ENVIRONMENT AND HEALTH

Symposium: Reducing the Environmental Impact of Poultry Production: Focus on Phosphorus

Agricultural Phosphorus, Water Quality, and Poultry Production: Are They Compatible?

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ABSTRACT With the concentration of poultry production and increase in operation size in several regions of the U.S., more manure is applied to agricultural land. This application of manure has resulted in more P being added than crops require, an accumulation in soil P, and increased potential for P loss in surface runoff. This situation has been exacerbated by manure management being N-based. Increased outputs of P to fresh waters can accelerate eutrophication, which impairs water use and can lead to fish kills and toxic algal blooms. As a result, information is needed on the effect of poultry production on the fate of P in agricultural systems so that compatible production and water quality goals can be met. Overall, these goals will be met by focusing on ways to increase P use-efficiency by attempting to balance inputs of P in feed and fertilizer into a watershed with output in crop and livestock. This will involve refining feed rations, using feed additives to increase P absorption by the animal, moving manure from surplus to deficit areas, finding alternative uses for manure, and targeting conservation practices, such as reduced tillage, buffer strips, and cover crops, to critical areas of P export from a watershed. These critical areas are where high P soils coincide with parts of the landscape where surface runoff and erosion potential is high. Development of management systems that address both production and environmental concerns must consider the socioeconomic and political impacts of any management changes on both rural and urban communities, and of the mechanisms by which change can be achieved in a diverse and dispersed community of land users.

(*Key words*: phosphorus, manure application, eutrophication, conservation, poultry production)

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INTRODUCTION

Phosphorus is an essential element for plant and animal growth and its input to agriculture is necessary to maintain profitable crop and animal production. However, P inputs to fresh waters can accelerate eutrophication (Schindler, 1977; Carpenter *et al*., 1998). Although N and C are also essential to the growth of aquatic biota, most attention has focused on P because of the difficulty in controlling the exchange of N and C between the atmosphere and water, and fixation of atmospheric N by some blue-green algae. Thus, control of P inputs is critical to reducing freshwater eutrophication.

Eutrophication has been identified as the main problem in surface waters having impaired water quality (USEPA, 1996). Eutrophication restricts water use for fisheries, recreation, industry, and drinking, due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their death and decomposition. Associated periodic surface blooms of cyanobacteria (blue-green algae) occur in drinking water supplies and may pose a serious health hazard to animals and humans. Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern U.S. have been linked to excess nutrients in affected waters (Burkholder *et al*., 1992). Neurological damage in people exposed to the toxic volatile chemicals produced by this dinoflagellate has dramatically increased public awareness of eutrophication and the need for solutions (Matuszak *et al*., 1997; Bever *et al*., 1998; Grattan *et al*., 1998).

Nitrogen-based management has been practiced and advocated by farm advisors for many years. Despite an intensive research effort on P and water quality since the early 1980s, farmers are only now becoming aware of P issues. Many farmers and advisors are confused and feel that science has misled them or let them down by not emphasizing the P management issues. This paper

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addresses these issues relative to the compatibility of poultry production and water quality. The results of a study of the fate of P in poultry litter added to soil and transfer to runoff water is also presented, along with implications for the development and integration of agricultural systems that sustain production, environmental quality, and farming communities.

THE ROLE OF PHOSPHORUS IN AGRICULTURE

Poultry Production

Confined animal feeding operations are now a major source of agricultural income in several states. Poultry manure can be a valuable resource improving soil structure and increasing vegetative cover, thereby reducing surface runoff and erosion potential. However, the rapid growth and intensification of crop and poultry production in many areas has created regional and local imbalances in P inputs and outputs. Currently, 97% of poultry sales in the U.S. are controlled by operations that each produce more than 100,000 broilers a year (Gardner, 1998). On average, only 30% of the fertilizer and feed P input to farming systems is output in crop and animal produce. Thus, there is an inherent tendency for P to accumulate in confined animal feeding operations.

Prior to World War II, farming communities tended to be self-sufficient, in that enough feed was produced locally to meet animal requirements and the manure nutrients could be effectively recycled to meet crop needs. As a result, a sustainable food chain tended to exist. After World War II, increased fertilizer use in crop production fragmented farming systems, created specialized crop and animal operations that efficiently coexist in different regions within and among countries. As farmers did not need to rely on manures as nutrient sources (the primary source until fertilizer production and distribution became cheaper), we could spatially separate grain and animal production. By 1995, the major animal-producing states imported over 80% of their grain for feed (Lanyon and Thompson, 1996). In fact, less than a third of the grain produced on farms today is fed on the farm where it is grown (USDA, 1989). This evolution of our agricultural systems is resulting in the transfer of P in feed from grain-producing areas to animal-producing areas and an accumulation of P in the soils in those areas.

The potential for P surplus at the farm scale can increase when farming systems change from cropping to intensive animal production, as P inputs become dominated by feed rather than fertilizer (Table 1). With a greater reliance on imported feeds, only 30% of the P in purchased feed for a 74,000 layer operation on a 12-ha farm in Pennsylvania could be accounted for in farm outputs (Table 1). This nutrient budget clearly shows that the largest input of nutrients to a poultry farm, and thus the primary source of any on-farm nutrient excess, is in animal feed. Annual P surpluses of 90 to 120 kg P/ha per yr were estimated by Sims (1997) for a typical poultry-grain farm in Delaware. This scenario is consistent with other concentrated animal production industries, including dairy and swine.

TABLE 1. Farming system and P balance (data adapted from Lanyon and Thompson, 1996)

Data	Farming system		
	Crop[1]	Dairy[2]	Poultry[3]
	(kg P/ha/yr)		
Input			
Fertilizer	22	11	. . .
Feed	. . .	22	1,540
Output	20	15	365
Balance	+2	+18	1,175

[1]A 30-ha cash crop farm growing corn and alfalfa.

[2]A 40-ha dairy farm with 65 dairy Holsteins averaging 6,600 kg milk/cow/yr, 5 dry cows, and 35 heifers. Crops were corn for silage and grain, alfalfa and rye for forage.

[3]A 12-ha poultry farm with 74,000 layers; output includes 375 kg P/ha/yr in eggs, 22 kg P/ha/yr sold in crops (corn and alfalfa), and 11 kg P/ha/yr manure exported from the farm.

Phosphorus accumulation on farms has built-up soil P to levels that often exceed crop needs. Today, there are serious concerns that agricultural runoff (surface and subsurface) and erosion from high P soils may be major contributing factors to surface water eutrophication. Although P loss in agricultural runoff is not of economic importance to farmers, amounting to only 1 or 2% of that applied, environmental problems associated with P losses from soils can have significant off-site economic impacts on water quality. In some cases, these impacts are manifested many miles from the site where P loss in soil erosion and runoff originally occurred. By the time the water quality impacts are noticeable, remedial strategies are difficult and extensive to implement. Remediating surface waters impacted by P is further complicated by the time involved (years to decades) and the fact that surface waters often cross political boundaries (e.g., state lines).

The Fate of Phosphorus in Soils

Continual long-term application of fertilizer or manure at levels exceeding crop needs will increase soil P levels (Table 2). In many areas of poultry production, manure application rate recommendations are routinely based on their N content and crop N requirement to minimize the purchase of commercial fertilizer N and risk of nitrate leaching. This application often results in a buildup of soil test P above amounts sufficient for optimal crop yields, due to the generally lower ratio of N:P added in poultry manure and litter (2:1; Gilbertson *et al.*, 1979; Eck and Stewart, 1995) than taken up by major grain and hay crops (8:1; White and Collins, 1982). The ratio of N:P in manure can be reduced even further during stockpiling of manure because of gaseous N loss. This N loss reduces the N:P ratio and hastens soil P build-up. For example, a plant-available N value of 60% for poultry litter can reduce the N:P ratio from 2:1 to 2:1.5.

The accumulation of P is evident from soil test results. In 1996, several state soil test laboratories in the Northeast

TABLE 2. Available soil P concentration of soil treated with fertilizer or manure for several years and untreated soil

Soil[1]	Crop	Added P	Time	Available soil P Method	Untreated	Treated	Reference and location
		(kg/ha/yr)	(yr)	(mg/kg)			
Fertilizer							
Raub, sil	Mixed	22	25	Bray I	18	24	Barber (1979); Indiana
		54	25		18	71	
Portsmouth, fsl	Mixed veg.	20	9	Mehlich I	18	73	Cox *et al.* (1981); North Carolina and Rothamsted
Batcombe, cl		27	19	Olsen	16	44	
Richfiled, scl	Mixed veg.	20	14	Bray I	12	54	Hooker *et al.* (1983); Kansas
	.	40	14		12	56	
Pullman, cl	Sorghum	56	8	Bray I	15	76	Sharpley *et al.* (1984); Texas
Keith, sil	Wheat	11	6	Bray I	22	31	McCallister *et al.* (1987); Nebraska
		33	6		24	47	
Rosebud, sil	Wheat	11	6	Bray I	10	28	
		33	6		10	48	
Poultry litter							
Cahaba, vfsl	Grass	130	12	Bray I	5	216	Sharpley *et al.* (1993); Oklahoma
Ruston, fsl		100	12		12	342	
Stigler, sl		35	35		14	239	
Sandstones	Grass		10	Mehlich I	30	230	Kingery *et al.* (1994); Alabama

[1]vfsl = very fine sandy loam, fsl = fine sandy loam, sl = sandy loam, sil = silt loam, scl = silty clay loam, cl = clay loam.

reported the majority of soils analyzed had soil test P levels in the high or very high categories which require little or no P (Figure 1). Moreover, distinct areas of general P deficit and surplus can also exist within states. For example, soil test summaries for Delaware indicate the magnitude and localization of high soil test P levels that can occur in areas dominated by intensive poultry production (Figure 1). In Sussex County, DE, with a high concentration of poultry operations, 87% of fields tested in 1992 to 1996 had optimum (25 to 50 mg/kg) or high soil test P (> 50 mg/kg; determined as Mehlich-1 P); whereas in New Castle County, with only limited poultry production, 72% of fields were rated as low (< 13 mg/kg) or medium (13 to 25 mg/kg).

Though rapidly built up by applications of P, the decline in available soil P is slow once further applications are stopped. Thus, the determination of how long soil test P will remain above crop sufficiency levels is of economic and environmental importance to farmers who must integrate manure P into sustainable nutrient management systems. For example, if a field has a high potential to enrich agricultural runoff with P due to excessive soil P, how long will it be before crop uptake will lower soil P levels so that manure can be applied again without increasing the potential for P loss? McCollum (1991) estimated that without further P additions, 16 to 18 yr of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production would be needed to deplete soil test P (Mehlich-1 P) in a Portsmouth fine sandy loam from 100 mg/kg to the agronomic threshold level of 20 mg/kg.

THE TRANSPORT OF PHOSPHORUS IN AGRICULTURAL RUNOFF

The term “agricultural runoff” encompasses two processes that occur in the field; surface runoff and subsurface flow. In reality, these can be vague terms to describe very dynamic processes. For example, surface or overland flow can infiltrate into a soil during movement down a slope, move laterally as interflow, and reappear as surface flow. In this article, agricultural runoff refers to the total loss of water from a watershed by all surface and subsurface pathways.

Forms and Processes

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms (Figure 2). Sediment P includes P associated with soil particles and organic material eroded during flow events and constitutes 60 to 90% of P transported in surface runoff from most cultivated land (Sharpley *et al*., 1992). Surface runoff from grass, forest, or noncultivated soils carries little sediment, and is, therefore, generally dominated by dissolved P. The dissolved form of P comes from the release of P from manure, soil, and plant material (Figure 2). This release occurs when rainfall or irrigation water interacts with a thin layer of surface soil (2 to 5 cm) and plant material before leaving the field as surface runoff (Sharpley, 1985). Most dissolved P is immediately available for biological uptake. Sediment P is not readily available but can be a long-term source of P for aquatic biota (Sharpley, 1993; Ekholm, 1994).

In most watersheds, P export occurs mainly in surface runoff rather than subsurface flow. However, in some regions, notably the Coastal Plains and Florida, as well as fields with subsurface drains, P can be transported in drainage waters. Generally, the concentration of P in water percolating through the soil profile is small due to fixation of P by P-deficient subsoils. Exceptions occur in sandy, acid organic, or peaty soils, with low P fixation or holding capacities, and in soils where the preferential flow of water can occur rapidly through macropores and earthworm holes (Sharpley and Syers, 1979; Bengston *et al.*, 1992).

Transformations between dissolved and particulate forms of P such as sorption / desorption and deposition / resuspension occur during stream flow (Figure 2). On arrival at the receiving lake, further exchange of P at the sediment-water interface influences algal availability of P. These transformations in P availability should be considered in assessing the potential biological impact of P from agriculture and, thus, P management options.

Manure Management and Phosphorus Loss in Runoff

Increases in P loss in surface runoff have been measured after manure or fertilizer applications (Table 3). Phosphorus losses are influenced by the rate, method, and time of application; form of P applied; amount and time of rainfall after application; and vegetative cover (Sharpley *et al.*, 1998). As expected, larger additions of P in manure or litter increased P losses and in most cases, the proportion of added P lost in runoff. In a couple of studies, fertilizer P applications reduced P loss in surface runoff, probably due to reduced runoff and erosion associated with increased protective vegetative cover afforded by fertilization (Table 3). Similar improvements in ground cover and water quality can occur following poultry manure or litter applications.

Incorporation of manure into the soil profile either by tillage or subsurface placement reduces the potential for P loss in surface runoff. Mueller *et al.* (1984) showed incorporation of dairy manure by chisel plowing reduced total P loss in surface runoff from corn 13-fold compared to no till areas receiving surface applications. However, the concentration of total P in surface runoff was slightly greater with chisel plowing (1.7 mg/L) than no till (1.5 mg/L). This difference was due to an increase in infiltration rate with chisel plowing and consequent decrease in surface runoff volume (Mueller *et al.*, 1984). Thus, P loss in surface runoff was decreased by a lower surface soil P content and reduction in surface runoff volume caused by incorporation of manure.

A similar situation was observed by Pote *et al.* (1996) following application of poultry litter to fescue in

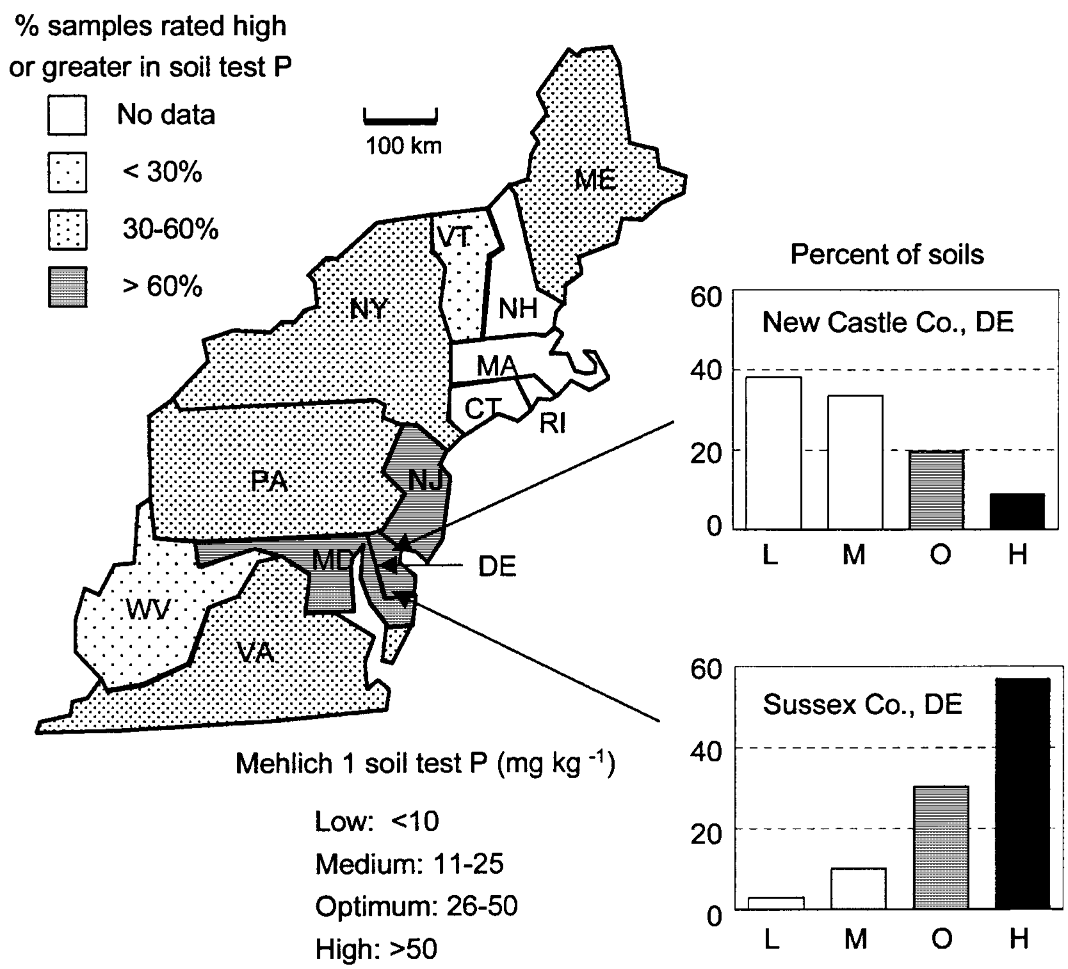

FIGURE 1. Percentage of soils testing high or above for P in 1995 for the northeast U.S. Also shown is the percentage of soils rated as low, medium, optimum and high from 1995 soil test summaries for Delaware counties with little animal production (New Castle Co.) and with concentrated poultry production (Sussex Co.).

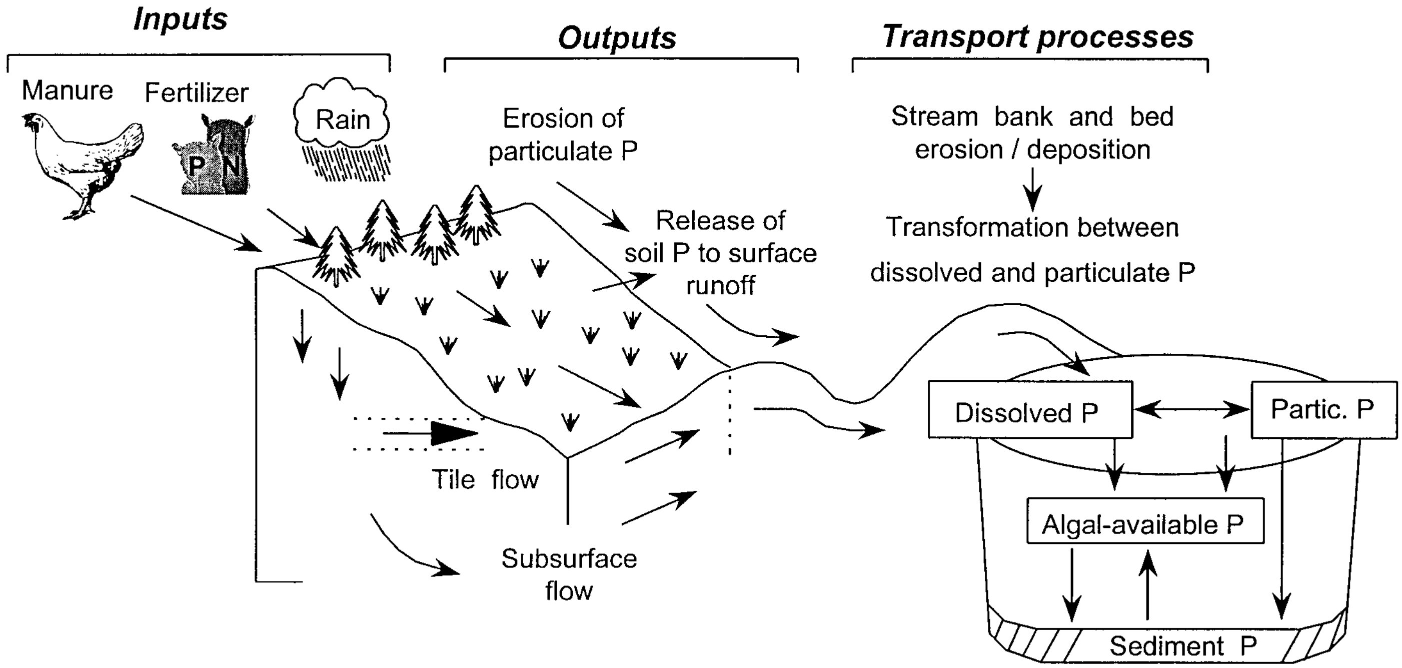

FIGURE 2. The inputs, outputs, and processes important to transport of P to surface waters in agricultural systems.

Arkansas. Although soil test P, as altered by poultry litter, was related to the dissolved P concentration of surface runoff ($r^2 = 0.76$; Figure 3), no significant relationship was obtained between the mass of dissolved P lost (kilograms per hectare) and soil test P (milligrams per kilogram) ($r^2 = 0.05$) as variability in surface runoff was controlling P loss. Incorporation of poultry litter increased organic C content and decreased bulk density of the surface 5 cm of soil, with the result that surface runoff decreased. From the results of Pote *et al.* (1996), it appears that we can have soils of 59 and 381 mg/kg soil test P, which both supported a dissolved P loss of 0.18 kg/ha during a 30-min runoff event, even though dissolved P concentration was higher with elevated soil test P (0.49 and 1.26 mg/L, respectively). These data highlight one danger of using soil test P as the sole criterion to determine manure applications based on the potential loss of P in surface runoff.

Timing of manure applications relative to occurrence of rainfall influences N and P loss in surface runoff. The major portion of annual P losses in surface runoff usually occur in only a few storms each year. For example, more than 75% of annual surface runoff from catchments in Ohio (Edwards and Owens, 1991) and Oklahoma (Smith *et al.*, 1991) occurred in one or two severe storms. Further, these events contributed over 90% of annual total P export (0.2 and 5.0 kg/ha per yr, respectively). If manure applications are made during periods of the year when intense storms are likely, then the percentage of applied P lost should be higher than if applications are made when surface runoff probabilities are lower.

An increase in the length of time between applying manure and a surface runoff event reduces P transport in surface runoff (Sharpley, 1997). When surface runoff occurred 3 d rather than 1 h after poultry manure application to fescue in North Carolina, Westerman and Overcash (1980) found the initial high concentrations of total P in surface runoff were reduced approximately 90%, due to increased sorption of P by soil. With longer periods between manure application to fescue and rainfall-runoff initiation in Arkansas (up to 14 d), Edwards and Daniel (1993) found little effect of time on P loss in surface runoff. These studies suggest intervals of more than about a week between manure application and surface runoff may not greatly affect P loss; however, more research is needed before application timing can be used as another criteria for manure management.

Clearly, there is a great deal of information on the fate of P from manure in soil and its transport in surface runoff. However, few studies have investigated the effect of manure addition on the transport of P in both surface runoff and subsurface flow. This paper reports a study of P movement in surface runoff and subsurface flow from a grassed soil following annual poultry litter applications and the effect of stopping litter applications on P transport.

MATERIALS AND METHODS

Experimental Plots

Poultry litter was applied to one of two adjacent plots established in bermudagrass (*Cynodon dactylon*) for several years, in Durant, OK. The soil type was Ruston fine sandy loam (*Typic Paleudult*) with 6 to 8% slope, consisting of three natural horizons having a total thickness of about 70 cm. Plots were approximately 2.0 m wide × 8.0 m in length (Heathman *et al.*, 1995). The plots were isolated from each other and adjacent areas by sheetmetal plates

TABLE 3. Effect of fertilizer and manure application on P loss in surface runoff

Land use	P added	Phosphorus loss: Dissolved	Phosphorus loss: Total	Phosphorus loss: Percentage	Reference and location
	(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(%)	
Fertilizer					
Grass	0	0.02	0.22		McColl *et al.* (1977); New Zealand
	75	0.04	0.33	0.1	
No-till corn	0	0.70	2.00		McDowell and McGregor (1984); Mississippi
	30	0.80	1.80	–0.7	
Conventional corn	0	0.10	13.89		
	30	0.20	17.70	12.7	
Wheat	0	0.20	1.60		Nicholaichuk and Read (1978); Saskatchewan, Canada
	54	1.20	4.10	4.6	
Bahiagrass	0	0.88	1.29		Rechcigl *et al.* (1990); Florida
	12	1.10	1.15	–1.2	
	48	2.36	2.87	3.3	
Grass	0	0.50	1.17		Sharpley and Syers (1979); New Zealand
	50	2.80	5.54	8.7	
Poultry litter					
Grass	0	0.01	0.91		Heathman *et al.* (1996); Oklahoma
	140	0.10	2.96	1.5	
Fescue	0	0.00	0.10		Edwards and Daniel (1993); Arkansas
	54	1.20	1.20	2.2	
	108	2.40	2.70	2.5	
	215	4.70	5.80	2.7	
Fallow	0	0.10	0.40		Westerman *et al.* (1983); North Carolina
	83	1.72	5.61	6.3	
	165	4.71	15.58	9.2	
Poultry manure					
Grass	0	0.00	0.10		Edwards and Daniel (1992); Arkansas
	76	1.10	2.10	2.6	
	304	4.30	9.70	3.2	
Grass	0	0.10	0.40		Westerman *et al.* (1983); North Carolina
	47	0.21	5.00	9.8	
	95	1.40	12.4	12.6	

extending 15 cm above ground to 90 cm below ground. Plastic gutters at the downslope face of each plot diverted surface runoff to containers where the total water flow for each event was collected. A metal sheet was inserted horizontally 15 cm into the soil surface of each plot at a depth of 70 cm. Plastic guttering diverted all interflow water leaving the soil face at this depth to large collectors.

Prior to poultry litter application, bermudagrass on both the untreated and treated plots were trimmed to within 5 cm of the soil surface. Poultry litter was broadcast at 11 mg/ha (5 tons/acre), a level commonly used annually by poultry producers in eastern Oklahoma to one of the plots in April 1991, 1992, and 1993. The total P content of litter applied in 1991, 1992, and 1993 was 15, 16, and 14 g/kg, respectively. The other untreated plot received no poultry litter.

Litter, Soil, and Water Flow

Poultry litter (pine-bark shavings bedding material) was collected on the day of land application from a broiler house in McCurtain Co., southeastern Oklahoma. The sample was thoroughly mixed and stored at "house moisture" in plastic bags at 4 C, until applied to the plots 4 d after collection. The moisture content of the litter was determined by gravimetric analysis for correction of N and P contents, and averaged 9.8%.

The bermudagrass was harvested for plant yield and nutrient content in late August or early September each year. At the same time, soil samples were collected at 5-cm intervals to a 70-cm depth. Plant samples were air-dried and ground to 60 mesh for subsequent P analysis. Soil samples were also air-dried and sieved (< 2 mm) prior to storage and P analysis.

Total surface runoff and subsurface flow to a depth of 70 cm were collected from individual plots downslope in a large subsurface roofed collection area (Heathman *et al.*, 1995). During each rainfall event, a collection system diverted all surface runoff and subsurface flow to separate large metal containers from which total volumes of flow were measured and subsamples collected for chemical analysis and determination of sediment loss.

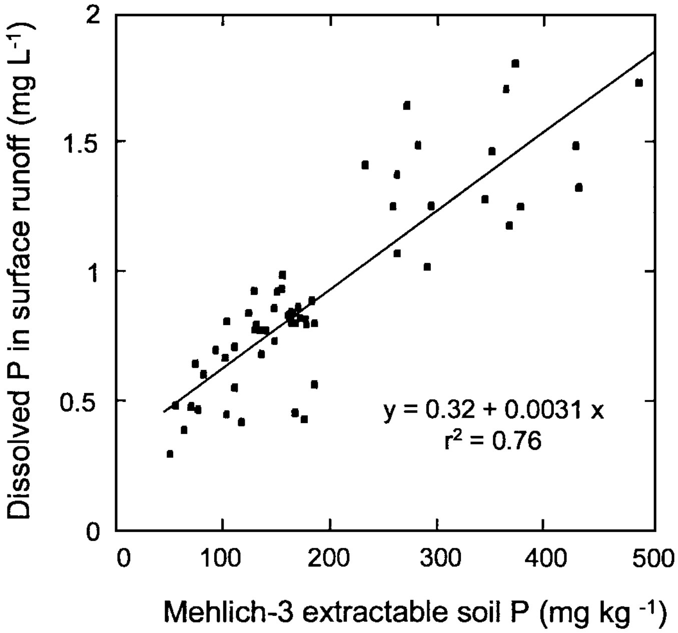

FIGURE 3. Effect of soil test P (Mehlich-3) on the dissolved P concentration of surface runoff from fescue receiving poultry litter in Arkansas.

Chemical Analyses

The total P contents of litter applied to the plots, soil, and plant material were determined by a semimicro-Kjeldahl procedure (Bremner and Mulvaney, 1982). The total P content of the Kjeldahl digest was measured by the colorimetric method of Murphy and Riley (1962). Soil test P was determined using the Mehlich-3 procedure, in which 1 g of soil was shaken end-over-end with 10 mL 0.2 *M* CH_3COOH, 0.25 *M* NH_4NO_3, 0.15 *M* NH_4F, 0.013 *M* HNO_3, and 0.001 *M* EDTA for 5 min (Mehlich, 1984).

Aliquots of each surface runoff and interflow sample were filtered (< 0.45 μm) prior to dissolved P determination, whereas total P was determined on unfiltered samples. Total P was analyzed by standard automated methods described in Methods for Chemical Analysis of Water and Wastes (USEPA, 1979). Dissolved P was determined using the colorimetric method of Murphy and Riley (1962).

RESULTS AND DISCUSSION

Fate of Poultry Litter Phosphorus in Soil

The application of poultry litter at a rate of 140 kg P/ha per yr increased the Mehlich-3 P concentration in the surface 10 cm of soil (Figure 4). In fact, applying litter for 3 yr at this rate increased the Mehlich-3 P concentration of the 0 to 5 cm depth of soil from 10 to 235 mg P/kg. After a cumulative litter application of 420 kg P/ha over 3 yr, little increase in soil P was observed below 20 cm (Figure 4). A similar accumulation of added P in the surface 20 to 30 cm of soil has been observed by Kingery *et al.* (1994) and Sharpley *et al.* (1993).

Transport of Poultry Litter Phosphorus in Surface Runoff and Subsurface Flow

Prior to litter application the mean average dissolved P concentration of surface runoff from the two study plots averaged 0.08 mg/L (Figure 5). Following litter application, the dissolved P concentration of surface runoff increased from 2.93 mg/L in 1991 to 4.08 mg/L in 1993. When litter application was stopped, there was an immediate decline in surface soil (0 to 5 cm depth) Mehlich-3 P and mean annual dissolved P concentration (Figure 5). In the 3 yr following the last litter application, Mehlich-3 soil P decreased from 235 to 182 mg/kg and dissolved P concentration from 4.08 to 1.45 mg/L. Surface soil Mehlich-3 P declined due to the sorption of P in forms less available for plant uptake (Sharpley and Smith 1995), which, in turn, contributed to the decrease in the dissolved P concentration of surface runoff. Even so, Mehlich-3 P concentrations (182 mg/kg) were still appreciably greater than the fescue crop requirements (20 to 60 mg/kg, Mehlich-3 P).

The concentration of dissolved P in subsurface flow at a depth of 70 cm also increased following poultry liter application (Figure 5). As might be expected, the dissolved P increase was delayed compared to surface runoff,

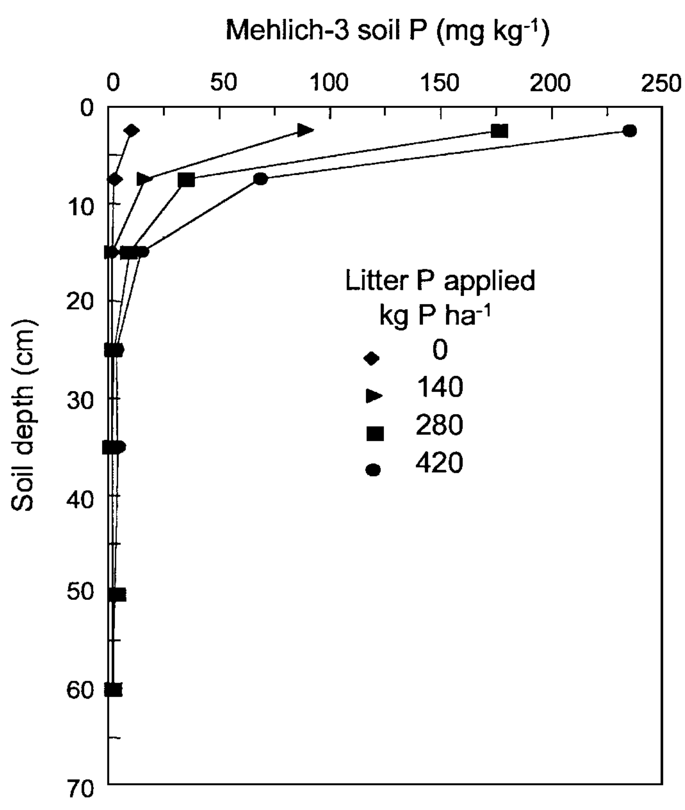

FIGURE 4. Effect of poultry litter application at 140 kg P ha^{-1} yr^{-1} for three years on the Mehlich-3 P concentration in the profile of a Ruston fine sandy loam.

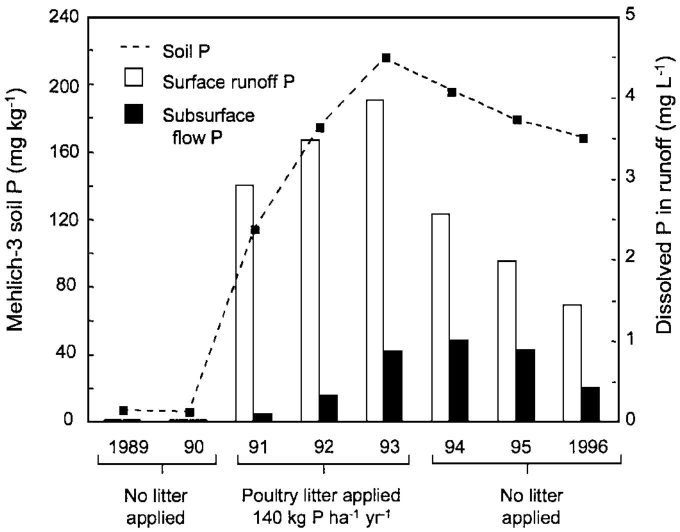

FIGURE 5. Surface soil (0 to 5 cm) Mehlich-3 P and mean annual dissolved P concentration of surface runoff and subsurface flow (70-cm depth) from bermudagrass before, during, and after poultry litter application (11 Mg ha^{-1} yr^{-1}; 140 kg P ha^{-1} yr^{-1}).

with the highest mean annual concentration (1.02 mg/L) occurring in 1994, 1 yr after litter application stopped. Mean annual dissolved P concentration prior to litter application and from the control plot averaged 0.02 mg/L.

Although no significant increase ($P < 0.05$) in Mehlich-3 P was observed below 30 cm in the soil with litter application (Figure 4), the dissolved P concentration of subsurface flow at 70 cm in the soil increased from 0.02 to 1.02 mg/L. This increase suggests the importance of preferential flow pathways through the soil profile, such as macropores, earthworm holes, and old root channels. Apparently, the lack of any accumulation of soil P in a subsoil does not preclude the fact that some P may be moving through this profile.

Phosphorus Balance

At the end of each growing season, bermudagrass yield and P content were determined, and P uptake by the bermudagrass was calculated (Table 4). The loss of total P in surface runoff and subsurface flow during each flow event was calculated as the product of total P concentration and flow volume (Table 4). A simple annual P budget was calculated from the input of P in litter and output in bermudagrass harvest, surface runoff, and subsurface flow (Table 4).

Prior to litter application, there was a negative P balance, with about 7 kg P/ha per yr being removed from the plot (Table 4). When litter was applied, there was a surplus of 116 hg P/ha per yr. Over the 8-yr study, there was a total P surplus of 226 kg P/ha (Table 4). Applying poultry litter to meet the N requirements of bermudagrass resulted in 365 kg P/ha being applied that was not removed by bermudagrass. Clearly, this results in an accumulation of soil P and increase in P loss in surface runoff and subsurface flow occurs. The results of this study and those discussed earlier have important implications to the management of manures from poultry operations to maximize productivity and protect water quality.

IMPLICATIONS FOR PHOSPHORUS MANAGEMENT

The overall goal of our efforts to reduce P losses to water should be to increase P use efficiency by attempting to balance P inputs in feed and fertilizer into a watershed with outputs in crop and animal produce, together with managing the level of P in the soil. Reducing P loss in agricultural runoff may be brought about by source and transport control strategies. We have generally been able to reduce the transport of P from agricultural land in erosion. However, less attention has been directed toward source management and the control of dissolved P losses in surface runoff.

Source Management

Soils. Environmental concern has forced many states to consider the development of recommendations for manure and watershed management based on soil P and on

TABLE 4. Phosphorus budget of poultry litter application, P uptake by bermudagrass, and total P loss in surface runoff and subsurface flow

Time	Year	Litter P added	Bermudagrass Yield	Bermudagrass Uptake	Total P loss Surface	Total P loss Subsurface	P budget
		(kg/ha/yr)					
Before litter application	1989	0	3,500	5.9	0.2	0.1	–6
	1990	0	4,010	6.4	0.2	0.1	–7
During litter application	1991	140	8,110	16.9	3.8	0.1	119
	1992	140	8,210	18.6	5.1	0.4	116
	1993	140	8,510	20.0	7.8	0.5	112
After litter application	1994	0	8,220	22.5	5.6	0.7	–29
	1995	0	8,040	18.2	4.2	0.6	–23
	1996	0	7,120	13.2	2.2	0.5	–16
	Total	420	. . .	121.7	29.1	3.0	+226

TABLE 5. Threshold soil test P values and P management recommendations (adapted from Sharpley *et al.*, 1996)

State	Threshold values: Agronomic[1]	Threshold values: Environmental	Soil test P method	Management recommendations for water quality protection
	(mg/kg)	(mg/kg)		
Arkansas	50	150	Mehlich 3	*At or above 150 mg/kg soil P*: Apply no more P, provide buffers next to streams, overseed pastures with legumes to aid P removal, and provide constant soil cover to minimize erosion.
Delaware	25	50	Mehlich 1	*Above 50 mg/kg soil P*: Apply no more P until soil P is significantly reduced.
Idaho	12	50 and 100	Olsen	*Sandy soils—above 50 mg/kg*: *Silt loam soils—above 100 mg/kg*: Apply no more P until soil P is significantly reduced.
Ohio	40	150	Bray 1	*Above 150 mg/kg soil P*: Reduce erosion and reduce or eliminate P additions.
Oklahoma	30	130	Mehlich 3	*30 to 130 mg/kg soil P*: Half P rate on >8% slopes. *130 to 200 mg/kg soil P*: Half P rate and reduce surface runoff and erosion. *Above 200 mg/kg soil P*: P rate not to exceed crop removal.
Michigan	40	75	Bray 1	*Below 75 mg/kg soil P*: P application not to exceed crop removal. *Above 75 mg/kg soil P*: Apply no P from any source.
Texas	44	200	Texas A&M	*Above 200 mg/kg soil P*: P addition not to exceed crop removal.
Wisconsin	20	75	Bray 1	*Below 75 mg/kg soil P*: Rotate to P demanding crops and reduce P additions. *Above 75 mg/kg soil P*: Discontinue P applications.

[1]Agronomic threshold concentrations are average values for nonvegetable crops; actual values vary with soil and crop type. Also, vegetables have higher agronomic P requirements.

the potential for P loss in surface runoff. A major difficulty is the identification of a threshold soil test P level to estimate when soil P becomes high enough to result in unacceptable P enrichment of agricultural runoff. Table 5 gives examples from several states, along with agronomic threshold concentrations for comparison. Environmental threshold levels range from 2 (Delaware, Michigan) to 4 (Texas) times agronomic thresholds.

We must be careful how we interpret soil test results for environmental purposes. Interpretations given on soil test reports (i.e., low, medium, optimum, high, etc) were established based on the expected response of a crop to P. Some people would simply extend the levels used for interpretation for crop response and say a soil test that is above the level at which a crop response is expected is in excess of crop needs and therefore is potentially polluting (Figure 6). However, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and surface runoff enrichment potential, which highlights one of the crucial issues facing P management at the moment: At what levels should recommendations for P application change from being agronomic to environmentally based? The interval between threshold soil P levels for optimum crop yield and unacceptable P enrichment of surface runoff will be important in determining the flexibility farmers will have to manage P (Figure 6).

Manures. Farm advisors and resource planners are now recommending that P content of both manure and soil be determined by soil test laboratories before land application of manure. This determination is important because there is a tendency among farmers and their advisors to underestimate the fertilizer value of manure without these determinations. Soil test results can also demonstrate the positive and negative long-term effects of manure use and the time required to build-up or deplete soil nutrients. For instance, they can help a farmer identify the fields in need of P fertilization, those for which moderate manure applications may be made, and those fields containing excess P that should not be manured.

Manipulation of dietary P intake by animals may help balance farm P inputs and outputs in animal operations as feed inputs are often the major cause of P surplus. There is a clear indication that amounts of excreted P can be

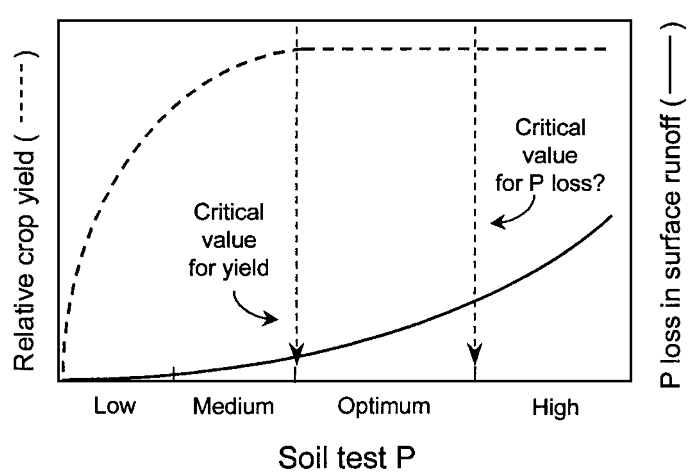

FIGURE 6. As soil P increases so does crop yield and the potential for P loss in surface runoff. The interval between the critical soil P value for yield and runoff P will be important for P management.

reduced by decreasing mineral P supplements to carefully match dietary P requirements of dairy cows (Morse *et al.*, 1992; Wadman *et al.*, 1987). It is common to supplement poultry feed with mineral forms of P because of the low digestibility of phytin, the major P compound in grain. This supplementation contributes to P enrichment of poultry manures and litters. Enzyme additives for poultry feed that will increase the efficiency of P uptake from grain during digestion are now used. For example, phytase enhances the efficiency of P recovery from phytin in grains fed to poultry. Use of this enzyme has become cost-effective in terms of bird-weight gain and lower mineral P supplementation of feed, and can reduce the P content of manure. In the Northeast, several feed mills now routinely provide phytase to producers and are refining the process of adding the enzyme to pelletized poultry feed.

Another approach is to increase the quantity of P in corn that is available to poultry by reducing the amount of phytate produced by corn. This will decrease phytate P, which contributes as much as 85% of P in corn grain, and increase inorganic P concentrations in grain. Ertl, *et al.* (1998) manipulated the genes controlling phytate formation in corn and showed that phytate P concentrations in “low-phytic acid” corn grain were as much as 51% less than in “wild-type” grain. Subsequently, P concentrations in the litter of poultry fed the “low-phytic acid” grain were 23% less than those in the litter of poultry fed the “wild type” corn grain. Thus, the use of low-phytate corn in poultry feed can increase the availability of P and other minerals and proteins that are typically phytate-bound.

Commercially available manure amendments, such as alum, can reduce NH_3 volatilization, leading to improved animal health and weight gains; they can also reduce the solubility of P in poultry litter by several orders of magnitude; and decrease dissolved P, metal, and hormone concentrations in surface runoff (Moore and Miller, 1994; Moore *et al.*, 1995; Nichols *et al.*, 1997). For example, the dissolved P concentration (11 mg/L) of surface runoff from fescue treated with alum-amended litter was much lower than from fescue (83 mg/L) treated with unamended litter (Shreve *et al.*, 1995). Perhaps the most important benefit of manure amendments for both air and water quality, would be an increase in the N:P ratio of manure, via reduced N loss because of NH_3 volatilization. An increased N:P ratio of manure would more closely match crop N and P requirements.

Composting, another potential tool, may also be considered as a management tool to improve manure distribution. Although composting tends to increase the P concentration of manures, the volume is reduced and thus, transportation costs are reduced. Additional markets are also available for composted materials. Composted materials are more uniform in physical and chemical properties and, therefore, can be spread more uniformly and at more accurate rates. However, it should be noted that composting increases NH_3 volatilization, which aggravates N:P ratios even more.

At the moment, manures are rarely transported more than 10 miles from where they are produced. A mechanism should be established to facilitate movement of manure from surplus to deficit areas. This movement may initially require incentives to facilitate subsequent transport of manures from one area to another. Even so, innovative methods are being used by some farmers to transport manure. For example, grain or feed trucks and railcars are transporting dry manure back to the grain source area instead of returning empty. In Delaware, a local poultry trade organization has established a “manure bank” network that puts manure-needy farmers in contact with manure-rich poultry growers. Even so, large scale transportation of manure from producing to non-manure-producing areas is not occurring. The main reason for this is the concern that avian diseases will be transferred from one farm (or region) to the next. Consequently, there is a need to develop a means to ensure the biosecurity of any manure transportation network that is developed.

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. Liquid wastes can be digested anaerobically to produce methane, which can be used for heat and energy. As the value of clean water and cost of sustainable manure management is realized, it is expected that alternative entrepreneurial uses for manure will be developed, become more cost-effective, and, thus, create expanding markets.

Transport Management

Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops, and impoundments (settling basins). Basically, these practices reduce rainfall impact on the soil surface, reduce surface runoff volume and velocity, and increase soil resistance to erosion. None of these measures should be relied on as the sole or primary practice to reduce P losses in agricultural runoff.

Most of these practices are generally more efficient at reducing sediment P than dissolved P. Several researchers have indicated little decrease in lake productivity with reduced P inputs following implementation of conservation measures (Gray and Kirkland, 1986; Young and DePinto, 1982). Many times, the impact of remedial measures to help improve poor water quality will be slow, as P stored in lake and stream sediments can be an existing long-term source of P in waters even after inputs from agriculture are reduced. Therefore, immediate action may be needed to reduce future problems.

Targeting Remediation

In most cases, the agencies that have proposed threshold soil P levels to guide manure management are promoting a standard threshold level to all areas and states under their jurisdiction. Establishing these levels is often a highly controversial process for several reasons. The data base relating soil test P to surface runoff P is limited to a few soils and crops and there is a reluctance to generalize the data to other regions. Also, there are major economic implications in establishing soil test P levels that could limit manure applications. For example, in many areas dominated by animal-based agriculture there simply is no economically viable alternative to land application.

Most importantly, threshold soil P levels are too limited to be the sole criterion to guide manure management and P applications. For example, adjacent fields having similar soil test P levels but differing susceptibilities to surface runoff and erosion, due to contrasting topography and management, should not have similar P management recommendations. Also, it has been shown that in many agricultural watersheds 90% of annual algal-available P export from watersheds comes from only 10% of the land area during a few relatively large storms (Pionke *et al.*, 1997). Therefore, threshold soil P levels will have little meaning unless they are used in conjunction with an estimate of a sites' potential for surface runoff and erosion.

A sounder approach advocated by researchers and an increasing number of advisory personnel is to identify critical source-areas where high soil P levels coincide with high surface runoff and erosion potentials. This approach addresses P management at multi-field or watershed scales. Further, a comprehensive P management strategy must address down-gradient water quality impacts such as the proximity of P-sensitive waters. Conventionally applied remediations may not produce the desired results and may prove to be an inefficient and poor cost-effective approach to the problem if this source-area perspective to target application of P fertility, surface runoff, and erosion control technology is not used.

A simple P index has been developed by USDA-NRCS in cooperation with several research scientists as a screening tool for use by field staffs, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in surface runoff (Lemunyon and Gilbert, 1993). The index accounts for and ranks transport and source factors controlling P loss in surface runoff and sites where the risk of P movement is expected to be higher than that of others (Table 6). Each site characteristic affecting P loss is weighted, by assuming that certain characteristics have a relatively greater effect on potential P loss than others. Each user must establish a range of P loss potential values (Table 6) for different geographic areas. An assessment of site vulnerability to P loss in surface runoff is made by selecting the rating value for each site characteristic from the P index. Each rating is multiplied by the appropriate weighting factor. The P index value for the site is the sum of weighted values of all site characteristics, which can then be used to categorize site vulnerability to P loss (Table 7).

The index is a tool for field personnel to help identify agricultural areas or practices that have the greatest

TABLE 6. The modified P indexing system to rate the potential P loss in runoff from site characteristics

Factors (Weight)	None (0.6)	Low (0.7)	Medium (0.8)	High (0.9)	Very high (1.0)
Soil erosion (1.0)[1]	Negligible	< 10	10 to 20	20 to 30	> 30
Irrigation erosion (1.0)	Negligible	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes < 5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soil with slopes > 5%
Runoff Class (1.0)	Negligible	Very low or low	Medium	High	Very high
	None (0.2)	Low (0.4)	Medium (0.6)	High (0.8)	Very high (1.0)
Contributing distance, m (1.0) [return period, yr]	> 170 [> 0]	170 to 130 [10 to 6]	130 to 80 [5 to 3]	80 to 30 [2 to 1]	> 30 [> 1]
	Phosphorus source potential (Value)				
	None (0)	Low (1)	Medium (2)	High (4)	Very high (8)
Soil test P (1.0)[2]	< 10	10 to 30	30 to 100	100 to 200	> 200
Fertilizer P rate (0.75)[3]	None applied	1 to 15	16 to 45	46 to 75	> 76
Organic P source application rate (0.5)[3]	None applied	1 to 15	16 to 30	30 to 45	> 45
Application method for fertilizer and/or organic source (1.0)	None	Placed with planter or injected deeper than 5 cm	Incorporated immediately before crop	Incorporated > 3 mo before crop or surface applied < 3 mo before crop	Surface applied > 3 mo before crop

[1]Units for soil erosion are milligrams per hectare.

[2]Units for Mehlich-3 soil P are milligrams of P per kilogram.

[3]Units for P application are kilograms of P per hectare.

TABLE 7. Site vulnerability to P loss as a function of total weighted rating values from the modified P index and generalized interpretations of the index

P Index	Generalized interpretation of the P index
< 5	**LOW** potential for P loss. If current farming practices are maintained, there is a low probability of adverse impacts on surface waters
6 to 12	**MEDIUM** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss.
13 to 20	**HIGH** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a P management plans are needed to minimize the probability of P loss.
> 20	**VERY HIGH** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss.

potential to accelerate eutrophication. It will identify management options available to land users that will allow them flexibility in developing remedial strategies. Determination of the P index for soils adjacent to sensitive waters is the first step to prioritize the efforts needed to reduce P losses; then management options appropriate for soils with different P index ratings can be implemented. Some general recommendations are given in Table 7; however, P management is very site-specific and requires a well-planned, coordinated effort between farmers, extension agronomists, and soil conservation specialists.

Strategic Initiatives

Perhaps the most critical, yet challenging, area to initiate real and lasting changes in agricultural production will be to focus on consumer driven programs and education. Farmers are at the bottom of the food chain with regional and often global economic pressures and constraints, which farmers have little or no control over, influencing their decisions (Lanyon, 1994). Since World War II, greater fertilizer N availability via increased production and reduced cost, along with soybean breeding, dramatically increased animal productivity. Improved breeding, specialized feed concentrates, and new production technologies have also led to greater animal productivity on a smaller land area. As a result, poultry production has changed from land-based to capital-based or economically driven systems. Thus, manure production and management issues facing farmers are to a large extent driven by external economic factors rather than environmental issues.

Clearly, we have to look at new ways of helping farmers implement best management practices. 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 P-related concerns. Rather than assume that inappropriate farm management is responsible for today’s water quality problems, we must address the underlying causes of the symptoms (Lanyon and Thompson, 1996). These causes are related to marketplace pressures, the breakdown and imbalances in global P cycling, and economic survival of farms. Research is needed to develop programs that encourage farmer performance and stewardship to achieve agreed environmental goals. These programs should focus on public participation to resolve conflicts between economic production efficiency and social issues such as water quality.

CONCLUSIONS

From the preceding discussion it is clear that agricultural P, poultry production, and water quality can be compatible in most areas, as long as the following factors are considered and management criteria met.

1) Attempts should be made to balance P inputs and outputs at a watershed scale.
2) We must develop, implement, and monitor the success of cost-effective best management practices that increase the utilization of manure P and reduce the vulnerability of P loss to surface waters.
3) Remedial strategies should be targeted to critical source areas of P in a watershed.
4) Stewardship programs that provide some form of economic incentive or reward for producers to implement environmentally sound practices should be considered.

In some areas, however, the increased number of poultry operations may produce much more P than the crop needs of the region. If alternative uses for the manure or its transportation to areas of need cannot be developed, then production and water quality goals may not be compatible. At some stage, attainment of these goals will have to be prioritized and decisions made as to the relative importance of production or water quality.

We have not been successful at translating basic P research information to implementation of management programs that are both effective and practical to farmers. In many cases, participation in such programs is still voluntary; thus, we must continue to emphasize interdisciplinary research involving soil scientists, hydrologists, agronomists, limnologists, and animal scientists. Development of guidelines to implement such programs will also require consideration of the socioeconomic and political impacts of any management changes on both rural and urban communities, and of the mechanisms by which change can be achieved in a diverse and dispersed community of land users.

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