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Assessment of best management practices to minimise the runoff of manure-borne phosphorus in the United States

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Abstract Phosphorus (P), an essential nutrient in crop and livestock agriculture, can cause and accelerate freshwater eutrophication. Intensification of farming systems has resulted in local accumulations of P in some agricultural watersheds with related increases in P runoff. In most cases, continual land application of manure at rates exceeding crop P removal is the proximate cause of P runoff. To mitigate associated water quality impairments, P-based agricultural best management practices (BMPs) are now becoming a part of farm nutrient planning. This planning involves the selection, timing, and implementation of source and transport BMPs at field, farm, and watershed scales. Source measures include balancing P imports and exports, improved livestock feed management, chemical and physical treatment of manures, appropriate rate, method, and timing of land application based upon regular soil and manure testing, adequate manure storage and transport infrastructure, and composting. Transport measures aim to reduce runoff and erosion via practices such as conservation tillage, contour ploughing, and vegetative filter strips. To be effective, these measures must be carefully selected and targeted to areas at greatest risk to P loss. This vulnerability can be identified and ranked by P indices, which account for source and transport factors controlling P loss. We demonstrate that the P Index can provide flexible yet reliable manure management and provide farmers with options to minimise the risk of P loss from several farms in Pennsylvania, United States. Overall, a comprehensive and holistic approach to manure management can decrease P transfers from land to water.

Keywords eutrophication; leaching; non-point source pollution; risk assessment; soil conservation; surface runoff; watersheds

INTRODUCTION

Phosphorus (P) is an essential nutrient for crop and animal production which, when transferred from land to fresh water, can accelerate eutrophication (Carpenter et al. 1998; Sharpley 2000). Recent assessments of water quality status have identified eutrophication as one of the most ubiquitous water quality impairments in the United States, Europe, and Australasia (Heaney et al. 2001; MfE 1997; USGS 1999). 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 (NRC 2000).

In the last 20 years, crop and livestock operations have specialised into spatially separate production systems (Evans et al. 1996; Lander et al. 1998). In the United States for instance, beef, dairy, pig, and poultry numbers have increased 10–30% since 1990, while the number of farms on which they are reared has decreased 40–70% (Gardner 1998). Similar intensification has occurred in Europe and Australasia, driven by a greater demand for animal products and improved profitability (Lanyon 2000). Intensification of livestock production has also resulted in a major transfer of P from grain- to animal-producing areas, where localised surpluses of manure rich in P can occur. Land application of manure can increase the potential loss of P to surface waters (Iserman

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1990; Kellogg & Lander 1999; Withers & Lord 2002). Thus, attention has focused on the role of livestock operations in agriculture's role in water quality impairment and the need for best management practices (BMPs) for manures, which are an integral part of remedial strategies (Gillingham & Thorrold 2000; USDA 1999; USEPA 1999, 2000; Withers et al. 2000).

This paper discusses BMPs that are designed to minimise P loss in runoff associated with the land application of manures produced in livestock operations. Practices are grouped into three categories: (1) source management, which addresses sources of P applied to land (i.e., animal diet and feed management, manure treatment, appropriate application methods); (2) transport management, which addresses hydrologic pathways of P transport (i.e., decreasing runoff and leaching potential); and (3) targeted management, which integrates source and transport management to prioritise remedial activities (i.e., critical source areas at farm and watershed scales).

SOURCE BMPS

Source management attempts to minimise the build-up 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 localised area (Table 1).

Farm gate management of P

Addressing farm gate imbalances of P is fundamental to reducing non-point source P loss because long-term accumulation of P on farms ultimately drives diffuse transfers of P from soil to water.

Feed P management

Manipulation of dietary P intake by animals can reduce P inputs as feed, often the major cause of P surpluses in livestock agriculture (Table 2). Phosphorus intake above minimum dietary requirements established in the United States by organisations such as the NRC (2001) does not appear to confer

Table 1 Phosphorus best management practices (BMPs) that minimise the impacts of land applied manures on P loss to surface waters.

Source BMPs—practices that minimise P loss at the origin
1. Minimise P in livestock feed
2. Test manure and soil to optimise P management
3. Physically treat manure to separate solids from liquid
4. Chemically treat manure to reduce P solubility, e.g., alum, flyash, water treatment residuals
5. Biologically treat manure, e.g., microbial enhancement
6. Calibrate manure application equipment
7. Apply proper application rates of manure
8. Use proper manure application method, i.e., broadcast, ploughed in, injected
9. Careful timing of manure to avoid imminent heavy rainfalls
10. Remedial management of excess P areas (spray fields, loafing areas)
11. Compost and/or pelletise manures and waste products to provide alternate use
Transport BMPs—practices that minimise the transport of P
12. Minimise erosion, runoff, and leaching, i.e., terracing, strip cropping, contour ploughing
13. Use cover crops to protect soil surface from erosion
14. Install filter strips and other conservation buffers to trap eroded P and disperse runoff
15. Manage riparian zones, grass waterways and wetlands to trap eroded P and disperse runoff
16. Stream bank fencing to exclude livestock from water courses
Source and transport BMPs—systems approach to minimise P loss
17. Retain crop residues and reduce tillage to minimise erosion and runoff
18. Grazing (pasture and range) management to minimise erosion and runoff
19. Install and maintain manure handling systems (houses/lagoons)
20. Barnyard storm water management
21. Install and maintain milk-house waste filtering systems
22. Comprehensive nutrient management plan implementation

any growth or health advantages and actually reduces profitability through increased feed costs (Knowlton & Kohn 1999). Based upon recent research on the effects of P feeding level on milk production and reproductive performance, the NRC has recently published new guidelines for dairy cattle P requirements, which reduced P to 0.31–0.38% for cows producing 25–50 kg day^{-1} of milk (NRC 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 instance, data summarised from 2 years of research on lactating dairy cows show a linear relationship between P intake and faecal P excretion (Wu et al. 2000, 2001) (Fig. 1). According to this relationship, a reduction in dietary P from 0.48 to 0.38% can result in 30–35% less manure P. This reduction 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.

Powell et al. (2001) showed that at a recommended dairy diet-P level of 0.38% P, land application of the manure generated would require 0.7 ha cow^{-1} to avoid increasing the Bray-1 soil-P concentration of a typical dairy farm in Wisconsin with 80 ha tillable land and 90 lactating dairy cows. In contrast, an excessive dietary P level of 0.55% would increase the area needed for manure spreading to 1.2 ha cow^{-1} or would increase Bray-1 soil-P levels in excess of crop needs (>30 mg kg^{-1}) on all tillable farm land within 6 years if no additional land was made available. On farms where manure P exceeds crop P requirements, reducing dietary P to the NRC recommendation would reduce the number of farms and area with an excess P balance by approximately two-thirds (Powell et al. 2002). In addition to inorganic-P supplementation of livestock feed, some protein supplements can contribute substantial amounts of P to animal diets (NRC 2001). Common protein supplements vary greatly in cost and P content (0.3–4.7% 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 2).

Recently Ebeling et al. (2002) showed that increasing the P concentration of dairy cow diets (from 3.1 to 4.9 g P kg^{-1} feed) increased the potential for P loss in runoff from land-applied manures, even at the same P application rate. For example, 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 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 with high-P (40%) than low-P diets (29%).

Feed additives

A significant amount of the P in grain is in phytate (phytic acid), an organic form of P that is digested in low proportions by non-ruminant animals such as pigs and chickens. As a result, it is common to supplement feed with mineral forms of P that are readily digestible. This supplementation contributes to P enrichment of manures and litters. Enzymes such as phytase, which break down phytate into forms available to non-ruminant animals, can be added to feed to increase the efficiency of grain-P absorption by pigs and poultry. Such enzymes reduce

Table 2 Potential for feed management strategy to impact manure P (data adapted from Federation of Animal Sciences Societies 2001).

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

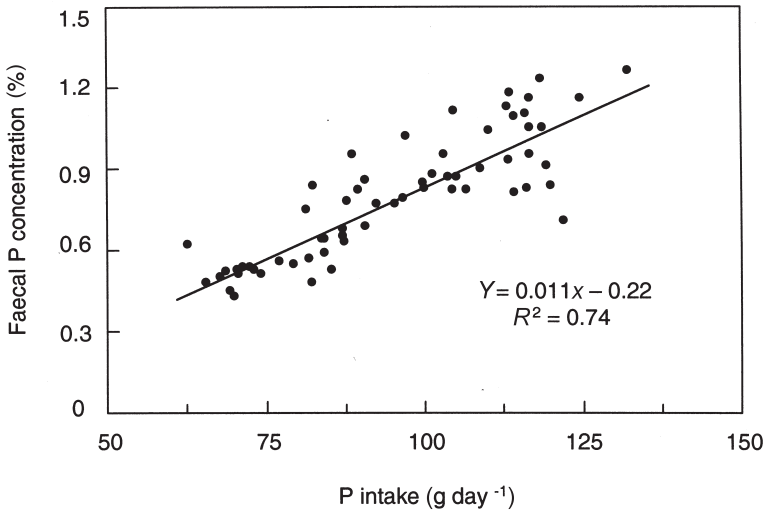

Fig. 1 P excreted by lactating dairy cows is a function of P intake (adapted from Wu et al. 2000, 2001).

the need for P supplements in feed and potentially reduce the total P content of manure (Table 2).

Also, corn hybrids are available which contain small 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). This study also showed that P availability to non-ruminants from low-phytate, high available phosphate (HAP) corn is about two to three 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 use of phytase feed amendments and low-phytate corn resulted in a 60% reduction in P excreted by swine (Table 2).

Manure treatment

Chemical amendments

Commercially available manure amendments, such as alum, are used to reduce ammonia (NH_3) volatilisation, 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 grow-out with alum is proving to be a popular BMP because it not only reduces ammonia in the house, but has also been shown to reduce P concentration in the runoff by 85% once the material is land applied (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 through NH_3 volatilisation. An increased N:P ratio of manure would more closely match crop N and P requirements.

Physical treatment

Large dairy and swine operations commonly rely on a flush-water system 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, resulting in elevating the P content of the soil above that required by the crop. Coagulant and flocculent techniques commonly used by municipalities are being used to solve such problems. For example, researchers have shown that using a coagulant such as an aluminium-containing salt (e.g., $AlCl_3$) in combination with commercial polymers (polyacrylamide) not only doubles the removal of solids but it also dramatically reduces the soluble P in the effluent (Timby et al. 2000). While this does not change the total amount of nutrients that must be handled, it enables better targeting of the individual nutrients to locations where they are most needed, reducing the potential for environmental problems to occur. Also, because the solid fraction is more concentrated, it is more feasible to transport it to remote fields, or it can serve as an input for other related biosolids products.

Sieving to separate fine and coarse fractions may increase management options for manures such as

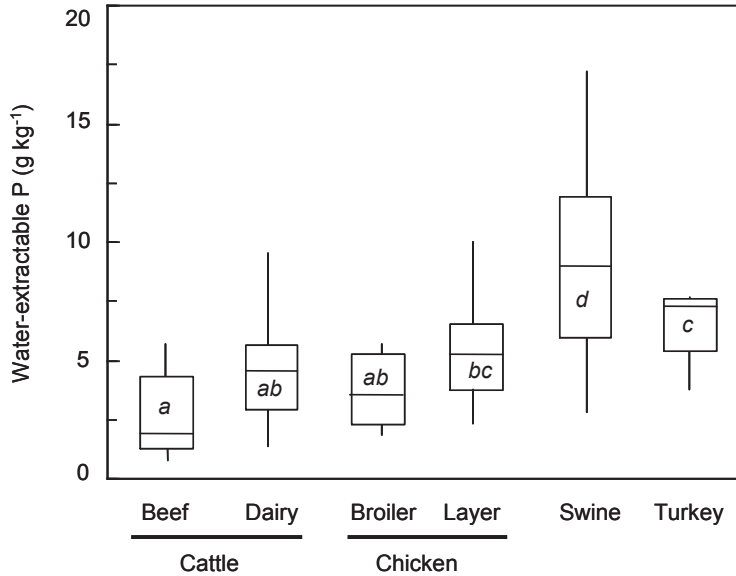

Fig. 2 Box-and-whisker plot of water-extractable P concentration in livestock manures, adapted from Kleinman et al. (2004). Duncan mean categories are represented by italic letters.

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 lower than that required by plants. In addition, the proportion of mineralisable N can be larger in the fine fraction than in the unfractionated litter (Cabrera et al. 1994).

Managing land applications of manure

Soil and manure testing

Rates of P application are usually established by crop needs and modified by P that is already in the soil, as determined by established soil test P methods, as well as P in applied manure. At present, 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 plough horizon (15–30 cm) for cultivated fields where surface soils are periodically mixed, and to shallower depths (5–10 cm) for fields under conservation tillage or pastures where vertical stratification of soil P is expected.

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 following receipt of manure analysis to ensure that the condition of applied manure corresponds to that of the sample. Until recently, concerns over nitrate leaching into ground water had prompted N-based manure application at rates that meet crop N requirements. As P-based manure management is needed to obtain operating permits for high density livestock farms that have more than 1 animal unit ha^{-1} (i.e., 454 kg of animal live-weight equivalent or one dairy cow), manure P testing will be necessary to ensure compliance.

At present, manure P tests generally quantify total P in manure. However, increasing use of amendments such as alum and coal-combustion by-products to reduce P solubility in manures (discussed below) 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 manures, which has already been adopted by several state soil testing laboratories in the United States (Wolf et al. 2002). A recent survey of 200 livestock manures by Kleinman et al. (2004) revealed significant differences in water-extractable P between various livestock species (Fig. 2). These differences have been incorporated in some P site assessment indices to credit producers for varying availabilities of manure P to runoff water (Sharpley et al. 2003).

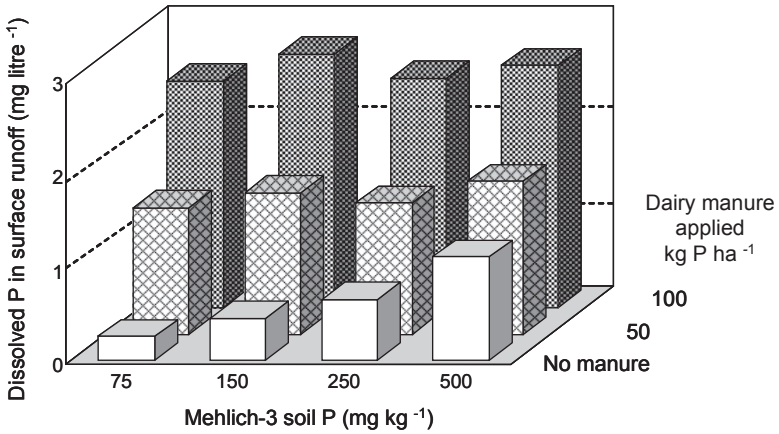

Fig. 3 The concentration of P in surface runoff from a grassed Berks silt loam, as a function of Mehlich-3 soil P concentration and amount of dairy manure applied 2 weeks before rainfall.

Rate, method and timing of manure applications

The rate, method, and timing of manure applications can be managed to minimise the potential for P loss in runoff (Sharpley et al. 1998; Withers & Jarvis 1998). As might be expected, P loss in runoff increases with greater applications of manure (Edwards & Daniel 1993a; Sharpley et al. 2001) (Fig. 3). Also, incorporation of manure into the soil profile either by tillage or subsurface placement decreases the potential for P loss in runoff (Fig. 3). Rapid incorporation of manure also reduces N volatilisation, improving the N:P ratio for crop growth. Mueller et al. (1984) showed incorporation of dairy manure by chisel ploughing reduced total P loss in runoff from corn 20-fold, compared with 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 volume following incorporation of manure (Mueller et al. 1984; Pote et al. 1996).

The timing of manure applications relative to rainfall also influences runoff P. With an increase in length of time between rainfall and manure application, runoff P decreases, due to the sorption of manure P by soil and dilution of applied P by infiltrating water from rainfall insufficient to cause runoff (Sharpley 1997; Westerman et al. 1983; Edwards & Daniel 1993b). For instance, in our rainfall simulation studies in an experimental watershed located in central Pennsylvania, the dissolved P concentration of surface runoff from the Berks silt loam decreased from 2.75 to 0.40 mg litre^{-1} when rainfall occurred 35 days rather than 2 days after a surface broadcast application of 100 kg P ha^{-1} as dairy manure (Fig. 4). Even so, Pierson et al. (2001) observed that broadcasting poultry litter to meet pasture N demands produced elevated concentrations of P in surface runoff for up to 19 months after application.

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

Manure management and alternative uses

In areas where there is a high density of concentrated animal operations and manure production exceeds local or even 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, such as composted manure by-products, pelletised manures, soil conditioners, and as bio-energy sources. The market demand and economic viability of these uses is expected to be greater as the costs of attaining and maintaining clean waters increases.

Manure storage

As livestock constantly generate manure, storage facilities provide farmers with flexibility in manure management, particularly as to when manure must be land applied. Specific storage options vary with livestock type and individual farm characteristics, ranging from concrete storage pads to anaerobic and aerobic lagoons, to oxidation ponds and ditches (Day & Funk 1998). For instance, Giasson et al. (2003), in evaluating manure storage options for New York dairy farms currently land-applying manure on a

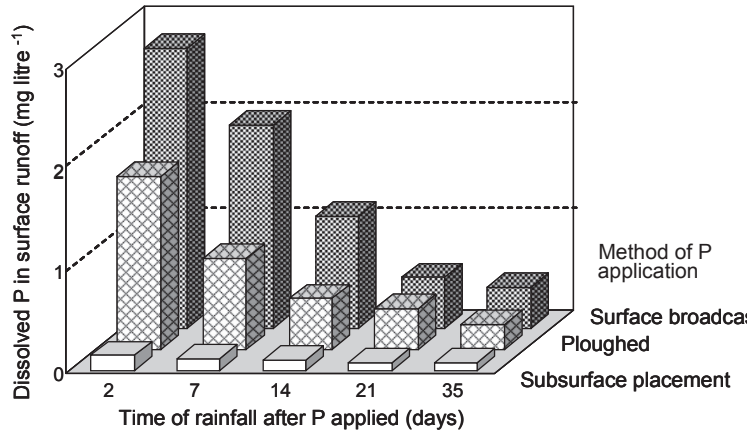

Fig. 4 The effect of application method and timing of rainfall after application of dairy manure (100 kg P ha^{-1}) on the concentration of P in surface runoff from a grassed Berks silt loam.

daily basis, found that installation of manure lagoons with 3 months' storage capacity resulted in the most cost-effective control of non-point source P losses.

Clearly, storage of manure will allow more flexibility in timing applications. A wide range of storage methods and costs are available to farmers (USDA—NRCS 1992). Inexpensive plastic sheeting can perform well with very low cost for some solid manures. However, all storage methods must be managed carefully to fully realise their potential in an agronomically and environmentally sound BMP. Also, stored manure must be spread as part of a comprehensive nutrient management programme that includes appropriate timing and rates of manure application.

Transporting manure

At present, manure is rarely transported more than 16 km (10 miles) from where it is produced, severely restricting disposal options (Moore et al. 1998a). 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 programmes currently exist in the north-eastern United States to improve placement of manure across farm boundaries. In an increasing number of states, extension and local trade organisations have established "manure-bank" networks that put manure-needy farmers in contact with manure-rich growers (Maryland Department of Agriculture 2000; Delaware Department of Agriculture 2004). 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 (Moore et al. 1998a). 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 composting makes manure more uniform in its physical and chemical properties and therefore able to be spread more evenly and at more accurate rates (Day & Funk 1998; Osei et al. 2000). 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.

Manure can also be used along with biosolids and woodchips to reclaim soils which have been disturbed, for example, by mining and urban construction (Millner et al. 1998). In these cases, manure can be used as an excellent soil conditioner for the 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 manures 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 (UKDE 1990). Liquid wastes can be digested anaerobically to produce methane, which can be used for heat and energy (Wright 2000). These processes reduce the volume of manure needing to be managed, but still requires the utilisation or disposal of residual by-product material (ash). As the value of clean water and cost of sustainable manure management is realised, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost-effective, and thus create expanding markets. Again, the most efficient long-term solution is to match livestock numbers with utilisation 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 (Table 1). 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 (e.g., settling basins). Basically, these practices reduce rainfall impact on the soil surface, reduce runoff volume and velocity, increase soil resistance to erosion, and trap sediment (Unger et al. 1998; Gillingham & Thorrold 2000).

Manure application at low rates (<50 kg P ha^{-1}) that meet plant sufficiency requirements, can improve water quality by enhancing vegetative ground cover to protect surface soil from runoff and erosion (McDowell & McGregor 1984; McDowell & Sharpley 2003). For instance, the addition of organic matter and cations such as Mg and Ca via manure improves soil stability and structure, which lead to increased soil-water-holding capacity and infiltration rates (Pote et al. 1996; Mamedov & Levy 2001). Further, McDowell & Sharpley (2003) found that P loss in runoff (0.9 kg total P ha^{-1}) after surface application of low rates of dairy manure (<50 kg P ha^{-1}) was lower than from untreated soil (1.2 kg total P ha^{-1}). The beneficial effect of manure application on P loss potential was attributed to increased aggregation and decreased surface soil slaking imparted by added C in manure (McDowell & Sharpley 2003). At greater application rates, manure appreciably increases P transport (Sharpley et al. 1998; Kleinman et al. 2002a; McDowell & Sharpley 2003).

Despite these advantages, none of these measures should be relied upon as the sole or primary means of reducing P losses (Sharpley & Rekolainen 1997). These practices 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 long after inputs from agriculture have been reduced. Several researchers have indicated little decrease in lake productivity with reduced P inputs following implementation of conservation measures (Gray & Kirkland 1986; Meals 1996; McComb et al. 1998). Thus, the effect of remedial measures in the contributing watershed will be slow for many cases of poor water quality (Clausen et al. 1992).

IMPLEMENTING BMPS BY TARGETED RISK ASSESSMENT

Rationale and principles of P indices

In response to mounting water quality concerns, many American states have developed guidelines for land application of P and watershed management based on the potential for P loss in agricultural runoff (USDA and USEPA 1999). These actions have been spurred, in part, by a federal initiative in which the USDA and the USEPA created a joint strategy to implement Comprehensive Nutrient Management Plans on Animal Feeding Operations, with a national deadline of 2008. Under this strategy, three P-based approaches will be used in nutrient management planning policy that ultimately guide or determine manure rate, method, and timing of manure application. These approaches are agronomic soil test P recommendations, environmental soil test P thresholds, or a P Index to rank fields according to their vulnerability to potential P loss.

Most states have selected the P Index, because the other P-management options (i.e., agronomic and environmental soil test P) are inflexible, overly restrictive, and do not account for the critical role of transport mechanisms in determining a site's P loss potential (Fig. 5; Sharpley et al. 2003). The P Index was originally developed to identify the vulnerability of agricultural fields to P loss (Lemunyon & Gilbert 1993). Phosphorus indices include assessments of both source management and transport factors that determine P loss in most cases to facilitate the assessment and identification of critical source areas. Generally, source management factors include soil test P and P application rate, method, and timing. Transport factors include erosion, surface runoff, subsurface P loss, and distance to receiving water body. While these represent the general categories

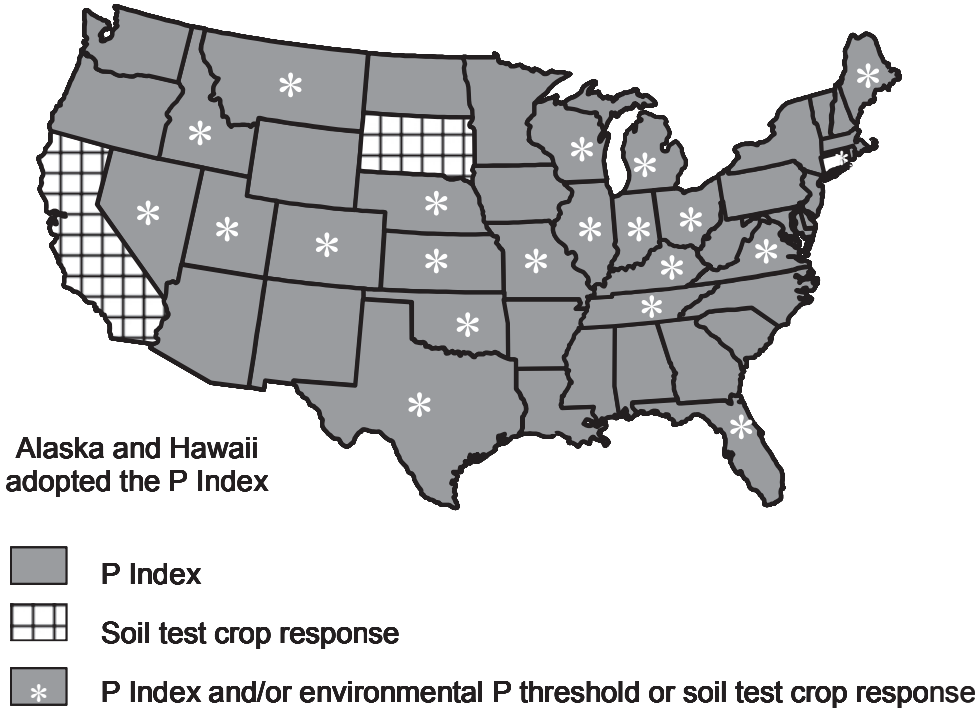

Fig. 5 Summary of P-based management strategies adopted in the United States.

of parameters, many indices have selected to include specialised parameters and categories to appropriately represent their unique regional conditions or areas of environmental concern (Sharpley et al. 2003).

Indices now include an additional source factor that accounts for the relative solubility of applied P and its susceptibility to loss in runoff (Sharpley et al. 2003). Phosphorus solubility has been shown to vary across manure types and manure treatments, and in the index, P solubility can be used as an indicator of dissolved-P loss from a site (Moore et al. 2000; Kleinman et al. 2002a,b). For instance, the use of alum to decrease manure P solubility can be credited (Moore et al. 2000), while credit can be deducted for the use of phytase in poultry and swine feed, due to its effect on increasing the solubility of P in manure and dissolved P loss in surface runoff (Moore et al. 1998b; Smith et al. 2001).

Using P indices to assess the risk of P loss

The most recent version of the Pennsylvania P Index, shown in Tables 3 and 4, is used in this study to exemplify how this risk assessment tool can be used to highlight manure management BMPs. Included as an initial step in the Pennsylvania P Index is a "screening tool" (Table 3—Part A); if a field has a soil test P greater than 200 mg kg^{-1} Mehlich-3 P and is 150 ft (50 m) or closer to a stream or water body, then a more comprehensive evaluation of the field using the "full" P Index (Table 3—Parts B and C) is required. The corollary is that if a field has a soil test P less than 200 mg kg^{-1} and is located more than 150 ft (50 m) from a stream, the full index need not be run. In this last situation, the field is assumed to be of a lower risk to contribute P. Thus, time and effort expended in calculating index ratings can be directed to those fields that are more likely to be at risk of P loss.

Source factors of the P Index, soil test P, fertiliser and manure rate, method, and timing of application (Table 3—Part B) are all obtained from farm management records. If necessary, soil test P and P concentration of applied manure should be determined. As all source factors do not all have the same quantitative effect on P loss, a coefficient of 0.2 is used to convert soil test P to a value that directly relates to P in manure and mineral fertilisers. This conversion

is based on field data that show a five-fold greater concentration of dissolved P in surface runoff with an increase in mineral fertiliser or manure addition compared with an equivalent increase in Mehlich-3 extractable soil P.

Values for each transport factor (Table 3—Part C) are determined from soil information, widely used equations and soil-water relationships, and site-specific details. Erosion is estimated for each field based on current practices with the Revised Universal Soil Loss Equation (RUSLE; http://www.iwr.msu.edu/rusle/ and http://bioengr.ag.utk.edu/rusle2/), which accounts for soil tillage, slope length, and vegetative cover (Renard et. al. 1997). In some

Table 3 P Indexing approach using Pennsylvania's Index version (August 2002), as an example (Weld et al. 2003).

PART A—SCREENING TOOL

	Evaluation Category	
Soil Test P	>200 mg P kg^{-1}	**If yes to either factor then proceed to Part B**
Contributing distance	<150 ft (50 m)	

PART B—SOURCE FACTORS

Soil test	Soil Test P (mg P kg^{-1})				
Soil Test P Rating = 0.20 × Soil Test P (mg P kg^{-1})					
Fertiliser P rate	Fertiliser P (lb P_2O_5/acre) (kg P ha^{-1} × 0.489)				
Manure P rate	Manure P (lb P_2O_5/acre) (kg P ha^{-1} × 0.489)				
P source application method	0.2 Placed or injected 2″ (5 cm) or more deep	0.4 Incorporated < 1 week	0.6 Incorporated > 1 week or not incorporated Apr–Oct	0.8 Incorporated > 1 week or not incorporated Nov–Mar	1.0 Surface-applied to frozen or snow-covered soil
Fertiliser Rating = Rate × Method					
Manure P availability	0.5 Treated manure/Biosolids		0.8 Dairy		1.0 Poultry/Swine
Manure Rating = Rate × Method × Availability					
Source Factor = Soil Test P Rating + Fertilizer Rating + Manure Rating					

PART C—TRANSPORT FACTORS

Erosion	Soil loss (ton/acre/yr)				
Runoff class	0 Very low	2 Low	4 Medium	6 High	8 Very high
Sub-surface drainage	0 None		1 Random		2* Patterned
Contributing distance	0 >500 ft (150 m)	2 350–500 ft (100–150 m)	4 250–350 ft (75–100 m)	6 150–250 ft (50–100 m)	8 <150 ft (50 m)
Transport Sum = Erosion + Runoff Potential + Subsurface Drainage + Contributing Distance					
Modified connectivity	0.7 Riparian buffer – applies to distance < 150 ft (50 m)		1.0 Grassed waterway or none		1.1 Direct connection – applies to distance > 150 ft (50 m)
Transport Factor = Modified Connectivity × (Transport Sum/22)					

*Or rapid permeability soil near a stream

Phosphorus Index Value = 2 × Source Factor × Transport Factor

states, actual erosion values are available in the farm's soil conservation plan. Runoff class is determined from soil permeability class or saturated hydraulic conductivity (K_{Sat}) and the percent slope of the site (USDA—NRCS 1993, p. 115 tables 3–10). Leaching potential is determined from soil type, the presence of artificial drainage in the field, or if the field is near a stream and has rapid permeability soils (USDA—NRCS 1993). "Random" drainage is a single or a few tile lines in a field and "patterned" drainage is when most or the entire field is drained with a full patterned drainage system. Contributing distance is the distance from the lower edge of the field to a stream or other water body and is based on the concept that the closer a field is to a body of water the more likely it is that P in or on that field will reach a body of water. The distance category in the index that contains the majority of the edge of the field is selected.

Transport potential for each site is calculated by first summing erosion, surface runoff, leaching potential, and connectivity values (Table 3—Part C). The summed value is then divided by 22, the value corresponding to "high" transport potential (erosion is 6, surface runoff is 8, leaching potential is 0, and connectivity is 8), to determine a relative transport potential (Table 3—Part C). This normalisation process assumes that when a site's full transport potential is realised, 100% transport potential is realised. Thus, transport factors < 1 represent a fraction of the maximum potential (Table 3—Part C). However, because erosion is open-ended, it is possible at high erosion rates to have a transport factor > 1.

A final P Index value, representing a cumulative site vulnerability to P loss, is obtained by multiplying the summed transport and source factors (Table 3). Pennsylvania P Index values are normalised so that the break between "high" and "very high" categories is 100, representing an initiative in the north-eastern United States to ensure that P Index output is consistent across state boundaries (Table 4). Normalisation is done by calculating the site P Index value in which all transport and source factors are assumed to be "high". In the Pennsylvania P Index, erosion is set at 6 tonnes ha^{-1} yr^{-1} (6 tons $acre^{-1}$ yr^{-1}) and soil test P is set at 200 mg kg^{-1} Mehlich-3 P. Breaks between "medium" and "high" and between "low" and "medium" are calculated using the same method with soil test P set at 50 and 30 mg kg^{-1} Mehlich-3 P, respectively. These Mehlich-3 P levels correspond to crop response and fertiliser recommendations for Pennsylvania, where > 50 mg kg^{-1} is sufficient for production and no P addition is recommended, 30–50 mg kg^{-1} where no crop response is expected but maintenance P is recommended, and < 30 mg kg^{-1} is low and will respond to added P.

Identifying manure management options with the P Index

As pointed out earlier, the P Index can be used to identify the risk of P loss from fields at a farm or watershed scale and provide farmers some flexibility as to which management options to implement in order to decrease this risk. To address the common misconception that a "high" or "very high" index value will result solely in a decrease in the amount of manure that can be applied, we evaluated other management scenarios. Using the Pennsylvania P Index, hypothetical scenarios are given to highlight the range of options available (Table 5). Scenarios considered are a change in the timing of manure application, installation of a riparian buffer, and a reduction in the amount of P in dairy cow ration.

Management of the baseline scenario is for a field on a dairy farm, obtained from a farm-scale testing of the Pennsylvania P Index on 11 farms (Weld et al.

Table 4 General interpretations and management guidance for the P Index.

P Index value	Rating	General interpretation	Management guidance
<59	Low	If current farming practices are maintained, there is a low risk of adverse impacts on surface waters.	N-based applications
60–79	Medium	Chance for adverse impacts on surface waters exists, and some remediation should be taken to minimise P loss.	N-based applications
80–100	High	Adverse impact on surface waters. Conservation measures and P management plan are needed to minimise P loss.	P application limited to crop removal of P
>100	Very high	Adverse impact on surface waters. All necessary conservation measures and P management plan must be implemented to minimise P loss.	No P applied

2002). The field was no-till corn and had received manure and starter fertiliser in the past, hence had an elevated soil test P level of 150 mg kg^{-1} Mehlich-3 P. Planned source management included a 45 kg P ha^{-1} (91 lbs P_2O_5 $acre^{-1}$) surface application of dairy manure in November (i.e., application method and availability factors of 0.8) and 10 kg P ha^{-1} (20 lbs P_2O_5 $acre^{-1}$) starter mineral fertiliser placed with planting in May (i.e., application factor of 0.2). Erosion (calculated by RUSLE) and runoff rating from the no-till field is low (1 and 2, respectively) and there was some subsurface drainage evident from an old tile drain (Table 5). The field was within 150 ft (50 m) of the stream channel, thus, any runoff was assumed to contribute directly to stream flow. The resulting P Index value for this field was 101 (Table 5). Based on Pennsylvania's nutrient management guidance, the field would be subject to P-based management with no P application recommended.

In **Scenario 1**, timing of the surface manure application was changed from autumn (November) to spring (May). In fact, applying manure a month earlier in late September or October, will decrease the application factor from 0.8 to 0.6 (Table 5).

Table 5 Phosphorus Index management scenarios based on Pennsylvania's P Index (the factor that changed in each scenario is highlighted in bold and calculated factors are italicised).

Factors	Baseline management	Manure application method[a]	Riparian buffer[b]	Dairy cattle ration[c]
Source Factors				
Soil test P (mg kg^{-1} Mehlich-3 P)	150	150	150	150
Soil test rating	*30*	*30*	*30*	*30*
Fertiliser rate (lbs P_2O_5/A) (kg P ha^{-1} × 0.489)	20	20	20	20
Fertiliser application method	0.2	0.2	0.2	0.2
Fertiliser Rating	*4*	*4*	*4*	*4*
Manure rate (lbs P_2O_5 A^{-1}) (kg P ha^{-1} × 0.489)	91	91	91	**68**
Manure application method	0.8	**0.6**	0.8	0.8
Manure P availability	0.8	0.8	0.8	0.8
Manure rating	58	44	58	44
Source Factor	**92**	**78**	**92**	**78**
Transport Factors				
Erosion (ton/acre/yr) (Mg ha^{-1} yr^{-1} × 2.24)	1	1	1	1
Runoff class	2	2	2	2
Subsurface drainage	1	1	1	1
Contributing distance	8	8	8	8
Transport sum/22	**0.55**	**0.55**	**0.55**	**0.55**
Modified connectivity	1.0	1.0	**0.7**	1.0
Transport Factor	**0.55**	**0.55**	**0.39**	**0.55**
Phosphorus Index value	**101**	**86**	**72**	**86**
Management guidance	No P applied	Applied P limited to crop removal	N-based nutrient application	Applied P limited to crop removal

[a]Change in the timing of surface manure application from fall (Nov) to spring (May).
[b]Establishment of an edge-of-field riparian buffer.
[c]Decreased dietary concentration of P fed to lactating dairy cows from 0.48 to 0.38%.

Neither of the methods of application in scenario 1 involved manure incorporation and, thus, no-till requirements will be met and erosion or runoff potential not increased. As a result of a change in timing of manure application, the P Index rating for the field decreased from 101 to 86, with applied P limited to crop removal (Table 5).

In **Scenario 2**, the establishment of a riparian buffer at the down-slope edge of the field decreases transport factor from 0.55 to 0.39 (Table 5). Although source management remains the same, overall P loss potential as reflected in the P Index value decreased (72) compared with the baseline scenario (101) and nutrient management would revert to being N based. However, the riparian buffer must be carefully installed and maintained so that, for example, channelised flow through the buffer does not develop, ensuring long-term protection against P loss. Clearly, if there is significant subsurface flow or tile drainage under a buffer, then this BMP would be ineffective at decreasing P loss.

In **Scenario 3**, dairy ration was modified so that the amount of P fed to lactating dairy cows more closely meets animal nutritional requirements (Table 5). Wu et al. (2000) have shown a direct relationship between the amount of P in excess of cow requirements and faecal P. For instance, using a 25% reduction in faecal-P excreted when dairy cow ration was decreased from 0.48 to 0.38% P on a dry-matter basis, is translated into an equivalent decrease in manure P applied (45–34 kg P ha^{-1} [91–68 lbs P_2O_5 $acre^{-1}$]). By simply altering feed P ration, the P Index value for the field was 87 ("high" risk of loss) compared with the baseline scenario of 101 ("very high" risk of loss) (Table 5).

If all three scenarios were adopted (i.e., rescheduling manure application, establishment of a riparian buffer, and changing the feed management programme), the P Index rating for the same field would be 52. Clearly, the P Index can identify several opportunities to decrease the overall P Index rating of a field, which in the scenarios given did not include a reduction in the amount of manure applied. This provides the farmer with long-term flexibility of nutrient management and may slow down soil test P build-up, as less manure P is applied.

CONCLUSIONS

Controlling the fate of P applied in manure requires efforts at many scales, which range from field specific BMPs to watershed-wide planning. Ultimately, system-level changes in farm and regional P balances are required to check the effects of long-term localised P accumulations. Even so, even when nutrient balances are maintained, P transfers from land to water are possible. Because manure contains high concentrations of nutrients in ratios inconsistent with crop demands, prudent land application of manure requires a holistic approach to P management. Thus, tools such as the P Index are required to elucidate opportunities for improved management of land-applied manure.

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