there is the least amount of human impact. These values become a benchmark against which similar watercourses in the area can be compared (Gibson et al. 2000) (figure 1). The difference between the reference condition for P and current measurements from a given stream or lake indicates the relative extent of management required to protect or restore the nutrient quality of that water to an approximately “natural” state. Pristine waters that existed before European settlement are almost impossible to achieve, but a reasonably natural condition reflecting reduced cultural impacts of human activities can be identified. The reference condition for P approach makes it possible to demonstrate that such minimally affected waters do in fact exist for that type and locale so that management efforts can be based on realistic background conditions for each geographic (ecoregional) area.

The significance of these regional nutrient criteria to agriculture is that resource managers and concerned farmers have an attainable target of P reduction to aim for in planning conservation farming practices. While these criteria have application to the regulatory function of EPA, in that nutrient standards and permit limits can be derived, criteria values are also suitable for voluntary planning and evaluation purposes. These nutrient reference condition values are available for freshwater streams, rivers, lakes, and reservoirs in the continental United States and can be obtained from the nutrient coordinator at the regional EPA office (appendix).

With these target values in mind, a given watershed can be divided into constituent subwatershed land units and the goal of a particular P level can be parceled out among the tributary systems. Subsequently, individual farmers can target P load amounts as their equitable share of the water quality protection objective. This, of course, is subject to considerable variability with an understanding of the hydrologic load capacity for those particular streams, the delivery rate from soils and slopes draining to those streams, and seasonal changes in precipitation. Specialists from EPA, USDA’s NRCS and USDA’s Cooperative State Research, Education, and Extension Service can assist in the development of individual target P values. When these goals are established, then the techniques and methods of P abatement can be adopted for development of a cost-effective, environmentally responsive farm management plan.

Source BMPs

Source management attempts to minimize buildup of P in the soil above levels sufficient for optimum crop growth by regulating P at the farmgate, controlling the quantity of P in manure, and controlling the amount of P that is applied in a localized area (table 3).

Farmgate Management of P

Fertilizer management

The excessive import of mineral fertilizers onto farms and overapplication of fertilizer P to agricultural soils are generally not seen as major causes of nonpoint source P pollution, because economic forces currently promote efficient management of fertilizers, and extension efforts have long been geared toward this area. The basis for efficient fertilizer management is regular soil

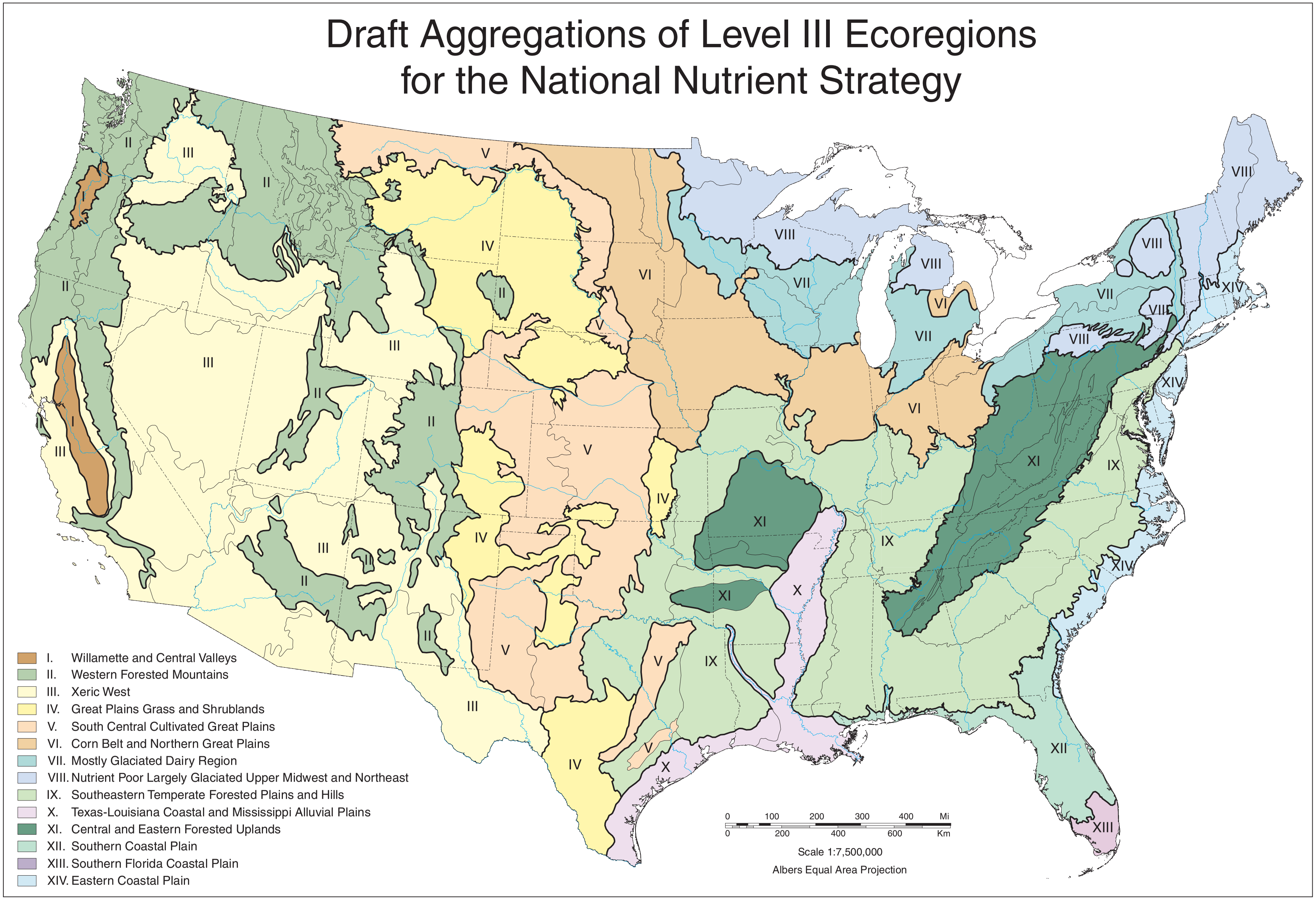

Figure 1. Ecoregions with similar reference conditions or background levels of nutrients found in pristine streams, lakes, reservoirs, and other surface waters. Data from the National Regional Nutrient Criteria Program, Gibson et al. 2000.

Table 3. Potential for feed management strategy to impact manure P

Feeding strategy	P loss reduction
Ruminants and nonruminants	*%*
Diet formulated closer to requirement	10 to 15
Growth promotion	5
Protein / carbohydrate enzymes	5
Use of highly digestible feeds	5
Phase feeding	5 to 10
Ruminants	
Reduced P in diet	20 to 30
Nonruminants	
Phytase / low-P diet	20 to 30
Phytase / low-P diet / high available P corn	40 to 60

SOURCE: Data from Federation of Animal Science Societies 2001.

testing, selection of appropriate nutrient application rates to meet reasonable crop yield expectations, and prescriptive application of mineral fertilizer using recommended methods that maximize availability of applied nutrients to growing crops (Havlin et al. 1999). These practices are elucidated later as part of the discussion of field management practices.

Feed P management

Addressing farmgate imbalances of P is fundamental to reducing nonpoint source P loss. Manipulation of dietary P intake by animals will help reduce P inputs as feed, often the major cause of P surplus (table 3). Phosphorus intake above minimum dietary requirements established by the National Research Council (NRC) (2001) does not appear to confer any growth or health advantages but actually reduces profitability through increased feed costs (Knowlton and Kohn 1999). The NRC recently published new guidelines for dairy cattle P requirements that reduced P from 0.38 percent to 0.31 percent for cows producing 25 to 50 kg day^{-1} of milk, based on recent research on the effects of P feeding level on milk production and reproductive performance (National Research Council 2001).

Carefully matching dietary P inputs to animal requirements can reduce the amounts of P excreted by animals (Poulsen 2000, Valk et al. 2000). For example, data summarized from 2 years of research on lactating dairy cows show a linear relationship between P intake and fecal P excretion (Wu et al. 2000, 2001) (figure 2). According to this relationship, a reduction in dietary P from 0.48 percent to 0.38 percent can result in 30 to 35 percent less manure P. This will have an obvious impact on farm P balance by reducing the potential on-farm accumulation of P and decreasing the land base needed for a balanced P-management plan.

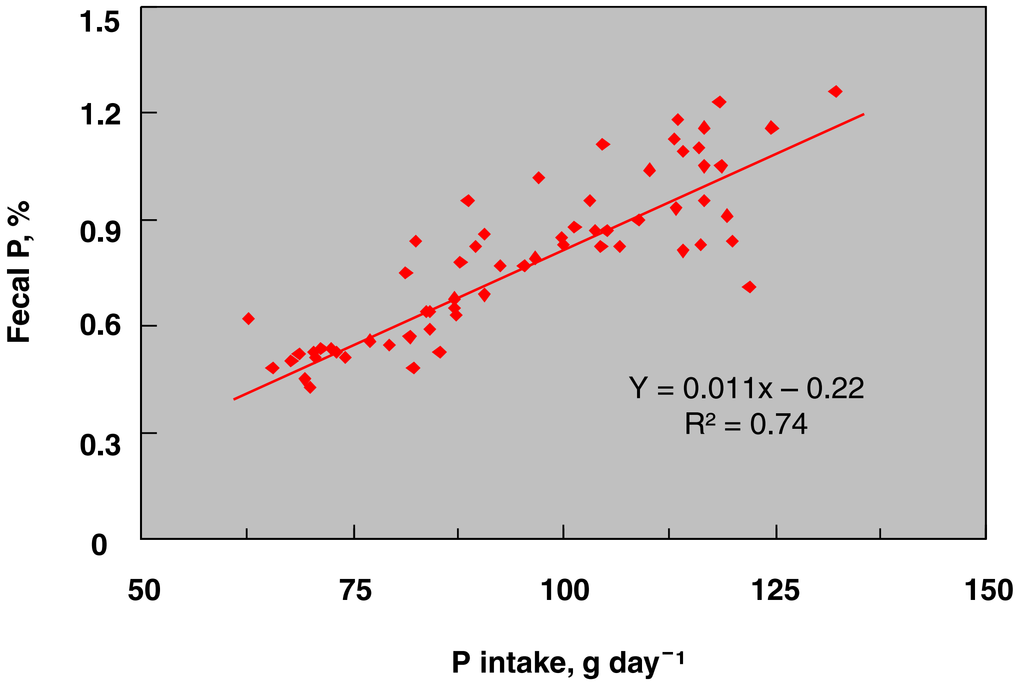

Figure 2. P excreted by lactating dairy cows is a function of P intake. Data from Wu et al. 2000, 2001.

Powell et al. (2001) showed that, at a recommended dairy diet P level of 0.38 percent P, land application of the manure generated would require 0.7 hectares per cow to avoid increasing soil test P (figure 3). In contrast, an excessive dietary P level of 0.55 percent would increase the area needed for manure spreading to 1.2 hectares per cow or would increase soil test P by 2.2 ppm per year if no additional land were available. On farms where manure P exceeds crop P requirements, reducing dietary P to the NRC recommendation would reduce the number of farms and acreage with an excess P balance by approximately one-half (Powell et al. 2002) (figure 3). In addition to inorganic P supplementation of livestock feed, some protein supplements can contribute substantial amounts of P to animal diets (National Research Council 2001). Common protein supplements vary greatly in cost and P content (0.3 to 4.7 percent P), and producers often select protein sources based on economics, not P content. For operations where an excess P balance exists, protein supplements with lower P concentrations should be selected (table 3).

Recently, Ebeling et al. (2002) showed that increasing the P concentration in dairy cow diets increased the potential for P loss in runoff from land-applied manures, even at the same P application rate. For example, total P losses in runoff from plots receiving high-P diet manure (108 kg P ha^{-1}) were 6 times greater (194 g total P ha^{-1}) than in runoff (31 g total P ha^{-1}) from low-P diet manure (40 kg P ha^{-1}) plots. When high- and low-P diet manures were applied at the same P rate (40 kg P ha^{-1}), total P losses in runoff were still greater from the high-P (67 g total P ha^{-1}) than from the low-P diet manure (31 g total P ha^{-1}) (Ebeling et al. 2002). This difference is likely due to a greater proportion of manure P being water soluble in high-P (40 percent) rather than in low-P diet manure (29 percent).

Export of P in produce

Carefully matching fertilizer P applications to match crop needs and yield goal potentials minimizes the accumulation of P in soil, with most of the added P being removed in crop produce as grain or forage (Haygarth et al. 1998, Sharpley et al. 1999, Withers et al. 1999). The export of manure and associated P, however, is not as easily accomplished.

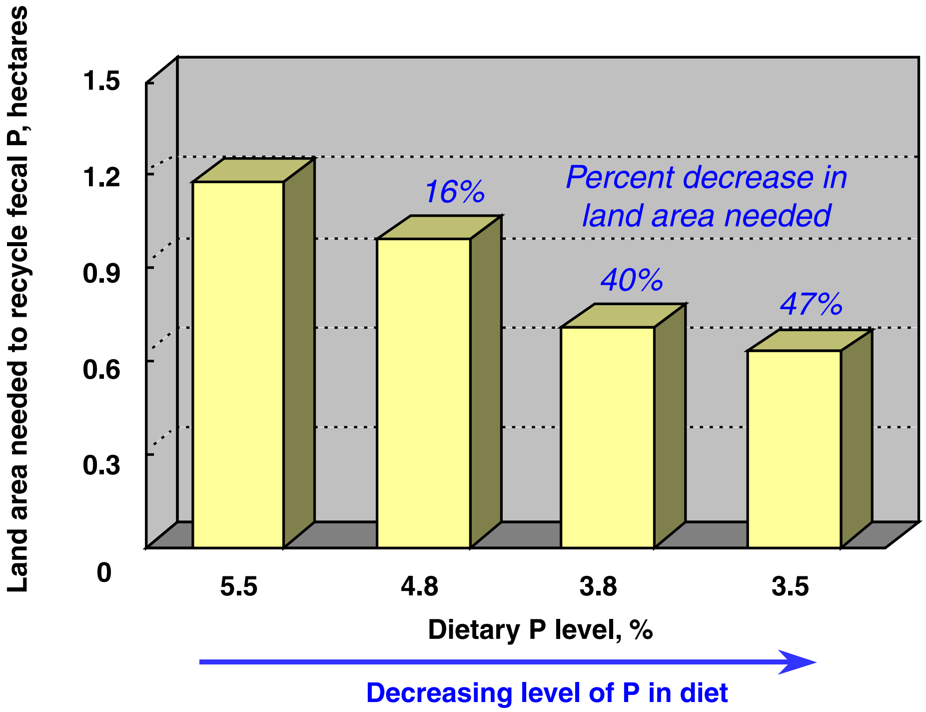

Figure 3. Reducing P level in a cow's diet reduces the area of land needed to recycle manure P. Annual cropping system comprised of 47% alfalfa, 37% corn grain, 9% soybean, and 7% corn silage having harvested dry matters of 11.2, 7.4, 2.9, and 17.2 mg ha^{-1}, respectively, and an area weighted P removal of 30 kg P ha^{-1}. Data from Powell et al. 2001.

At present, manure export from the farm is not considered a widely viable management option, though regulatory forces are increasingly driving the development of novel alternatives. Because the costs of hauling manure usually preclude its transport across long distances from its source, off-farm land application options are generally restricted to the nearest neighbors. Exceptions to these generalizations are increasing even though dewatering of liquid manure is essential to improving its value as a commercial source of fertilizer nutrients. Alternative uses of manures that currently represent feasible off-farm exporting options include composting, methane/energy generation, granulating/pelletizing, and even aquaculture, which are discussed in the section on "Manure Management and Alternative Uses" on pages 15-16.

Feed additives

A significant amount of the P in grain is in phytate, an organic form of P that is digested in low proportions by monogastric animals such as pigs and chickens. As a result, it is common to supplement feed with mineral forms of P. This supplementation contributes 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 animals such as pigs and chickens (photo 1). Such enzymes reduce the need for P supplements in feed and potentially reduce the total P content of manure (table 3).

In addition, corn hybrids are available that contain low amounts of indigestible phytate P. Pigs and chickens that were fed "low-phytic acid" corn grain excreted less P in manure than those fed conventional corn varieties (Ertl et al. 1998). This study also showed that P availability to nonruminants from low phytate, high available phosphate (HAP) corn is about 2 to 3 times higher than from normal corn. Currently, the challenge to plant breeders is to incorporate the low-phytate trait into commercial corn hybrids with other agronomically desirable traits (Doerge 1999). Combining phytase-feed amendments with low-phytate corn (Baxter et al. 1998) resulted in a 60-percent reduction in P excreted by swine (table 3).

Manure P Management

Chemical amendments

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 (Shreve et al. 1995, Moore et al. 2000). For example, treating broiler litter prior to flock growout with alum is proving to be one of the most popular BMPs because it not only reduces ammonia in the house but also reduces P concentration in the runoff by 85 percent once the material is land applied (Shreve et al. 1995). Perhaps the most important benefit of manure amendments for air and water quality would be an increase in the N:P ratio of manure by reduced N loss through NH_3 volatilization. An increased N:P ratio of manure would more closely match crop N and P requirements.

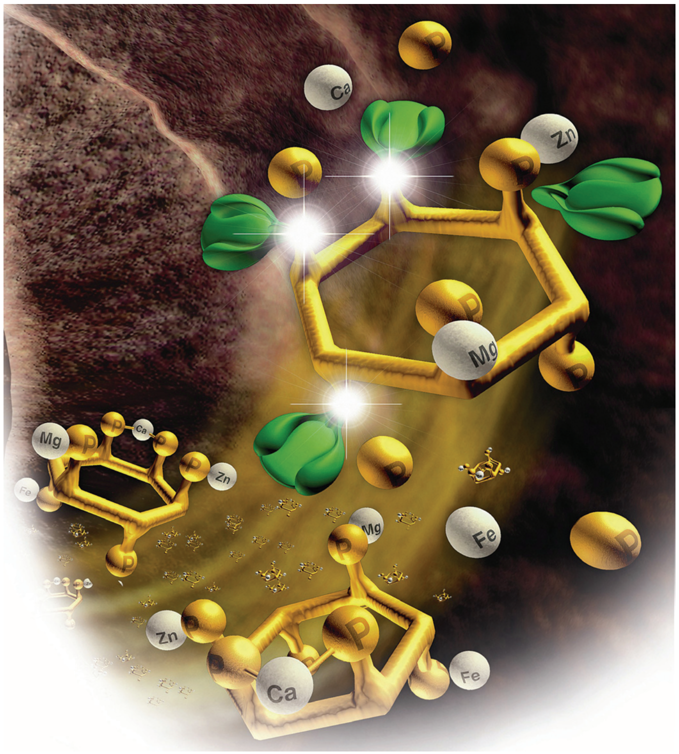

Photo 1. The addition of phytase enzymes to pig and poultry feed can increase grain P absorption by the animal, decreasing the need for mineral P supplements and thereby reduce the amount of P excreted. Photo courtesy of BASF.

Physical treatment

Large dairy and swine operations commonly rely on flush-water systems for managing their manure. While such systems are very efficient and rank high in overall cleanliness, large volumes of slurry high in solids and soluble nutrients are produced. Because of the transportation cost involved with such volumes, the slurry is usually land applied in close proximity to the production houses, which elevates the P content of the soil above that required by the crop. Coagulant and flocculent techniques commonly used by municipalities are also being used to solve such problems. For example, researchers have shown that using a metal coagulant, such as aluminum (Al) in combination with commercial polymers (polyacrylamide), not only doubles the removal of solids but also dramatically reduces the soluble P in the effluent (Temby et al. 2004). While this does not change the total amount of nutrients that must be handled, it enables better targeting of individual nutrients to locations where they will do the most good and have less potential for causing environmental problems. In addition, because the solid fraction is more concentrated, it is more feasible to transport it to remote fields or have it serve as the input stream for other biosolids products.

Sieving to separate fine and coarse fractions may increase management options for manures such as poultry litter. While P and K are uniformly distributed throughout the litter, the concentration of N is commonly greatest in the fine fraction, which results in an increase in the N:P ratio of that fraction (Ndegwa et al. 1991). A larger N:P ratio is desirable because the N:P ratio in unfractionated poultry litter is much smaller than that required by plants. In addition, the proportion of mineralizable N can be larger in the fine fraction than in the unfractionated litter (Cabrera et al. 1994).

Managing P Applications to Soil

Soil testing

Rates of P application are usually established by crop needs and modified according to what is already in the soil as measured by soil test P (STP) methods. The USDA-NRCS recommends soil sampling and testing at a minimum of every 3 years (USDA-NRCS 2002). Soil sampling depths are generally recommended to the bottom of the plow horizon for cultivated fields (15 to 30 cm) and to shallower depths (5 to 10 cm) for fields under conservation tillage and pastures. Environmental P sampling depths may be even shallower (< 5 cm), as the extreme soil surface serves as the source of P to runoff.

In commercial fertilizer P, applications can easily be tailored to match crop needs and minimize excessive accumulations of P in soil because an economic incentive exists if it is not overapplied. However, applications of manure have been made to meet the N needs of the crop, until recently. This has resulted in the buildup in STP above levels needed for optimum crop yields and in some situations has increased P loss in runoff (Sharpley et al. 1996a, Sims et al. 1998, Pote et al. 1999). Furthermore, a poultry litter application tailored to meet pasture N demands can have an effect on surface runoff P for up to 19 months after application (Pierson et al. 2001).

Manure testing

Sampling and testing manure to determine nutrient content is necessary for proper nutrient application to fields. Concerns include representative manure sampling and rapid application of manure followed by receipt of manure analysis to ensure that the condition of applied manure corresponds to the sample. Until recently, concerns over nitrate leaching into ground water had prompted N-based manure application at rates that met crop N requirements. As P-based manure management is mandated under certain contexts, manure P testing will be necessary to ensure compliance.

Manure P tests generally quantify total P in manure. However, increasing use of amendments such as alum and coal combustion byproducts to reduce P solubility in manure has prompted the development of manure tests that estimate P solubility (water extractable manure P concentration) and serve as indicators of P loss in surface runoff (Kleinman et al. 2002a). In fact, Kleinman et al. (2002b) developed a simple method for the water extraction of P from manure that has already been adopted by several State soil testing laboratories as an environmental risk indicator and as input to the P Indexing tool (Wolf et al. 2002, Sharpley et al. 2003).

Rate, method, and timing of P applications

The rate, method, and timing of P applications can minimize the potential for P loss in runoff (Withers and Jarvis 1998, Sharpley et al. 1998b). As might be expected, P loss in runoff increases with greater applications of P as fertilizer or manure (McDowell and McGregor 1984, Edwards and Daniel 1993, Sharpley et al. 2001) (figure 4). Though 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. Incorporation of manure into the soil profile either by tillage or by subsurface placement decreases the potential for P loss in runoff (figure 5). Mueller et al. (1984) showed that incorporating dairy manure by chisel plowing reduced total P loss in runoff from corn by 20-fold when compared to no-till areas that received surface applications. In fact, P loss in runoff decreased with a lower concentration of P at the soil surface and a reduction in runoff when incorporating manure (Mueller et al. 1984, Pote et al. 1996).

Because 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 should reduce the potential for loss. Also, an increase in the length of time between applying manure and a rainfall or runoff event will reduce P transport in runoff

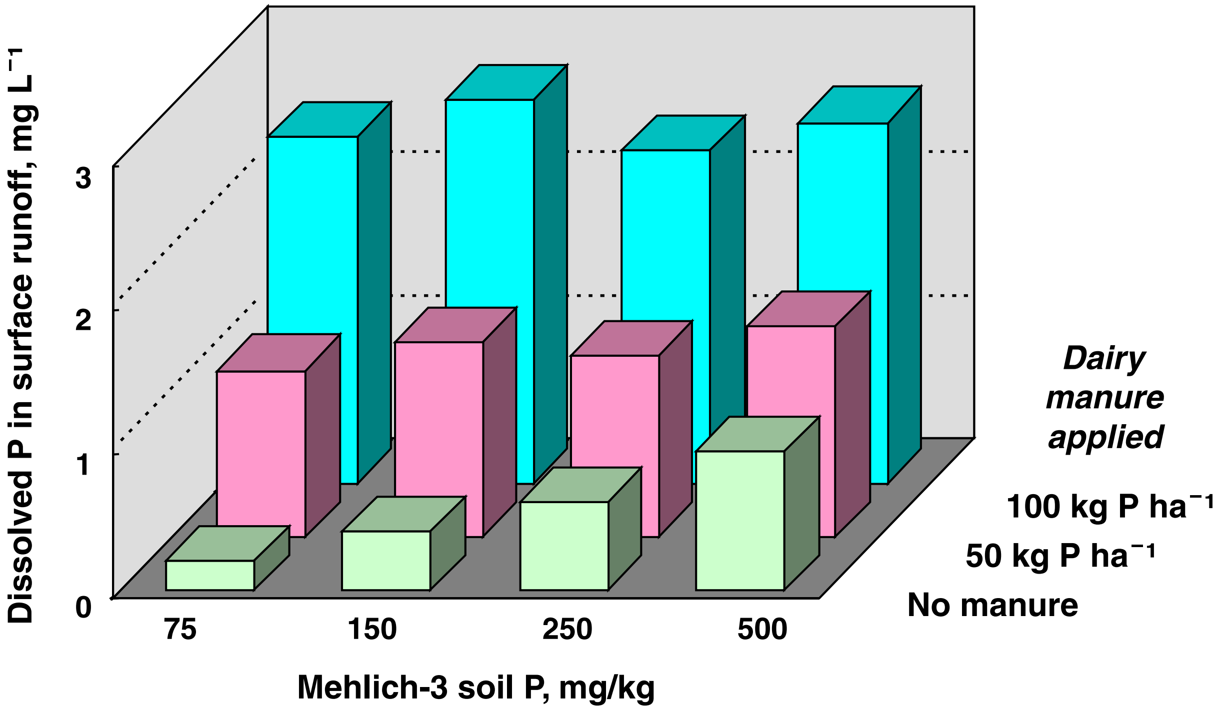

Figure 4. The concentration of P in surface runoff from a grassed Berks silt loam, as a function of Mehlich-3 soil P concentration. When dairy manure is surface applied 2 weeks before the rainfall, application rate controls runoff P, with soil P having little influence. Data from Sharpley et al. 2001.

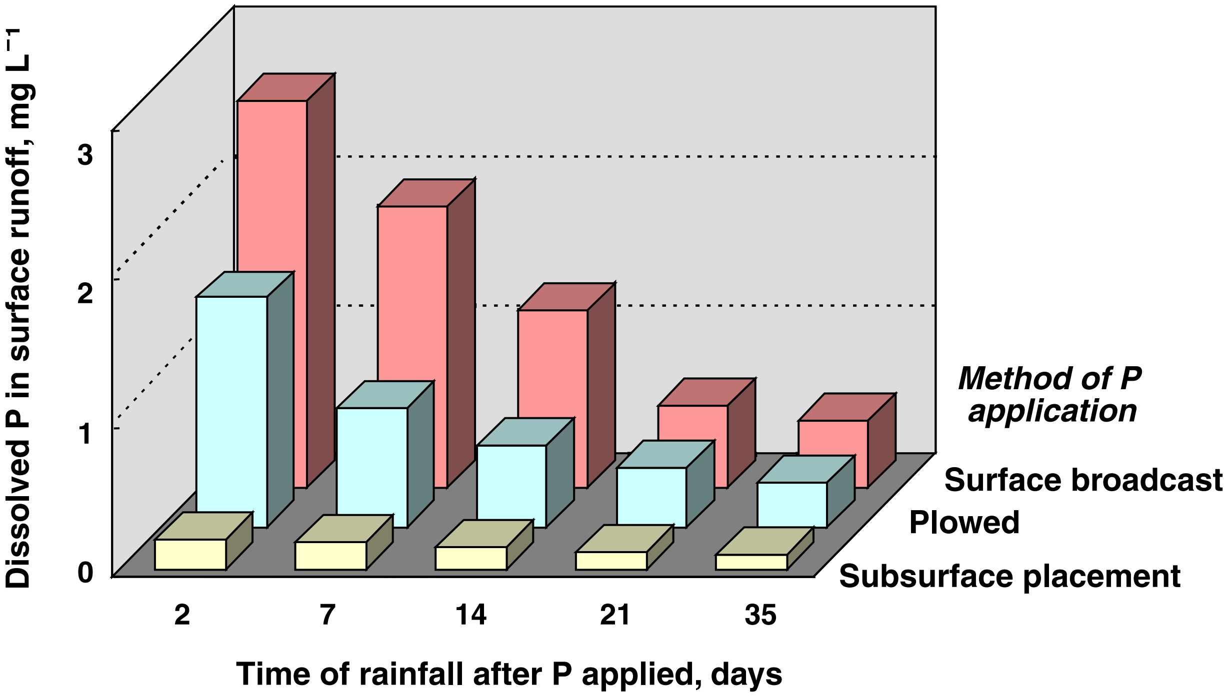

Figure 5. The effect of applying dairy manure (100 kg P ha^{-1}) and how it was applied on the concentration of P in surface runoff from a grassed Berks silt loam decreases with time after application. Data from Sharpley et al. 2001.

(Westerman and Overcash 1980, Sharpley 1997) (figure 5). Though these measures may reduce the risk for P loss in runoff, they are often not practical 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 when manure or litter is applied.

To fully realize the potential of land applying manure, there is still a need for development and use of manure application equipment that can be calibrated easily and accurately. This is probably more critical with the application of solid manures and on farms that apply several types of manures, where a spreader may need to be regularly recalibrated.

Assessing site vulnerability to P loss

As we move from agronomic to environmental concerns with soils containing P levels in excess of crop requirements, soil P testing is being used to indicate when P enrichment of runoff becomes unacceptable and when manure applications should be reduced or stopped altogether. However, knowledge of STP levels, and, for that matter, fertilizer or manure applications alone, provides an incomplete perspective of P loss potential and is 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 underscored by the observation that most of the P exported (> 75 percent) from many agricultural watersheds comes from a small definable part of the landscape (< 20 percent of land area) during a few storm events (Gburek and Sharpley 1998). Therefore, STP 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. In addition, there is the potential for catastrophic events (hurricanes, large snowmelts, and chronic rainstorms) that can dislodge soil and organic material and create large runoff amounts. These types of events often remove soil and P material that has been sequestered in the landscape for many years.

A P Indexing system was developed to identify the vulnerability of P loss in areas or fields (Lemunyon and Gilbert 1993). The P Index accounts for ranked transport and source factors controlling P loss in surface and subsurface flow from a given site. The Index is one of the most successful approaches that address this concept in a holistic way by attempting to combine important P loss variables into a practical program that assesses a specific field’s potential for P loss. A survey of 50 states enacting comprehensive nutrient management planning (CNMP) strategies showed that 47 adopted the P Index approach, which suggests a scientific and legislative consensus towards the P Index on which to base P management recommendations as part of the CNMP strategy (Sharpley et al. 2003). Other states are developing and implementing individual P Indexes that address local conditions, as encouraged by the original designers. While some states include BMPs as a component of the Index, others do not.

Soil amendments and plowing

Given the relationship between soil P and runoff or leachate P, a variety of management options that reduce either soil P or soluble P alone has been examined. Stout et al. (1998) determined that gypsum produced as a coal combustion byproduct reduces P solubility in soil without significantly reducing plant-available P. Elsewhere, Sharpley (2003) determined that deep tillage can decrease soil test P (as Mehlich-3 P) from 65 to 90 percent as a function of subsoil clay and Mehlich-3 P. Once grass was established and erosion minimized (about 20 weeks after plowing and planting), total P concentration in surface runoff was 1.79 mg L^{-1} compared with 3.4 mg L^{-1} prior to plowing, with dissolved P reduced from 2.9 to 0.3 mg L^{-1}. These potential benefits to surface runoff P by plowing highly P-stratified soils, result from the combined effects of dilution of high P surface soil and an increased sorption of P. Thus, the one-time plowing of P-stratified soils may reduce the long-term loss of P in surface runoff as long as plowing-induced erosion is minimized, providing landowners an additional option in keeping these soils in production under P-based nutrient management strategies.

While such options address the proximate concern of excessive soil P levels, they should not be seen as solutions to the greater problem of overapplication 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.

Manure Management and Alternative Uses

In areas where a high density of concentrated animal operations and manure production exceeds local or regional crop needs, the development of alternative uses of manure can be critical to the sustainable coexistence of these operations with unimpaired waters. Several alternative uses for manures are becoming available (figure 6).

Manure storage

As livestock continually generate manure, storage facilities provide farmers with flexibility in manure management, particularly in cases where manure must be land applied. Specific storage options vary with livestock type and individual farm characteristics, ranging from cement storage pads to anaerobic and aerobic lagoons to oxidation ponds and ditches (Day and Funk 1998). For instance, Giasson (2002), in evaluating manure storage options for New York dairy farms currently land applying manure on a daily basis, found that installation of manure lagoons with a 3-month storage capacity resulted in the most cost-effective control of nonpoint source P losses.

Clearly, storage of manure will allow greater flexibility in timing applications. A wide range of storage methods and costs are available to farmers. Inexpensive plastic sheeting can perform well at a very low cost for some solid manure. However, all storage methods must be managed carefully to fully realize their potential in an agronomically and environmentally sound BMP. Also, stored manure must be spread as part of a CNMP that includes appropriate timing and rates of manure application.

Transporting manure

Manure is rarely transported more than 10 miles from where it is produced, which severely restricts disposal options. As a result, manure is often applied to soils with sufficient nutrients to support

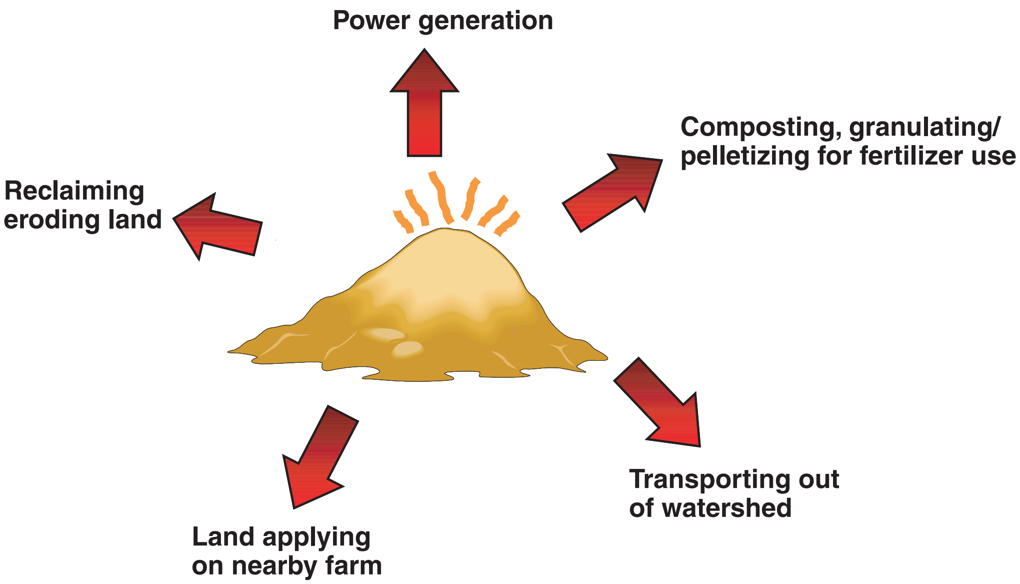

Figure 6. Management and alternative uses for manure other than land application on livestock producer's farm.

crop growth. Mechanisms need to be established to transport manure from surplus areas to deficit areas. However, it must be shown that the recipient farms are more suitable for manure application than the 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 could reach excessive levels.

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

Composting manure

Composting may also be considered a management tool to improve manure distribution, because it makes manure more uniform in its physical and chemical properties and therefore able to be spread more evenly and at more accurate rates (Day and Funk 1998, Osei et al. 2000). Though composting tends to increase the P concentration of manure, the volume and thus transportation costs are reduced. Additional markets may also become available for composted materials.

Manure can also be used along with biosolids and woodchips to reclaim soils that have been disturbed, for example, by mining and urban construction. In these cases, manure can be used as an excellent soil conditioner for reclamation of mine sites, urban lawn improvements, and major developments where topsoil or subsoil conditioning is needed.

Manure as a bioenergy source

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. These processes reduce the volume of manure needing to be managed and require the utilization or disposal of residual by-product material (ash). As the value of clean water and the cost of sustainable manure management are realized, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost effective, and create expanding markets. Again, the most efficient long-term solution is to match livestock numbers with the utilization area.

Transport BMPs

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, designed and managed riparian zones, terracing, contour farming, cover crops, and impoundments (for example, settling basins) (figure 7). Basically, these practices reduce rainfall impact on the soil surface, reduce runoff volume and velocity, increase soil resistance to erosion, and trap sediment.

Conservation tillage

Conservation tillage practices are designed to reduce runoff and erosion but appear to have differential effects on dissolved and particulate P losses. Given the effect of surface application of fertilizers and manures on runoff P losses, conservation tillage, particularly no-till, may exacerbate runoff P losses. Mueller et al. (1984) found that incorporating dairy manure by chisel plowing reduced total P loss in runoff from corn 20-fold when compared with no-till areas that broadcast and unincorporated applications of manure. Sharpley and Smith (1994) summarized the results of unit watershed experiments in Oklahoma and found that the conversion of conventional moldboard plow wheat to no-till wheat decreased total P concentrations in surface runoff but increased dissolved P concentrations.

Cover crops

Cover crops serve to protect soil surface from raindrop impact, improve infiltration relative to bare soil, and trap eroded particles (Sharpley and Smith 1991). In areas where dissolved P transport is the primary concern, cover crops may reduce runoff and, consequently, runoff P load (mass) but are unlikely to impact dissolved P in runoff. Kleinman et al. (2001) found that cover crops reduced total P concentration in springtime runoff to 36 percent of dissolved P in runoff from conventional corn. However, dissolved P concentrations were not significantly different between cover crops and conventional corn, because they were controlled by soil P content rather than by erosion.

Artificial drainage

The benefit of artificial drainage to P transport remains controversial (Dils and Heathwaite 1999). In areas where surface drainage of regional water tables is an integral component of agronomic management, ditches and other man-made drainage features may channel runoff directly to water bodies, truncating natural flow pathways and exacerbating P transport. Similarly, numerous studies have documented elevated P concentrations, both dissolved and total P, in tile drainage (Sims et al. 1998). As with surface drains, subsurface drains essentially create a shortcut using lateral preferential flow pathways, which under natural conditions are often discontinuous and tortuous (Simard et al. 2000). Despite such findings, it remains unclear whether benefits in reduced runoff potential from artificial drainage are outweighed by the costs of introducing preferential flow pathways.

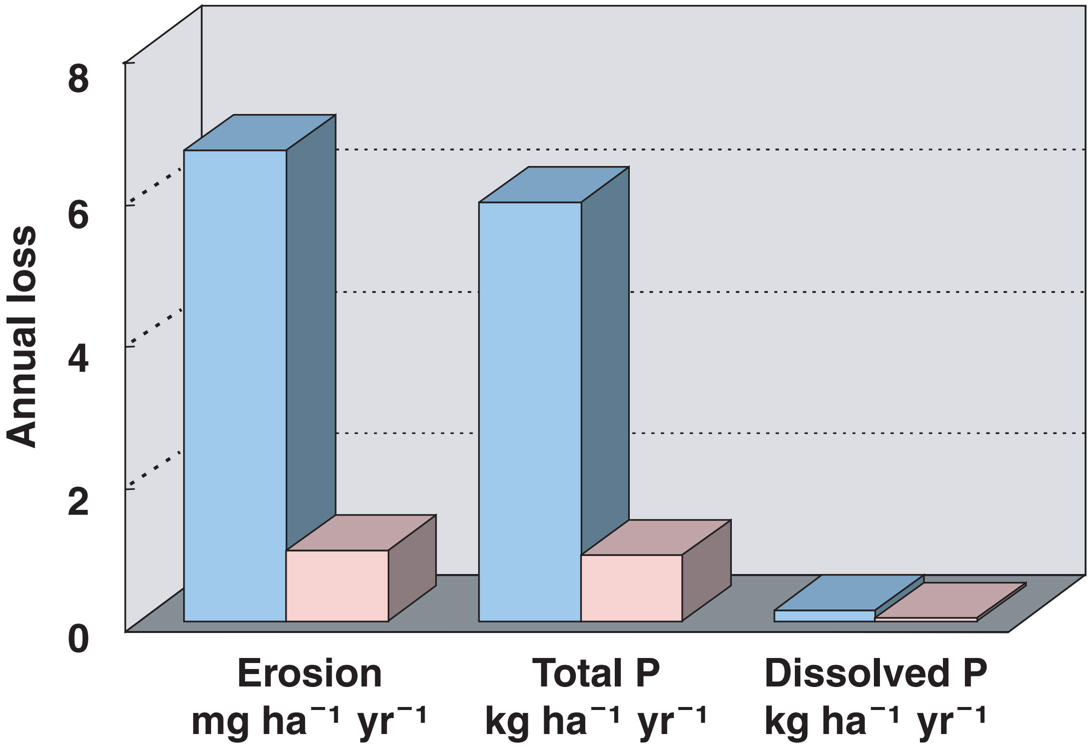

Figure 7. An alfalfa cover crop decreased erosion and P loss from conventionally tilled wheat fields in Oklahoma. Data from Sharpley and Smith 1991.

Grassed waterways

Grassed waterways are designed to trap sediment and reduce channel erosion. In some cases, they may be installed as cross-slope diversions designed to intercept runoff and break up effective slope length (photo 2). Chow et al. (1999) estimated that the installation of a grassed waterway or terrace combination produced a 20-fold reduction in annual erosion from a potato field in New Brunswick, Canada.

Irrigation management

Erosion under irrigation can greatly exceed that induced by natural rainfall, exacerbating particulate P losses in runoff (Lentz et al. 1998). In general, furrow irrigation is associated with the largest potential for erosion, followed by sprinkler, and then drip irrigation (Koluvek et al. 1993). Application of mulches to furrows or treatment of irrigation water with polyacrylamide can greatly reduce erosion and thus lower the potential for particulate P losses (Lentz et al. 1998).

Conservation buffers

Riparian areas can increase wildlife diversity, numbers, and aquatic habitat, as well as reduce P export. In addition to acting as physical buffers to sediment-bound nutrients, plant uptake captures P, resulting in a short-term and long-term accumulation of nutrients in biomass (Peterjohn and Correll 1984, Lowrance et al. 1985, Groffman et al. 1992, Uusi-Kamppa 2000) (figure 8).

A paired watershed study conducted in Connecticut evaluated the effectiveness of a 30-m riparian buffer of fescue (with woody species near the stream edge) adjacent to a field of silage corn (Clausen et al. 2000). Concentrations of total P and total suspended solids in surface runoff were reduced by 73 percent

Photo 2. Grassed waterways prevent erosion on cultivated fields. Photo by Jeff Vanuga from NRCS photo library.

and 92 percent, respectively. Another paired watershed study conducted in Vermont evaluated the effectiveness of field-edge buffers of mixed-grass legumes (7.5- and 15-m widths) in minimizing nutrient losses in runoff from a cornfield (Jokela et al. 1999). Preliminary results show significant reductions in total P and sediment concentrations in runoff with implementation of a 15-m buffer strip.

However, the effectiveness of conservation buffer areas as nutrient buffers can vary significantly. For instance, the route and depth of subsurface water flow paths, through riparian areas, can influence nutrient retention. Conservation buffers are most efficient when sheet flow rather than channelized flow occurs, because channelized flow often bypass(es) some of the retention mechanisms. Thus, these areas must be carefully managed to realize their full retention and filtration capabilities.

Barnyard runoff management

Two fairly inexpensive transport BMPs associated with feedlots or animal loafing areas are the installation of gutters and downspouts on barns and sheds. This is a simple way to divert clean rain water away from these areas and reduce runoff volumes. Similarly, a berm, constructed around the upslope side of the feedlots or loafing areas, can divert clean water and minimize the potential for runoff of P and erosion.

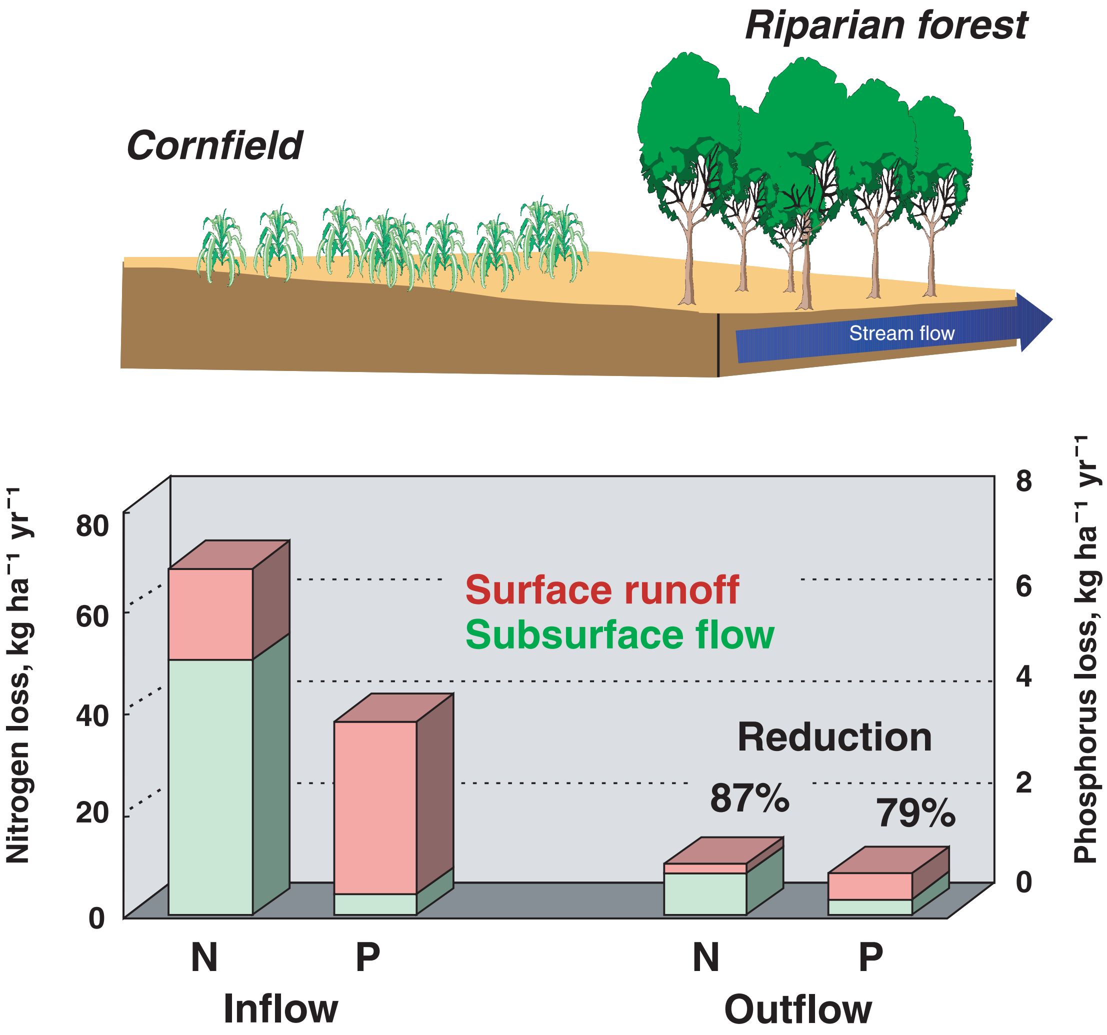

Figure 8. The loss of P and N in surface runoff and subsurface flow from cultivated fields in the Chesapeake Bay watershed can be decreased by well-managed conservation buffers along the riparian zones. Data from Peterjohn and Correll 1984.

Streambank protection

Streambank protection and fencing is another simple BMP that can reduce erosional inputs of P and direct deposition of manure in streams, respectively. Both BMPs were included in a recent remedial strategy for the Chesapeake Bay (Boesch et al. 2001). The effect of streambank protection, restoration, and livestock exclusion with fencing on the water quality of streams was evaluated in a larger-scale paired watershed study in north-central Vermont (Meals 2000). Following 3 years of calibration, the restoration and fencing treatment was implemented on approximately half of the pastured stream length in the treated watershed, which represented stream exclusion of 97 percent of the pastured livestock. Significant reductions in concentrations of total P, N, total suspended solids (TSS), and bacteria were measured resulting in 30- to 50-percent decreases in mass export of P, N, and TSS to the stream. Even with these reductions, streambank protection and fencing have not been a popular practice with many farmers and, thus, not widely implemented.

Off-stream water sources for cattle are another BMP that may reduce P contamination of surface waters. In a study conducted in Virginia, Sheffield et al. (1997) found that installation of an alternative water source reduced streambank erosion by 77 percent and total P concentration in the stream by 81 percent. The availability of water troughs away from the stream reduces the amount of time cattle spend in or near the stream (Godwin and Miner 1996, Sheffield et al. 1997).

Constructed wetlands and sediment basins

Constructed wetlands and sediment basins serve to reduce particulate P by intercepting sediment-laden flow. House et al. (1994) determined that a constructed wetland could reduce total P concentrations by 86 percent, with certain wetland species (for example, *Phragmites spp.*) substantially improving nutrient removal efficiency. Soon, constructed wetlands may attenuate dissolved P as it flows through the wetland. Finite sorption capacities of constructed wetlands and seasonal oxidation and reduction fluctuations may render constructed wetlands ineffective in controlling long-term losses of dissolved P (Mitsch and Gosselink 1986, Novotny and Olem 1994).

Despite these advantages, none of these measures should 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. In addition, 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 Kirkland 1986, Knuuttila et al. 1994). 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.

Integrating P and N Management in BMPs

Farm N inputs are usually more easily balanced with plant uptake than are P inputs, particularly where confined animal operations exist. In the past, separate strategies for either P or N were 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 control can negatively affect the other nutrient (table 4). 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 (Sims 1997, Sharpley et al. 1998b). 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) (figure 9).

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 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

Table 4. Best management practices for control of nonpoint sources of agricultural P and N

Practice	Description	Impact on loss	
		P	N
Source Measures			
Feed supplements	Match animals' nutritional requirements	Decrease	Decrease
Feed additives	Enzymes increase nutrient utilization by animals	Decrease	Decrease
Crop hybrids	Low phytic-acid corn reduces P in manure	Decrease	Neutral
Manure management	Compost, lagoons, pond storage; barnyard runoff control; and transport excess out of watershed	Decrease	Decrease
Rate of application	Match crop needs	Decrease	Decrease
Timing of application	Avoid application to frozen ground and apply during season with low runoff probability	Decrease	Decrease
Method of application	Application can be through incorporation, banding, or injecting in soil	Decrease	Decrease
Source application	P sources can differ in their P solubility	Decrease	Neutral
Crop rotation	Sequence different rooting depths to mine P	Neutral	Decrease
Manure amendment	Alum reduces NH_3* loss and P solubility	Decrease	Decrease
Soil amendment	Flyash, Fe oxides, and gypsum reduce P solubility	Decrease	Neutral
Cover crops / residues	If harvested, can reduce residual soil nutrients	Decrease TP[†] Increase DP[‡]	Decrease
Invert stratified soils	Redistribute surface P through profile by plowing	Decrease	Neutral

Table 4. Best management practices for control of nonpoint sources of agricultural P and N —continued

Practice	Description	Impact on loss	
		P	N
Transport Measures			
Cover crop	Do not leave soil bare during winter	Decrease	Decrease
Conservation tillage	Reduced and no-till cropping can increase infiltration and reduce soil erosion	Decrease TP[†] Increase DP[‡]	Decrease TN[§] Increase NO_3**
Grazing management	Keep animals away from streams and avoid overstocking	Decrease	Decrease
Buffer, riparian, wetland areas, grassed waterways	Remove sediment-bound nutrients and enhance denitrification	Decrease TP[†] Neutral DP[‡]	Decrease
Soil drainage	Tiles and ditches enhance water removal and reduce erosion	Decrease TP[†] Increase DP[‡]	Decrease TN[§] Increase NO_3**
Strip cropping, contour tillage, terraces	Reduce transport of sediment-bound nutrients	Decrease Neutral DP[‡]	Decrease Neutral NO_3**
Sediment delivery structures	Protect and stabilize streambank and sedimentation pond	Decrease	Decrease
Critical source area treatment	Target sources of nutrients in a watershed for remediation	Decrease	Decrease

* NH_3 Ammonia
† TP Total P
‡ DP Dissolved P
§ TN Total N
** NO_3 Nitrate

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 BMPs

Since the early 1980s, several studies have investigated the long-term (7 to 10 years) effectiveness of BMPs to reduce P export from agricultural watersheds. These studies quantified nutrient loss before and after BMP implementation or attempted to use untreated watersheds as controls. Overall, these studies showed that BMPs reduced P export from several watersheds. For example, water quality improvements have been demonstrated following BMP implementation in several areas of the U.S. (National Water Quality Evaluation Project 1988, USDA-Agricultural Stabilization and Conservation Service 1992, Goldstein and Ritter 1993, Richards and Baker 1993, Bottcher and Tremwell 1995). 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 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 with N. Studies have shown that even where P applications are stopped, elevated soil P can take up to 20 years to decline from crop uptake and removal to levels where crops will respond to additional 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.

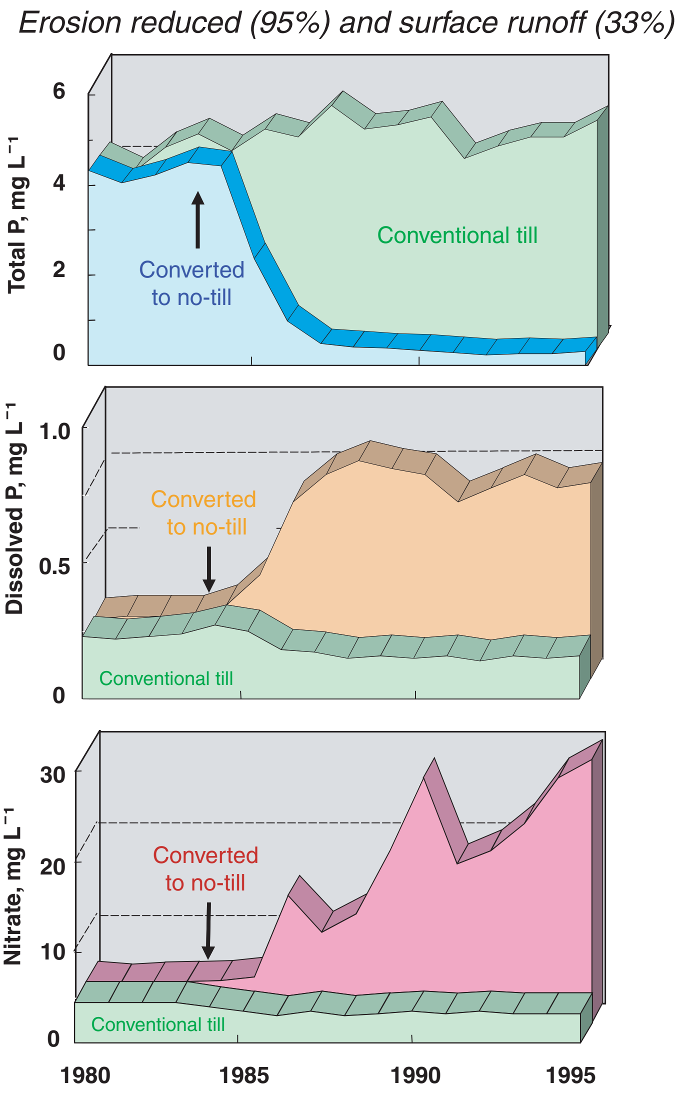

Figure 9. The conversion of conventional moldboard plow wheat to no-till wheat decreased total P transport in surface runoff but increased dissolved P in runoff and ground water nitrate (3 to 25 m) for several watersheds in Oklahoma. Data from Sharpley and Smith 1994.

Given 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, riparian areas and manure management (chemical amendments, storage, waste treatment, and barnyard runoff

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

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.
SOURCE: Data from USDA-ASCS 1992, Heathman et al. 1995.

control) can reduce runoff P more than tillage management, but conservation tillage is often a more cost-effective measure and may be preferable. Thus, it is advisable to determine the load reduction required for a given watershed and water body before selecting 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 facilities (table 6). Post-BMP losses of P were lower than those 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 to select appropriate BMPs. According to the example of the two watersheds in table 6, the most effective BMP installation priorities would be barnyard runoff control, milkhouse waste treatment, and animal waste storage facilities. BMPs may not produce expected reductions in P export without careful prioritizing and targeting of critical sources within a watershed. One method of targeting BMPs to critical areas of P loss is by using the P Index developed by USDA-NRCS, in cooperation with several research scientists, to rank the vulnerability of fields as sources of P loss in surface runoff (Lemunyon and Gilbert 1993, Sharpley et al. 1998a, Gburek et al. 2000). The various transport and source factors controlling P loss in surface runoff are accounted for by the P Index, which ultimately ranks the risk of P movement from any given site. The P Index is intended to serve as a practical screening tool for use by extension agents, watershed planners, conservation district personnel, and farmers to identify and target BMPs available to land users, while providing some flexibility in developing nutrient management plans and remedial strategies.

The importance of targeting BMPs within a watershed or basin is shown by several studies across the United States. In the Chesapeake Bay, a

Table 6. Cost-effectiveness of animal waste management BMPs in the LaPlatte River Basin project, Vermont, 1980–1989

Management	Watershed 1		Watershed 2	
	P Reduction	Effectiveness	P Reduction	Effectiveness
	kg	\$ kg P^{-1}	kg	\$ 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

SOURCE: Data from Meals 1990.

coordinated and intensive program of BMP adoption was implemented in the mid-1990s to decrease nutrient inputs to the Bay through a combination of education, cost share, and technical assistance (Boesch et al. 2001). Those BMPs used include streambank protection, manure storage, cover crops, and reduced tillage with an emphasis on decreasing sediment (and associated P) in surface runoff. Nutrient management plans with field-by-field nutrient recommendations were developed for about one-fourth of the agricultural acreage by 1997. Despite these efforts, nonpoint source P load estimates have been decreased by only 9 percent after 10 years, compared with 58 percent of P from point sources (Boesch et al. 2001). For example, in the German Branch watershed of Chesapeake Bay, which was targeted for aggressive BMP implementation, P concentrations have remained at elevated levels (Millard et al. 1997).

Studies showed that, in the Little Washita River watershed (54,000 ha) in central Oklahoma, there was little change in P export following BMP implementation (Sharpley and Smith 1994) (figure 10). Nutrient export from 2 subwatersheds (2 and 5 ha) were measured from 1980 to 1994, while BMPs were installed on about 50 percent 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, N export was reduced 14.5 kg ha^{-1} yr^{-1} (3 fold) and P loss 2.9 kg ha^{-1} yr^{-1} (10 fold) (Sharpley and Smith 1994) (figure 10). 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). However, BMP implementation had no effect on P concentration in flow from the main Little Washita River watershed (figure 10). Thus, a lack of effective targeting of BMPs and control of major sources of P export in the Little Washita River watershed resulted in no consistent reduction in watershed export of P.

Land application of dairy manure in the LaPlatte River Basin, Vermont, (8,832 ha) has been identified as an important source of P to Lake Champlain (2.2 kg P ha^{-1} yr^{-1}) (Meals 1990). As a result, animal waste control measures were implemented in the Basin during the early 1980s. These BMPs included control of barnyard runoff, milkhouse waste treatment, and construction of waste storage facilities detailed in table 6. There was no apparent reduction in either DP or TP concentration in runoff with an increasing percent of animals in a watershed under a BMP (figure 11) (Meals 1990). If the runoff P values for watersheds where less than 50 percent of the animals were under BMPs are not considered, then DP and TP in runoff were decreased significantly (r^2 of 0.68 and 0.75, respectively; $p < 0.05$) (figure 11). The low values of implementation (< 42 percent) represent the initial years of land treatment when BMP implementation was in-complete. Apparently, there is a minimum

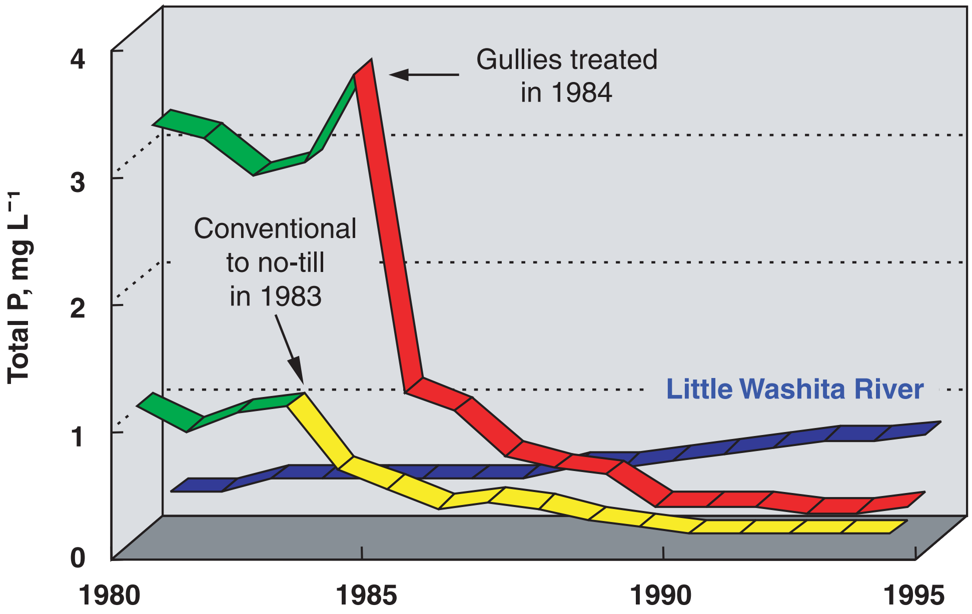

Figure 10. Where installed, BMPs (conversion of conventional to no-till wheat and gully restoration) decreased P loss but had no effect on losses from the whole watershed in the Little Washita River, OK. BMPs must be targeted to critical areas of P loss to be effective. Data from Sharpley and Smith 1994.

threshold level of implementation that must be achieved before a significant response to BMPs occurs.

These examples clearly demonstrate that careful targeting of BMPs at an appropriate level of intensity over sufficient time is required to effectively reduce P export from watersheds.

Selecting a BMP

The cost-effectiveness of BMPs for reducing P loss varies with the type of practice and watersheds used (tables 5 and 6). Remediation strategies are ongoing processes in which BMP selection and operation should be reevaluated continuously to optimize P export reductions.

Meals (1990) investigated the effectiveness of BMP implementation on P loss from Mud Hollow Brook watershed in Vermont, a contributor of P to the P-sensitive Lake Champlain. The watershed is 1,682 ha, of which 52 percent is hay, 21 percent pasture, 14 percent rural nonagriculture, 7 percent idle, and 6 percent corn. Dairy dominates animal activities in the watershed (80 percent), with 54 percent of the manure that is produced in-house being available for controlled field application. In the early 1980s, BMP implementation encompassed over 75 percent of the watershed and included animal waste management, conservation contour and strip cropping, pasture management, buffer zones, and streambank protection and diversion (Meals 1990). An initial evaluation determined that P export increased following BMP implementation. However, further analysis revealed that annual P export was dominated by some extremely high flows generally associated with snowmelt or intense rainfall events (Meals 1990). When these events were not included in the analysis, BMPs decreased P export. The capacity of BMPs to reduce P export was probably exceeded during these highly active runoff periods, representing less than 5 percent of the time and high-P export. Most of the time, however, BMPs functioned and P export was controlled or reduced. Thus, effective remedial strategies should consider such extreme events in situations where they can dominate P export.

Long-term monitoring of P budgets in farming and river systems in Ohio has found that, after nearly 20 years of BMP adoption and in spite of soil test P levels continuing to increase, there has been closer

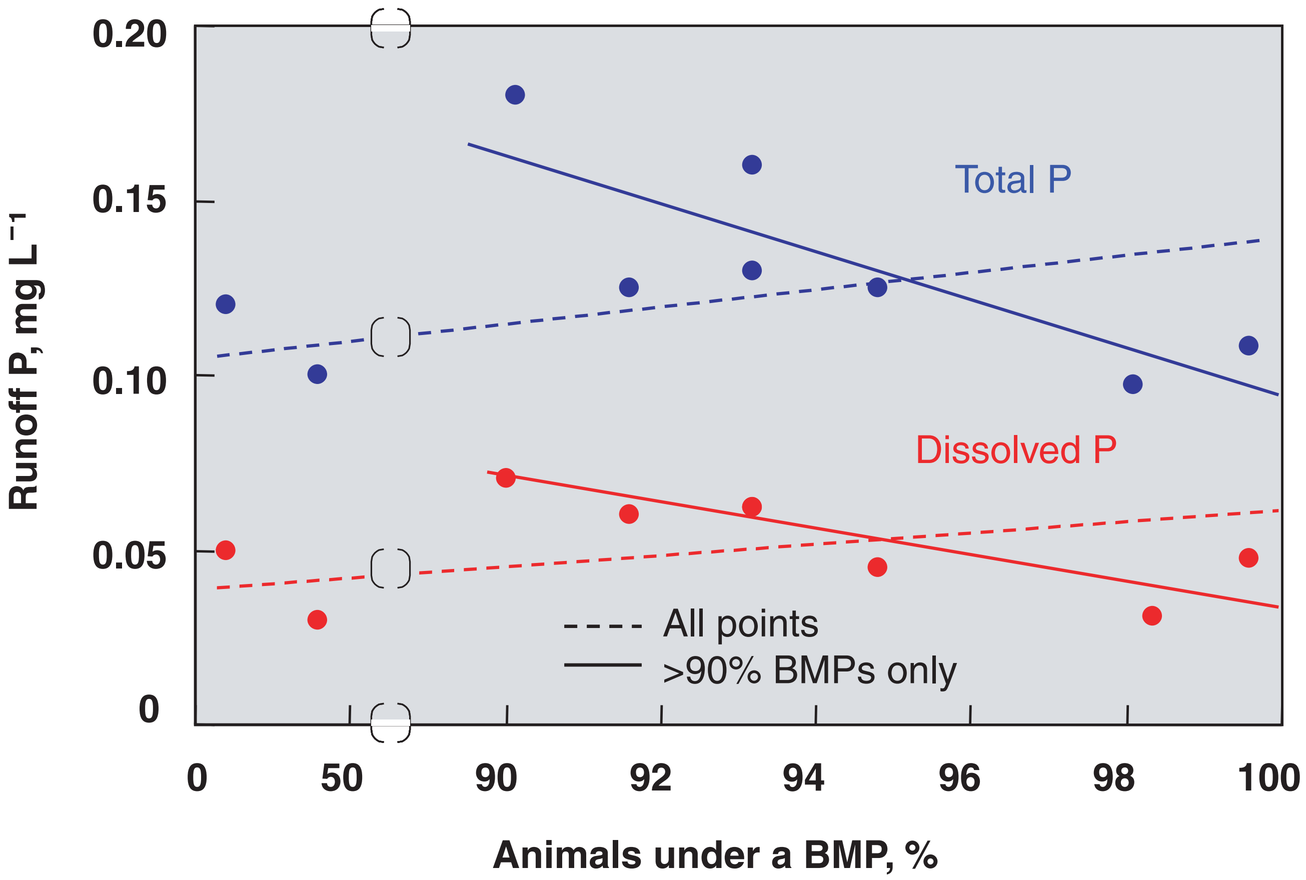

Figure 11. A critical level of BMP implementation (> 90%) will decrease mean annual P loss in the La Platte River Basin,VT. BMPs may not affect P loss until this level is reached. Data from Meals 1990.

management of P application and timing that has resulted in more efficient use of the nutrient and decreases in loss of soluble reactive P and total P (Baker and Richards 2002).

In an effort to better model the effect of BMPs on P export, Gitau et al. (2001) has assembled a large database of BMP efficacy from published studies. This effort involves the development of an interactive BMP database from which analyzed data can be extracted. An example of the type of information on BMP effectiveness that can be gleaned from such a database is shown in figure 12. Clearly, there is a wide range in the decrease of P loss after BMP implementation that is influenced by site-specific factors and weather (figure 12). Even so, general trends in efficiency are apparent, with dissolved P loss increasing after adoption of conservation tillage due to a buildup of surface soil P, though total P losses are more reduced (McDowell and McGregor 1984, Sharpley and Smith 1994) (figure 12). Similar reduction efficiencies are also developed for particulate P losses with BMP implementation (Gitau et al. 2001). Outputs from data analyses provide values that can be used as model inputs or modification factors, which enables simulation of post-BMP scenarios, thereby providing a basis for BMP selection.

Watershed and Surface Water Response

The response of watersheds and lakes to BMPs can often be delayed by watershed re-equilibration, internal recycling of P, incremental land treatment, difficulty in controlling natural sources, and short duration of monitoring. For example, a land treatment program involving animal waste management, cropland protection, permanent vegetative cover, nutrient management, and streambank protection was initiated in 1980 and

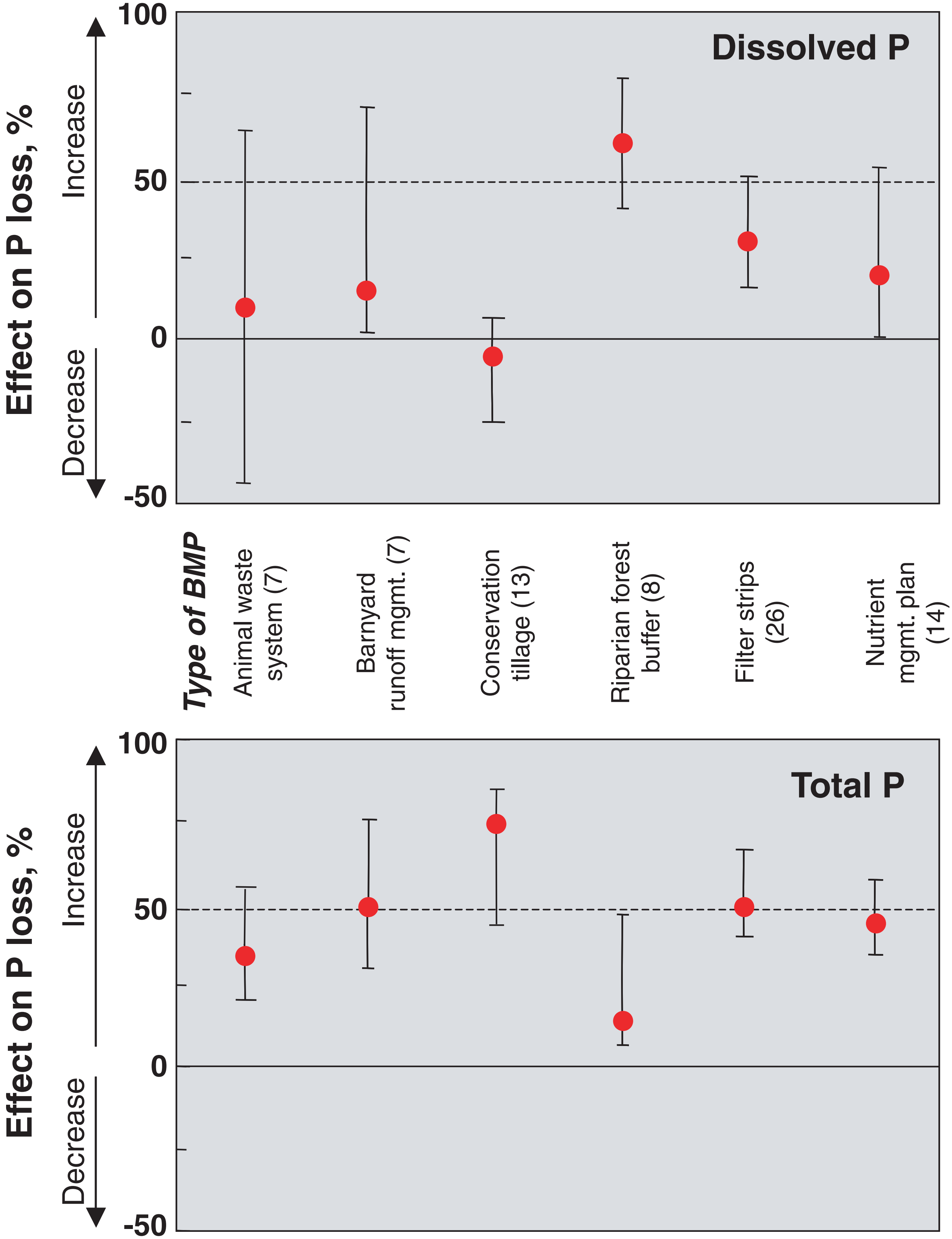

Figure 12. There is a wide range in effectiveness of various BMPs in decreasing P loss. The number of studies is in parenthesis. An increase effect on P loss means it is lower, that is, a benefit. Data from Gitau et al. 2001.

completed in 1991 on the St. Albans Bay watershed (13,000 ha—85 percent agriculture and forest) draining into St. Albans Bay of Lake Champlain (Meals 1992). Despite a significant reduction in mean annual P concentration in the main watershed tributary, after urban wastewater treatment was upgraded to include P removal in 1985, little subsequent decrease in P export was seen, possibly due to inadequate timing, type, or coverage of BMPs (figure 13).

In addition, the lag time between BMP implementation and water quality improvements may exceed the monitoring period (National Research Council 2001). While St. Albans Bay sediments appear to act as a reservoir for continued internal recycling and supply of P to overlying waters, many watershed soils with high P content will also continue to be a source of runoff P despite input or management changes (McDowell et al. 2002). Despite our knowledge of controlling processes, it is difficult for the public to understand or accept this lack of response. When public funds are invested in remediation programs, rapid improvements in water quality are usually expected and often required. Thus, effective BMP implementation should consider the re-equilibration of watershed and lake behavior, where P sinks may become sources of P with only slight changes in watershed management and hydrologic response. Education programs should also be established to highlight the long-term benefits of remedial measures.

Education and Technical Assistance

Development of sound extension and education programs are particularly important for the increasing number of farms integrating confined animal operations. Education and technical assistance are key to changing the traditional system of disposal of manure by land application into a system of managing nutrients and organics to match crop requirements and protect the surrounding environmental resources. In many areas, farmers with limited land have turned to concentrated animal feeding operations (CAFOs) as a possible source of steady income to supplement additional off-farm income. In such situations, farmers need sound information about proper manure-handling techniques to minimize possible water- and air-quality impacts because of the large amounts of manure that will be land applied.

Applying the Research

Dissemination of proper manure handling information is important to farmers who operate small areas (< 40 ha). These farmers often turn to confined animal operations to supplement inadequate cash returns on traditional grain and forage production due to local conditions of inherent low soil fertility, erratic rainfall, and reduced crop prices. Therefore, the local need for P additions for crop production will be lower than in areas of intensive crop or forage production. Many producers develop their skills as animal husbandmen at the expense of agronomic crop and soil management. Many farmers are still not fully aware of the nutrient value of applied manure. This illustrates the need for education and extension programs as well as an infrastructure that can collect, process, and redistribute manure to areas with high local demand for P.

Education starts with the basic knowledge of crop production and soil fertility. Producers are anxious to learn quick solutions for handling manure problems. Unfortunately, there are no simple, easy solutions to implementing practices for many of the concentrated animal feeding operations. A starting point is to work with the producer to calculate the farm balance of nutrients. Then, each field can be assessed for crop requirements and nutrient supplying power of the soil, plants, water, livestock, and air. The best management comes when there is sufficient land base to utilize the nutrients available on the farm. If land area is lacking, then other methods of nutrient utilization must be devised. As a goal of implementation, each field needs to have its own specific nutrient application rate, timing, source, and method of application planned. Soil and water conservation practices must then be put in place to prevent the transport of any applied nutrients.

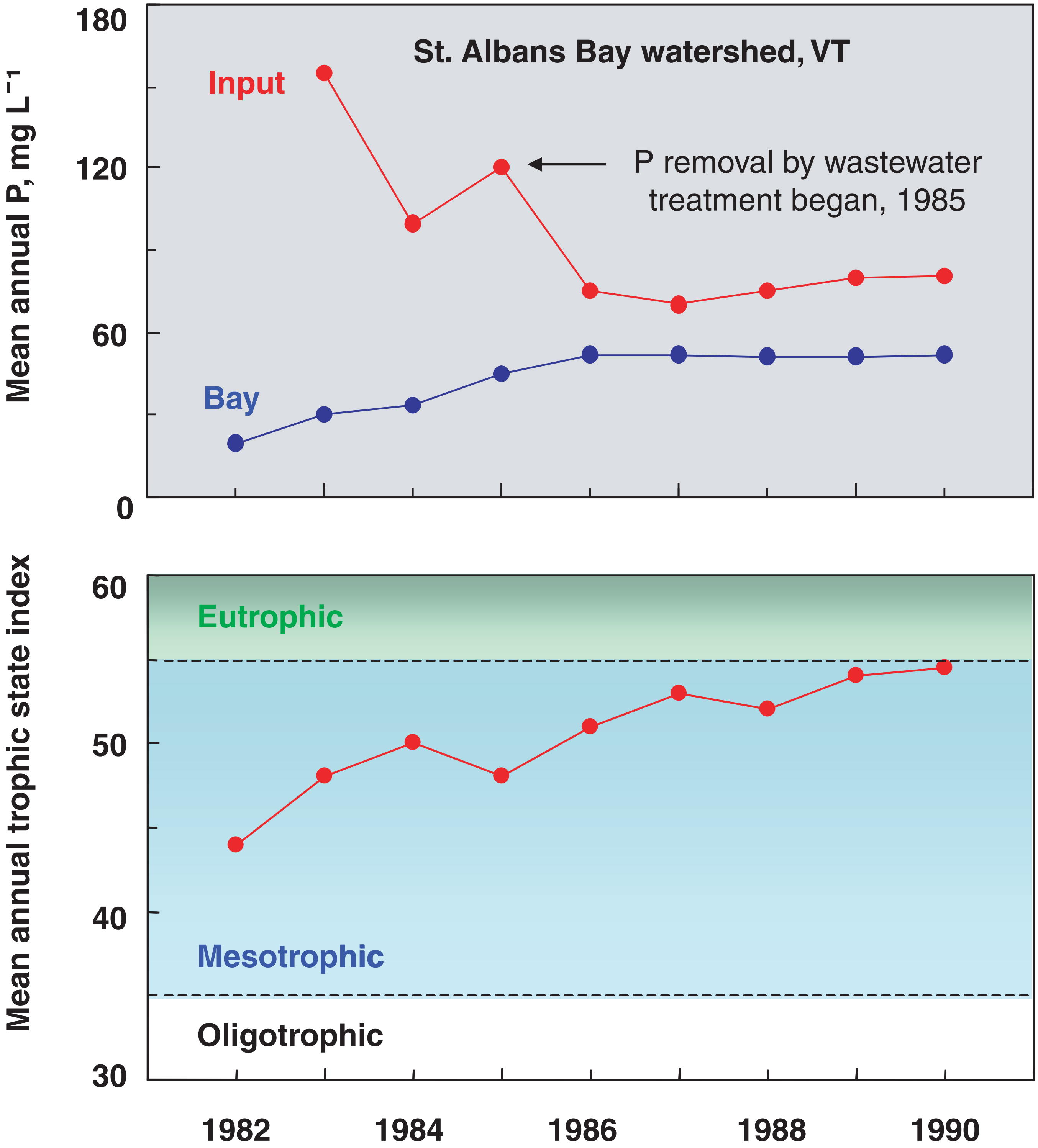

Figure 13. Although P input in the main tributary of St. Albans Bay, VT was decreased by wastewater treatment, P in the Bay and in the trophic state of the Bay did not decline. Data from Meals 1990.

To maintain the specific management, all planning tasks require a field-by-field assessment by the producer, working with a technical specialist, and a method of keeping records. Management tasks are time consuming and require planning skills and flexibility to carry out and maintain. The learning curve can be steep and the management persistent.

Comprehensive Nutrient Management Planning

Most field evaluations of BMP effectiveness at reducing watershed export of P conclude that nutrient management is the single most effective measure for controlling P losses. This involves the use of regional soil testing programs that are flexible enough to accommodate differences between watersheds and development of manure management plans for confined animal operations.

Nutrient management programs should be established on a regional rather than local basis to cover areas with similar soil types and other growing regions. Several classification systems have defined such ecoregions (Omernik 1987). Attainable water quality goals vary according to predominant land type and present use within these ecoregions (U.S. Environmental Protection Agency 1996b). As a result, an ecoregional approach to nutrient management may be useful for characterizing attainable water quality goals. In addition, nutrient management interpretations and guidelines within these regions should be consistent (Gartley and Sims 1994). Often, inconsistencies in recommendations and interpretation over short distances can make farmers question the reliability and philosophy of such programs and be reluctant to use them.

To develop nutrient management programs on a holistic watershed basis, a system of buying and selling pollution credits within a given watershed, similar to that recently adopted for air-quality control, has been suggested. Farmers who can limit P loss below recommended levels could sell credits to farmers unable to meet these levels. The number of credits a farmer has could be linked to farm area, crop production, and, where appropriate, number of animals. As a result, P export from a watershed may be kept within predetermined limits by sharing nutrient management responsibilities among farmers. It should be noted, however, that "pollution trading" has been criticized by some environmental groups because it is perceived as allowing wealthier operations to buy the "right to pollute." Heated debate will likely precede the adoption of pollution credits for agriculture; thus, careful planning to justify the actual value and need for pollution credits will be required.

Even so, it is clear that current technology will not permit an unlimited number of animals in a region without affecting water quality. Thus, it may be necessary to limit animal numbers within an area. Most states now require new animal facilities that exceed a certain size to have an "approved" nutrient management plan. It is essential that technology is rapidly and effectively transferred to implement environmentally sound recommendations for the management of nutrients, particularly in manure.

Incentives for BMP Adoption

To initiate real and lasting changes in agricultural production, emphasis must be placed on consumer-based programs and education instead of 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, over which they have little or no control, 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 mentioned earlier, much of today's problems result from system-level changes. The cause of today's problems is related to marketplace pressures, the breakdown and imbalances in global P cycling, and the economic survival of farms. Thus, research is 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 United States, 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 United States. In the Chesapeake Bay watershed, stakeholder alliances have developed among Federal, State, 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 City, 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 northeastern United States, for example, a collaborative multiagency venture, called the Dairy Network Partnership, has just released Chesapeake Milk in the Fresh Fields grocery chain. For every half-gallon of Chesapeake Milk sold, 2.5 cents will be returned to the certified Pennsylvania dairy farmers to reward them for 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.

Even though there has been a concerted effort to implement BMPs through voluntary and regulatory measures, the long-term challenges of P accumulating primarily on livestock operations has been and remains difficult to overcome. Research that better quantifies the sinks and sources of P as it is transported through a watershed will help develop realistic expectations for BMPs. However, more research is not the single or final solution. Many farmers simply do not have the financial resources to implement and maintain costly remedial measures. Despite there being many cost-share programs to help defray remedial costs, institutional redtape and conflicting requirements often limit program enrollment and hinder their widespread adoption.

Finally, continuing educational efforts with farmers and the public regarding the importance and impact of BMPs environmental quality parameters will be essential in reaching environmental goals. In some instances, local or regional governmental or agency controls may be necessary to enhance quicker adoption of practices that will have a positive influence on environmental outcomes.

Conclusions

There is a wide range of BMPs available to farmers that can minimize the potential for P loss in agricultural runoff. They are designed to control sources of P on farms as well as the processes by which P is transported from land to moving waters. As is evident from the large number of BMPs described in this publication that minimize P loss in surface and subsurface flow from agricultural lands, many diverse options are available to farmers that allow them some flexibility in how they can address their problems.

Even though there are a large number of BMPs available for P-based management, it is critical that the most appropriate BMP, or suite of BMPs, be selected and implemented in the right place on the landscape, following recommended installation and maintenance guidelines. This also requires consideration of the affected receiving waters, in terms of the forms and seasonality of P input controlling impairment.

Since source and transport management does not address the ultimate problem of farm and regional surpluses of P, long-term solutions must extend beyond the farmgate. Advances in crop and livestock breeding, feed processing, and manure utilization all hold promise. However, all options involve costs, which will most likely have negative impacts on farm income. Thus, fair and equitable financial support or cost-share programs will be needed.

Efforts to implement defensible remedial strategies that minimize P loss from agricultural land will require interdisciplinary efforts involving research, extension and demonstration projects that educate farmers, the livestock industry, and the general public as to what is involved in ensuring clean water. Hopefully, this will help overcome the common misconception that nonpoint sources are too difficult, costly, or variable to control or target substantial reductions for. Developing guidelines to implement remedial strategies will also require considering the socioeconomic and political impacts of any management changes on rural and urban communities and providing mechanisms where change can be achieved in a diverse and dispersed community of land users.

U.S. Environmental Protection Agency
Office of Water
National Nutrient Criteria Program

Nutrient Regional Coordinators

Region 1	Matt Liebman	(617) 918-1626
Region 2	Wayne Jackson	(212) 637-3807
Region 3	Tiffany N. Crawford	(215) 814-5776
Region 4	Jim Harrison Ed Decker	(404) 562-9271 (404) 562-9383
Region 5	Dave Pfeifer Ashley Moerke	(312) 353-9024 (312) 886-4012
Region 6	Phil Crocker	(214) 665-6644
Region 7	Gary Welker	(913) 551-7177
Region 8	Kathryn Hernandez	(303) 312-6101
Region 9	Suesan Saucerman	(415) 972-3522
Region 10	Ralph Vaga	(206) 553-5171
Corvallis Lab	Jim Omernik	(541) 754-4458
Narragansett Lab	Jim Latimer Edward Dettmann	(401) 782-3167 (401) 782-3039

For updates, visit www.epa.gov/waterscience/criteria/nutrient/coord.html

Headquarters
Nutrient Criteria Personnel

Amy Parker (Coordinator)	(202) 566-1341
George Gibson (Lakes, Coastal)	(410) 305-2618 (202) 566-1103
Iffy Davis (Database, Wetlands)	(202) 566-1096
Amie Howell (Coastal)	(202) 566-1143
Jim Keating (Standards)	(202) 566-0383
Lisa Larimer (Standards)	(202) 566-1017
Steve Potts (Rivers & Streams)	(202) 566-1121
Treda Smith (Biocriteria)	(202) 566-1128
Manjali Vlcan (Standards)	(202) 566-0373

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