Review

ANIMAL-BASED AGRICULTURE, PHOSPHORUS MANAGEMENT AND WATER QUALITY IN BRAZIL: OPTIONS FOR THE FUTURE

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ABSTRACT: Eutrophication has become a major threat to water quality in the U.S., Europe, and Australasia. In most cases, freshwater eutrophication is accelerated by increased inputs of phosphorus (P), of which agricultural runoff is now a major contributor, due to intensification of crop and animal production systems since the early 1990s'. Once little information is available on the impacts of Brazilian agriculture in water quality, recent changes in crop and animal production systems in Brazil were evaluated in the context of probable implications of the fate of P in agriculture. Between 1993 and 2003, there was 33% increase in the number of housed animals (i.e., beef, dairy cows, swine, and poultry), most in the South Region (i.e., Paraná, Rio Grande do Sul, and Santa Catarina States), where 43 and 49% of Brazil's swine and poultry production is located, respectively. Although grazing-based beef production is the major animal production system in Brazil, it is an extensive system, where manure is deposited over grazed pastures; confined swine and poultry are intensive systems, producing large amounts of manure in small areas, which can be considered a manageable resource. This discussion will focus on swine and poultry farming. Based on average swine (100 kg) and poultry weights (1.3 kg), daily manure production (4.90 and 0.055 kg per swine and poultry animal unit, respectively), and manure P content (40 and 24 g kg^{-1} for swine and poultry, respectively), an estimated 2.5 million tones of P in swine and poultry manure were produced in 2003. Mostly in the South and Southeast regions of Brazil (62%), which represent only 18% of the country's land area. In the context of crop P requirements, there was 2.6 times more P produced in manure (1.08 million tones) than applied as fertilizer (0.42 million tonnes) in South Brazil in 2003. If it is assumed that fertilizer P use represents P added to meet crop needs and accounts for P sorbed by soil in unavailable forms each year, if swine and poultry manure were to replace fertilizer, there would be an annual P surplus of 0.66 million tonnes in the South region alone. These approximations and estimates highlight that, similarly to other parts of the world, there is a potential for surplus P to quickly accumulate in certain regions of Brazil. Unless measures are developed and implemented to utilize manure P, repeated annual surpluses will create an increasingly difficult problem to solve. These measures can be grouped as source and transport management. Source management attempts to decrease dietary P, use feed additives, manure treatment and composting, as well as careful management of the rate, timing, and method of manure applications. Transport management attempts to control the loss of P in runoff from soil to sensitive waters via use of conservation tillage, buffer or riparian zones, cover crops, and trapping ponds or wetlands. These measures are discussed in the contest of Brazil's climate, topography, and land use, and how successful remediation programs may be implemented at farm and watershed level.
Key words: diffuse pollution, eutrophication, poultry production, swine production, surface runoff

PRODUÇÃO ANIMAL, MANEJO DE FÓSFORO E QUALIDADE DA ÁGUA NO BRASIL: OPÇÕES PARA O FUTURO

RESUMO: Eutrofização dos mananciais de água se tornou uma preocupação nos Estados Unidos, Europa e Austrália. Na maioria dos casos, a eutrofização de mananciais de água é acelerada pelo aumento na quantidade de fósforo adicionada, o que tem estreita relação com o escorrimento superficial deste elemento, em função da intensificação dos sistemas de produção de culturas e animais a partir do início dos anos noventa. Em virtude de pouca informação com relação aos impactos da agricultura na qualidade da água, este artigo enfatiza modificações nos sistemas de produção de culturas e animais no Brasil no contexto das

prováveis implicações quanto ao destino do fósforo no processo. Os dados apontam para um aumento de 33% no número de animais (gado de corte, gado de leite, suíno e frango) no período de 1993 - 2003, a maior parte deste aumento ocorrendo na região sul (Paraná, Rio Grande do Sul e Santa Catarina), onde se localizam 43% e 49% da produção de suínos e frangos, respectivamente. Enquanto a produção de gado de corte se dá predominantemente em sistema de pastejo a campo, com deposição do esterco sobre os pastos, a produção de suíno e frango ocorre em sistema intensivo de confinamento, o que resulta em elevadas quantidades de esterco em pequenas áreas. Assim sendo, a discussão irá focalizar na produção de suínos e frangos. Tendo em vista o peso médio de suíno (100 kg) e frango (1,3 kg), a produção diária de esterco (4,90 e 0,055 kg por suíno ou frango, respectivamente), e o conteúdo médio de P no esterco (40 e 24 g kg^{-1} para suíno e frango, respectivamente), estimou-se uma quantidade de 2,5 milhões de toneladas de fósforo nos estercos de suíno e frango, produzidas no Brasil em 2003. A maior parte foi produzida nas regiões sul e sudeste do Brasil (62% em conjunto), a qual representa apenas 18% da área do país. No contexto da exigência das culturas, os cálculos apontam para 2,6 vezes mais fósforo produzido nos estercos (1,08 milhões de toneladas) do que aplicado por meio de fertilizante (0,42 milhões de toneladas) na região sul em 2003. Diante do fato que a quantidade utilizada por fertilizantes representa o necessário para atender as exigências nutricionais das plantas, levando inclusive em consideração o fósforo adsorvido pelo solo, se o esterco de suíno e frango fosse considerado no sentido de substituir os fertilizantes aplicados, haveria uma sobra anual de 0,66 milhões de toneladas apenas na região sul. Estas aproximações e estimativas claramente indicam que, como em outras partes do mundo, existe potencial para esta sobra anual de fósforo rapidamente acumular em certas regiões do Brasil. A menos que medidas sejam desenvolvidas e implementadas para utilizar este esterco, repetidas sobras anuais irão conduzir a um problema de difícil resolução. Estas medidas podem ser agrupadas em dois tipos: as do manejo das fontes e as do transporte. As medidas que visam o manejo das fontes tendem a diminuir as quantidades de fósforo na dieta, usar aditivos no alimento, promover o tratamento e compostagem do esterco, bem como manejar com cuidado as doses, época, e método de aplicação dos estercos. As medidas visando o manejo no transporte objetivam controlar a perda de fósforo no escorrimento do solo para os corpos de água por meio da conservação do solo e resíduos, zonas vegetativas ribeirinhas de contenção, culturas de cobertura superficial, e pontes de aprisionamento ou áreas alagadas. Estas medidas são discutidas no contexto do clima, topografia, uso do solo, e ainda quanto ao sucesso dos programas de remediação a serem implementados em fazendas ou bacias hidrográficas.

Palavras-chave: eutrofização, fonte de poluição difusa, medidas corretivas, produção de aves, produção de suínos

INTRODUCTION

Recent assessments of water quality status have identified eutrophication as one of the most ubiquitous water quality impairments in the U.S., Europe, and Australasia (Heaney et al., 2001; New Zealand, 1997; U. S. Geological Survey, 1999). Eutrophication is the natural aging of lakes or streams brought on by nutrient enrichment. This process can be greatly accelerated by human activities which increase nutrient loading rates to water. While both phosphorus (P) and nitrogen (N) contribute to eutrophication, P is the primary agent in freshwater eutrophication, as many algae are able to obtain N from the atmosphere (Schindler, 1977). Thus, controlling eutrophication mainly requires reducing P inputs to surface waters, despite the fact that P is an essential nutrient for crop and animal production.

Eutrophication restricts water use for fisheries, recreation, and industry due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their death and decomposition. Also, an increasing number of surface waters have experienced periodic and massive harmful algal blooms (e.g., *cyanobacteria* and *Pfiesteria*), which contribute, along other things, to summer fish kills, unpalatability of drinking water, formation of carcinogens during water chlorination, and links to neurological impairment in humans (Burkholder & Glasgow Jr., 1997; Howarth et al., 2000).

Although concern over eutrophication is not new, there has been a profound shift in our understanding of, and focus on, sources of P in water bodies. Since the late 1960s, the relative contributions of P to water bodies, both from point and diffuse sources, have changed dramatically. On one hand, great strides have been made in the control of point source discharges of P, such as the reduction of P in sewage treatment plant effluent. These improvements have been due, in part, to the ease in identifying point sources. On the other hand, less attention has been directed to controlling diffuse sources of P, due mainly to the difficulty in their identification and control (Sharpley & Rekolainen, 1997). Thus, control of diffuse sources of P is a major hurdle to protecting fresh surface waters from eutrophication (Sharpley & Tunney, 2000; Withers et al., 2000).

While a variety of diffuse sources, ranging from suburban to construction areas, contribute P to water bodies, agriculture, particularly intensive animal agriculture, is receiving more research, public, and regulatory attention (Kellogg et al., 2000; Sharpley, 2000; U.S. Environmental Protection Agency, 2004). There is, however, no information on the role of agricultural management on P loss as related to water quality impairment in Brazil.

The aim of this paper is to (1) show how agricultural production systems in Brazil have changed over the last decade in ways that have increased the potential for P loss in runoff, (2) present research on factors controlling P loss from agricultural land to water, and (3) show how this information can be used to develop agricultural management strategies that minimize the potential for P loss from Brazilian agricultural systems. For this discussion, information will be present on the basis of the five regions of Brazil; North, Northeast, Central-west, Southeast, and South (Figure 1).

EVOLUTION OF AGRICULTURAL PRODUCTION SYSTEMS IN BRAZIL

Growth of Animal-Based Agriculture - An increasing world population that demands high qual-

ity protein and fiber production at a low cost has resulted in an intensification of agricultural production systems. Brazil is no exception, with annual population growth of 1.65%, the country expects to have a population of 257 million in 2030. However, the country does have the potential to increase crop and animal production for internal consumption as well as export. For example, with a diversified climate, regular rainfall, abundant solar energy, and almost 13% of the world's potable water, Brazil has 300 million hectares of highly productive, cultivated lands (Figure 1). There is an additional 90 million hectares of fertile lands that have not yet been brought into production (Brasil, 2004). Currently, Brazil is one of the world leaders in the export of a range of crop (coffee, sugar cane, alcohol, tobacco, and juice fruits) and animal produce (beef meat, hen meat, and leather).

To meet these needs there have been tremendous changes and growth of agricultural production systems in most developed countries, with crop and animal operations evolving into spatially-separated production systems (Evans et al., 1996; Lander et al., 1998). For animal agriculture, this change has involved an increase in the size of production units, greater reliance on technology, a corresponding decrease in human labor, increased confinement of animals, and a

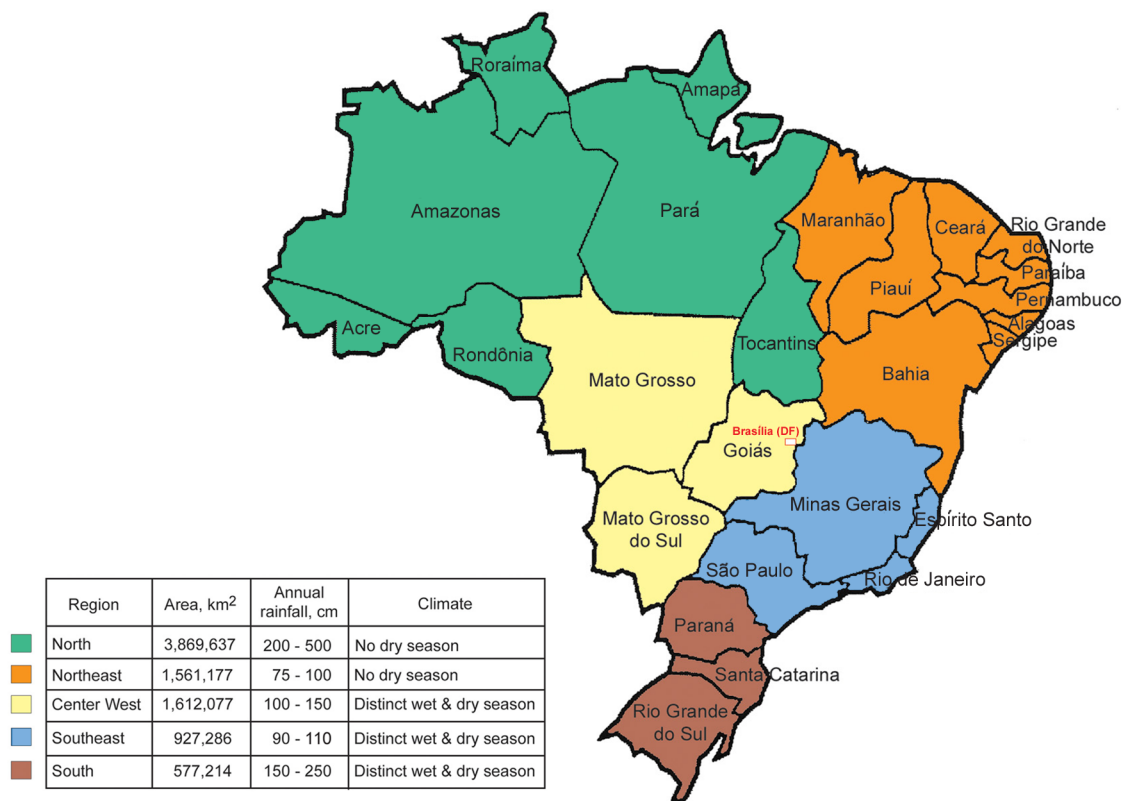|	Region	Area, km^2	Annual rainfall, cm	Climate
	North	3,869,637	200 - 500	No dry season
	Northeast	1,561,177	75 - 100	No dry season
	Center West	1,612,077	100 - 150	Distinct wet & dry season
	Southeast	927,286	90 - 110	Distinct wet & dry season
	South	577,214	150 - 250	Distinct wet & dry season

Figure 1 - The regions, area, and general climate of Brazil. Adapted from FAO (2005).

general trend towards monoculture or specialized production systems (Hogberg et al., 2005). In the U.S. for instance, beef, dairy, pig, and poultry numbers have increased 10 to 30% since 1990, while the number of farms on which they are reared has decreased 40 to 70% (Gardner, 1998). This intensification has been driven by a greater demand for animal products and improved profitability (Lanyon, 2000).

In the 1990's, there was a similar growth in the number of animal production systems in certain regions of Brazil. In fact, between 1993 and 2003, there was a 33% increase in the total number of animals in Brazil (Figure 2) (Instituto Brasileiro de Geografia e Estatística - Brazilian Geography and Statistics Institute, 2003). Most of this increase occurred in South Brazil (Figure 1), where 43 and 49% of the country's swine and poultry production is located. Although beef comprise the largest animal heard in Brazil (196 million head), their manure is not a manageable nutrient-rich resource as is swine and poultry manure. While grazing-based beef production is an extensive system where the manure is deposited over grazed pastures, confined or housed swine and poultry are intensive systems, producing large amounts of manure in localized areas (Seganfredo, 2000; Miranda et al., 1999). The large increase in size and number of animal production systems leads to an overall increase in the potential for environmental impacts, because of the major input of nutrients in animal feed from grain-producing areas, which create localized surpluses of nutrient rich manure (Cromwell, 2005; Patterson et al., 2005). The following discussion will, therefore, be limited to management of manure from swine and poultry production systems, and which conservation or best management practices are available to minimize the potential for nutrient losses from land to water.
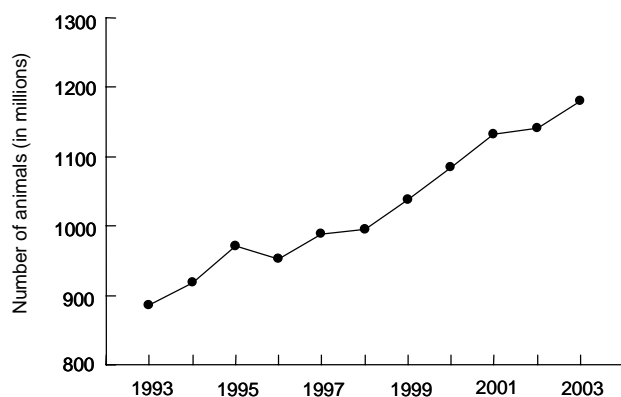
Manure Production and Phosphorus - Using estimates of the number of animals in Brazil from the recent national survey reported by the Instituto Brasileiro de Geografia e Estatistica (IBGE, 2003), we calculated the amounts of manure produced from representative average swine and poultry weights and excreta production (Table 1). An average animal weight of 100 kg for swine (Diesel et al., 2002) and 1.3 kg for poultry (Kellogg et al., 2000) was used. Daily production of 4.9 kg manure by each pig and 0.055 kg for each poultry bird was obtained from surveys conducted by Diesel et al. (2002) and Kellogg et al. (2000). Finally, chemical analysis of representative manures by Konzen (2003a) showed the concentration of total P in manure to average 40 and 24 g P kg^{-1} of swine and poultry manure, respectively (Table 1).

Clearly, animal weight, manure production, and P content of manure will vary greatly with animals' age, diet, and species. The concentration of P in manure is also influenced by manure treatment in the housing facility (e.g., amount of wash water and spillage from drinking troughs) and as well as subsequent manure storage and solid liquid separation, which will be discussed in a later section. However, the values of average animal weight, manure produced, and P concentration of manure that are presented in Table 1 and used to estimate regional manure P balances, are very similar to values for other parts of the world, as reported by Beegle (2002), Cromwell (2005), Patterson et al. (2005), and Kleinman et al. (2005). For instance, Sharpley & Moyer (2000) found total P concentration averaged 32 g P kg^{-1} for swine manure (ranging from 23 to 39 g P kg^{-1}) and 28 g P kg^{-1} for poultry manure

Table 1 - Swine and poultry numbers, weights, manure production and P content used to determine agricultural P budgets for regions in Brazil.

Variable	Swine	Poultry
Average weight, kg[†]	100	1.3
Life cycle, days[‡]	365	180
Manure produced		
kg manure per 1000 kg animal^{-1} day^{-1}	49	36
kg manure animal^{-1} day^{-1}	4.90	0.055
Manure dry matter, %[¶]	10	35
Manure total P, g P kg manure^{-1}[§]	40	24
Manure P produced, kg P animal^{-1} year^{-1}	72	0.24

[†] Average weight for breeding stock and meat production pigs and for broiler and laying poultry from Diesel (2002) and Kellogg et al. (2000), respectively. [‡]Number of days in a year animal produces manure. [¶] Manure production per unit weight of swine from Diesel (2002) and poultry from Kellogg et al. (2000). [§]Manure composition from Konzen (2003a).

Figure 2 - The number of animals in Brazil; includes beef, goat, horses, poultry, and swine. Source: Instituto Brasileiro de Geografia e Estatistica (Brazilian Geography and Statistics Institute, 2003).

(ranging from 20 to 36 g P kg^{-1}). The similarity of manure production and composition estimates from Brazil in Table 1 and estimates from other parts of the world, lends support and credibility to the calculated amounts of P in manure on a regional basis using Table 1 values.

Based on the number of swine and poultry animals in 2003 (IBGE, 2003), a total of 65 million tonnes of swine and poultry manure was estimated as being produced in Brazil. The South and Southeast regions (40 million tonnes) accounted for 62% of the national total. For the whole country, there was an estimated 2.49 million tonnes of P in swine and poultry manure produced (Figure 3). On a regional basis, it can be seen from this figure that most of the swine and poultry manure P is produced in the South (1.08 million tonnes of P) and Southeast regions of Brazil (0.45 million tonnes of P), which are both of smaller area (577,214 and 927,286 km[2], respectively) than the other regions (North, 3,869,637 km[2]; Northeast, 1,561,177 km[2]; and Center-west, 1,612,077 km[2]; Figure1).

To put this accumulation of P in swine and poultry manure into perspective in terms of annual crop production and P requirements, we compared manure P with fertilizer P use on farmed lands in Brazil (Figure 3). The amount of fertilizer applied in the production of a wide range of commercial crops in 2003 was obtained from POTAFOS (2005). For the whole country, there was 1.67 times more P produced annually in swine and poultry manure (2.49 million tonnes) than used as fertilizer (1.49 million tonnes) (Figure 3). On a regional basis, only Center-west used more fertilizer P in 2003 than was produced in swine and poultry manure. In the South region, 2.6 times more P was produced annually as manure (1.08 million tonnes) than used as fertilizer (0.42 million tonnes). If the P used in fertilizer was replaced by swine and poultry manure, the large surplus of P is clearly of environmental sig-

nificance. Assuming that fertilizer P use represents that being added at optimal rates to meet crop needs and account for P sorbed by soil in forms unavailable for crop uptake, production of swine and poultry manure creates an annual surplus of 0.66 million tonnes of P in the South region of Brazil alone. Even if fertilizer P use, underestimates crop P requirements by 20%, there will be 0.56 million tonnes of surplus manure P annually in the South and Southeast.

We have made these calculations and presented these approximations to highlight the fact that, as in the U.S. and Europe, there is a potential for P to quickly accumulate to levels that are much greater than crop needs in certain regions of Brazil. Unless measures are developed and implemented to utilize manures and P as soon as possible, repeated annual surpluses will create an increasingly difficult problem to solve. Again, we have focused on swine and poultry operations, because the manure produced is concentrated by animal confinement and is thus, a manageable resource.

Utilization of Manure in Agricultural Systems - As animals inefficiently utilize P in feed (only 30% is retained), most of the P entering animal operations ends up in manure, which is usually applied to land very close to where the manure is produced. Given the high nutrient and organic matter content of manure, when land applied it can be a valuable resource for improving soil structure and increasing vegetative cover, thereby reducing surface runoff and erosion potential. However, swine and poultry farms in the Southeast and South regions of Brazil are typically small farms, where production of manure P is much greater than the capacity to utilize this P on the farm (Oliveira, 2004). Further, these small farms do not have the necessary infrastructure to store, treat, or redistribute the manure. This leads to a rapid accumulation of P on the farm to levels that are well in excess of the crop requirements of the farm or even the region (Kellogg et al., 2000; Lander et al., 1998). Also, manure is often applied at rates designed to meet crop N requirements. This often results in a build up of soil test P above amounts sufficient for optimal crop yields, which can increase the potential for P loss in surface and subsurface runoff (Hart et al., 2004; Haygarth et al., 1998; Withers & Lord, 2002).

Although the high price of mineral fertilizers in the past few years has been stimulating farmers to better utilize manure, there is a lack of technical and economic support so that this can be realistically achieved (Nones et al., 2002; Seganfredo, 2001a). Currently, therefore, the pollution potential of manure is not usually converted to productivity (Hoffmann et al., 2001; Vieira et al., 2002).
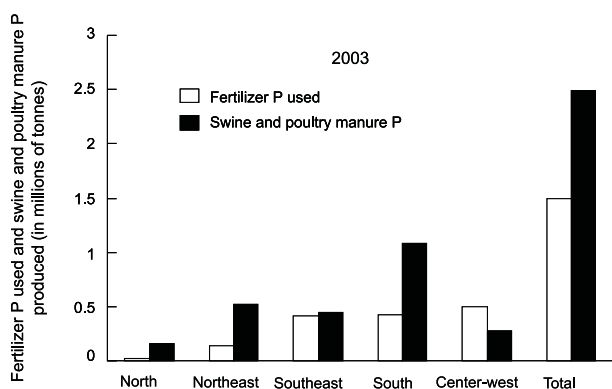

Figure 3 - The amount of fertilizer P used and P produced in swine and poultry manure in Brazil by region for 2003. Fertilizer use data adapted from Potafos (2005).

In the U.S., this has led the Environmental Protection Agency (EPA) and the Department of Agriculture (USDA) to devise a joint strategy for sustainable nutrient management for concentrated animal feedings operations (U.S. Department of Agriculture & Environmental Protection Agency, 1999). This strategy proposed a variety of voluntary and regulatory approaches, whereby all farms develop and implement a nutrient management plan, an important part of which outlines how acceptable application rates of P as mineral fertilizer or manure will be determined. In many countries, agencies charged with developing these strategies have challenged the scientific community to provide technical leadership in determining how and where P loss occurs and agricultural management options to decrease the loss.

In the U.S. and most European countries, legislation has been enacted to require farmers to implement management plans that provide for the sustainable use of manure nutrient and which protect the environment (U.S. Environmental Protection Agency, 2000; 2004). Only recently, however, has the Brazilian Government begun to look at developing nutrient and manure management guidelines, adoption incentives, and noncompliance penalties that address both agronomic production and environmental quality issues (Diesel et al., 2002).

Agronomic Response - Phosphorus applications in Brazilian crop production systems are based on the amount of plant-available soil P, as estimated from response curves that consider the best rate for agronomic effectiveness for each level of soil P (very low, low, medium, high or very high), as measured by recommended soil test P methods (most commonly resin or Mehlich-1 methods).

Early research in Brazil on the agronomic value of swine manure investigated native pasture production as influenced by swine manure application by Federal University of Santa Maria, Rio Grande do Sul, during 1998 and 1999 (Konzen, 2003b). When swine manure was applied to native grass pasture at a rate of 20 m^3 ha^{-1}, dry-matter production increased between 21 to 204% compared to untreated pastures. At a manure application of 40 m^3 ha^{-1}, there was a range in dry-matter increase of 32 to 307% (Konzen, 2003b). Similar increases in dry-matter yields (156%) of *Brachiaria brizantha* cv. Marandu were also observed compared with the control (without fertilization) following different rates of swine manure application at the Federal University of Goias (Barnabe, 2001).

Swine manure application can also benefit pasture productivity for grazing cattle. For instance, the productivity of 78 ha cultivated with *Brachiaria*

brizantha cv. Marandu following the application of 180 m^3 ha^{-1} of swine manure parceled in six annual applications for five years, was evaluated by Konzen (2003b) for a farm located in Rio Verde, Goias. It was found that after the 4th year it was possible to maintain 3.8 animal units per hectare in intensive grazing system.

There is little information detailing the effects of manure application on soil properties undertaken in Brazil. For the beneficial effects of manure application on soil nutrient status, general fertility, and structure, readers are directed to the reviews of Mullins et al. (2005) and Sharpley et al. (1998). Vieira et al. (2000), evaluating the effect of successive application of liquid swine manure on the chemical properties of a soil under native grass pasture over four years, did observe 1.0 and 3.3% increase in total C (0-20 cm depth) with respective 20 and 40 m^3 ha^{-1} manure applications.

Clearly, manure can be an important source of P to farmers when applications are based on agronomic response and crop yield goals. If carefully managed, manure can also be a valuable resource for improving soil structure and increasing vegetative cover, thereby improving water quality via reduced runoff and erosion potential. For example, McDowell & McGregor (1984) found that the application of P (30 kg P ha^{-1}) decreased runoff P in no-till corn (1.8 kg P ha^{-1} yr^{-1}) in comparison to no P applied (2.0 kg P ha^{-1} yr^{-1}), due to increased soil cover resulting from added P. Also, dairy and poultry manure applications at low rates (<50 kg P ha^{-1}) imparts physical benefits to surface soil, which decreased P loss potential (McDowell & Sharpley, 2003).

Environmental Response - Animal manure is typically land-applied to supply nutrients for crop growth, but the ratio of N and P in manure (typically 4:1) is not balanced relative to crop needs of N and P (typically 8:1). Land application of manure to meet the N needs of the crop, resulting in the over application and accumulation of P in soils, and subsequently elevated concentrations of P in runoff is frequent (Sharpley, 1995). Historically, P contamination of surface water was thought to be associated primarily to erosion. As application of P in excess of crop requirements continues, however, soils become saturated and runoff of P can occur independently of erosion (Carpenter et al., 1998; Daniel et al., 1998; Seganfredo, 2001b).

The ultimate goal of agricultural and environmental P management is to balance P inputs to the farm with outputs in primary produce, so that no excess P is applied and soil P concentrations are kept at an optimum level for agronomic performance and minimal

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environmental impact. However, when manure and nutrient applications are based on environmental rather than agronomic response, there is potential for major changes in agricultural management and negative economic impacts; it is thus necessary to explore short-term or temporary fixes.

One of the critical, unresolved issues with manure utilization is the definition of the amount of manure that can be applied to a specific crop to meet expected yield goals. Agronomic recommendations for P applications are reliably made based on soil test P, using regionally adopted methods and soil and crop type. However, there is little information on which to base manure application if environmental response is the primary concern (Seganfredo, 2001b).

Basically, two factors exacerbate the potential for environmental degradation from intensive swine and poultry production in Brazil. Firstly, these farms are concentrated in the strategically important Parana and Uruguai rivers basius, located in the relatively small Southern region (Oliveira, 2004). The potential for P-related water quality problems to occur in the Southeast and South regions of Brazil is aggravated by the fact that the region is typified by high rainfalls (90 to 250 cm yr^{-1}; Figure 1) and wavy landscapes. Secondly, these farms are comprised mainly of small rural producers that do not have the technical or financial support to introduce advanced manure treatment technology or conservation measures to minimize en-

vironmental impacts. Thus, there is a need to set incentive programs for nutrient management by the combined efforts of the farming community, animal industry, and government to facilitate the environmentally sound use of P in manure, rather than treating it as a disposal problem. To put the situation into a different perspective, the pollutant capacity of swine manure is much greater than human waste. Using the concept of population equivalency, one swine produces the same amount of manure as 3.5 people (Diesel et al., 2002). Thus, a farm with 600 pigs produces the same amount of P in manure as a town of 2,100 people.

FACTORS CONTROLLING P TRANSPORT IN RUNOFF

The transport of P can occur by surface runoff and subsurface flow. In reality, these are 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. The main factors influencing the loss of P in both surface and subsurface runoff are summarized in Table 2.

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms (Figure 4). Sediment P includes P associated with soil particles and organic material eroded during flow events and constitutes 60-90% of P transported in surface runoff from most cultivated land (Carpenter et al., 1998; Sims & Kleinman, 2005). Surface runoff from grass, forest, or

Table 2 - Factors influencing P loss from agricultural watersheds and its impact on water quality.

| Factors	Description
Site Management	
Soil P	As soil P increases, P loss in surface runoff and subsurface flow increases.
Applied P	The more P applied (mineral fertilizer or manure), the greater the risk of P loss.
Application method	P loss increases in the order; subsurface injection, plowed under, and surface broadcast with no incorporation.
Application timing	The sooner it rains after P is applied, the greater the risk for P loss.
P source	The P in some fertilizers and manures is more soluble than in others and thus, more susceptible to runoff.
Transport	
Erosion	Total P loss is strongly related to erosion.
Surface runoff	Water has to move off or through a soil for P to move.
Subsurface flow	In sandy, organic, or P-saturated soils, P can be leached.
Soil texture	Influences relative proportions of surface and subsurface flow.
Connectivity to stream	The closer the field to the stream, the greater the chance of P reaching it.
Channel effects	Eroded material and associated P can be deposited or resuspended with a change in stream flow. Dissolved P can be sorbed or desorbed by stream channel sediments and bank material.
Proximity of P-sensitive water	Some watersheds are closer to P-sensitive waters than others (i.e., point of impact).
Sensitivity P input	Shallow lakes with large surface area tend to be more vulnerable to eutrophication.
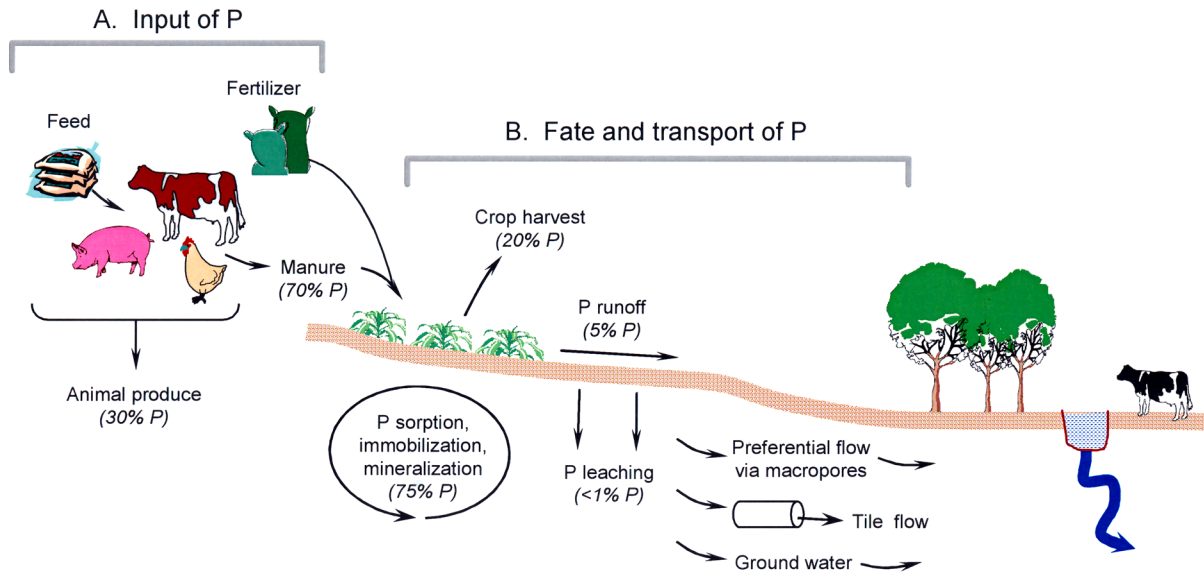
Figure 4 - Factors affecting the input, fate, and transport of P in agricultural systems. Numbers in parentheses are based on approximate farm inputs of P in animal feed and fertilizer and output in animal produce (A) and manure and fate in soils, crops, and transport in runoff (B). Adapted from Howarth et al. (2000) and Sims and Sharpley (2005).

noncultivated soils carries little sediment, and is, therefore, generally dominated by dissolved P (up to 80% of P) (Smith et al., 1991; Hart et al., 2004). Thus, erosion control is of prime importance in minimizing P loss from agricultural land. It may not, however, be sufficient in and of itself. Dissolved P originates from the release of P from soil, plants, and added fertilizer or manure (Figure 4). The release of P occurs when rainfall or irrigation water interacts with a thin layer of surface soil (1 to 5 cm) and plant material before leaving the field as surface runoff (Sharpley, 1985). While dissolved P is immediately available for biological uptake, sediment P is not readily available but can be a long-term source of P for algae (Sharpley, 1993).

Generally, P loss in surface runoff is much greater than in subsurface flow and is dependent on the rate, time, and method of P application; form of fertilizer or manure applied; amount and time of rainfall after application; and land cover (Andraski et al., 2003; Sharpley & Rekolainen, 1997). However, P loss by leaching can occur in sandy, organic, or peaty soils – those with low P adsorption capacities; and in soils with substantial preferential flow pathways (Djodjic et al., 2004; Sims et al., 1998; Van Es et al., 2004) (Figure 4). Even so, P losses are often agronomically small (generally < 2 kg P ha^{-1}), representing a minor proportion of applied fertilizer or manure P (generally $< 5\%$; Figure 4). Phosphorus uptake and harvest removal by crops ranges from 10 to 30% of applied P (on average 20%; Figure 4), due to the rapid and only slowing reversible sorption of P to Al, Fe, and Ca compounds in soil.

In Brazil, the predominance of Oxisols, rich in Al and Fe amorphous complexes tightly sorb large amounts of P (Fontes & Weed, 1991; Novais & Smyth, 1999). These soils occupy the major areas already developed for agricultural use, and are thus extremely important to crop and animal production and the overall economic viability of Brazilian agriculture (Fontes, 1996). This suggests that a major pathway for P loss from these Oxisols is going to be bound to sediment in surface runoff. This has important implications to the type of measures that would be needed to address P-related water quality problems. However, the amount of P loss necessary to cause water quality problems usually is very small compared to the amounts required by crops or contained in typical manure or fertilizer P applications. For example, lake water concentrations of P above 0.025 mg L^{-1} generally accelerate eutrophication (Table 3; Von Sperling, 1996). These values are an order of magnitude lower than P concentrations in soil solution critical for plant growth (0.2 to 0.3 mg L^{-1}), emphasizing the disparity between critical lake and soil P concentrations.

The loss of P in both surface and subsurface runoff has been shown to be related to the soil test P content of surface soils (McDowell & Sharpley, 2001; Simard et al., 2000). Thus, conventional soil P tests have been used to estimate a soil's potential to enrich runoff with P (Andraski et al., 2003; Daverede et al., 2003; Pote et al., 1996; Tarkalson & Mikkelsen, 2004a; Torbert et al., 2002). Although current soil test P methods used in Brazil (resin and Mehlich-1) were developed to estimate

plant availability of soil P, it is likely that they can also be used as surrogates of P loss potential. For instance, several studies have shown runoff P concentration to be closely related to resin and Mehlich-1 extractable soil P (Beck et al., 2004; Nair et al., 2004; Sharpley, 1995).

Surface runoff generally occurs only from limited source areas within a watershed. These source areas vary rapidly in time, expanding and contracting quickly during a storm as a function of rainfall intensity and duration, antecedent moisture conditions, temperature, soils, topography, ground water, and moisture status over a watershed. Because surface runoff is the main mechanism by which P and sediment is exported from most watersheds, it is clear that P export by water will be negligible if surface runoff does not occur. Thus, consideration of how water moves and where surface runoff occurs is criti-

Table 3 - Approximate total P concentrations in fresh surface waters that define trophic status (Von Sperling, 1996).

Trophic status	Total P concentration in a watershed
	mg L^{-1}
Ultraoligotrophic	<0.005
Oligotrophic	<0.010 - 0.020
Mesotrophic	0.010 - 0.050
Eutrophic	0.025 - 0.100
Hypereutrophic	>0.100

cal to a more detailed understanding of P export from agricultural watersheds. Overall, critical areas of P loss occur where high sources of P (soil P and P added) coincide with areas of high transport potential. Research in the Northeast U.S. has shown these critical source areas represent <20% of watershed area, but they can contribute with most (>80%) of P exported from a watershed (Gburek & Sharpley, 1998; Pionke et al., 2000). It is expected that in Brazil, a similarly small, but critical area of a watershed contributes most to the P exported.

REMEDIAL MEASURES

Remedial measures must begin with the long-term objective of increasing P use-efficiency, by attempting to balance P inputs within a watershed with P outputs, while simultaneously improving management of soil, manure, and mineral fertilizer P (Figure 5). There are several measures that can be used to reduce P loss in agricultural runoff. These measures aim to control P loss by decreasing the sources of P that could be transported in runoff and the potential for transport (i.e., runoff and erosion) itself to occur (Table 4). As swine and poultry operations have led to a potential imbalance of P in the southern region of Brazil, the following discussion will focus on these types of animal operations.

Source Management - Source management attempts to minimize the buildup of P in the soil above levels sufficient for optimum crop growth, by
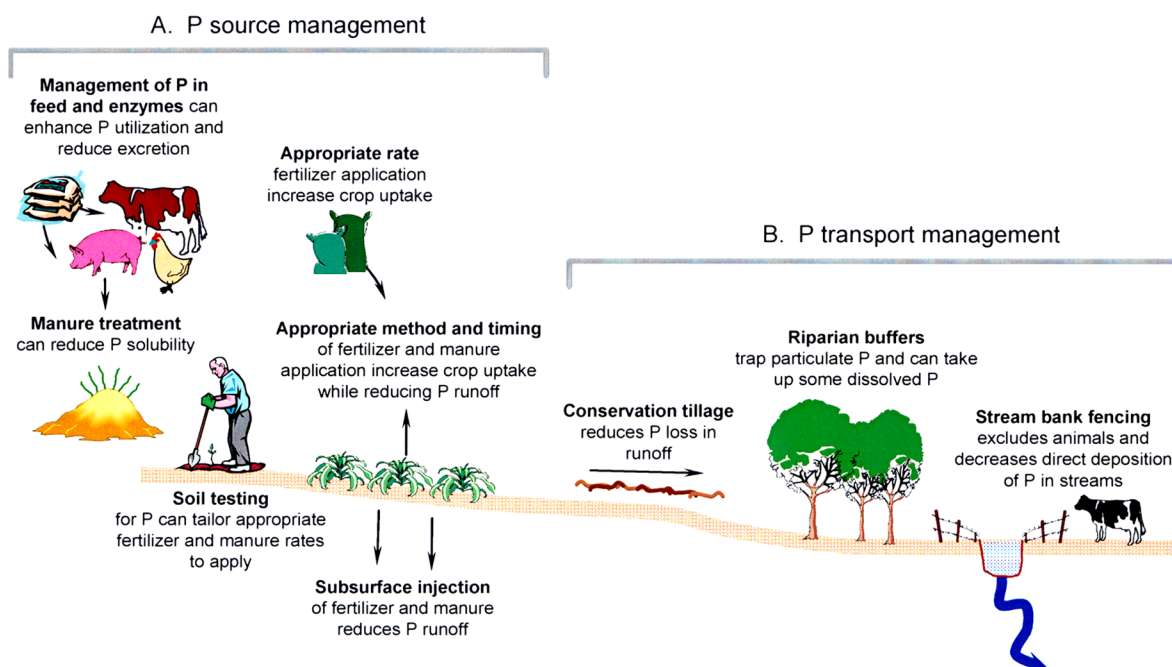

Figure 5 - The management of sources (A) and transport (B) of P on farms.

Table 4 - Best Management Practices for the control of diffuse sources of agricultural P.

Source BMPs - practices that minimize P loss at the origin
Attempts to match animal requirements for P with feed P
Enzyme added to feed to increase nutrient utilization by animals
Feed low phytic acid corn to reduce P in manure
Test soil and manure to optimize P management
Physically treat manure to separate solids from liquid
Chemically treat manure to reduce P solubility, e.g., alum, flyash, water treatment residuals
Biologically treat manure, e.g., microbial enhancement
Calibrate fertilizer and manure application equipment
Apply proper application rates of P
Use proper P application method, i.e., broadcast, plowed in, injected, subsurface placement, banding
Careful timing of P application to avoid imminent heavy rainfalls
Compost and/or pelletize manures and waste products to provide alternate use
Mine P from high P soils with certain crops and grasses
Transport BMPs - practices that minimize the transport of P
Minimize erosion, runoff and leaching, i.e., terracing, strip cropping, contour plowing
Use cover crops to protect soil surface from erosion
Install filter strips and other conservation buffers to trap eroded P and disperse runoff
Manage riparian zones, grassed waterways, and wetlands to trap eroded P and disperse runoff
Stream bank fencing to exclude animal from water course
Install and maintain impoundments or small ponds to trap sediment and P
Source and Transport BMPs - systems approach to minimize P loss
Retain crop residues and reduce tillage to minimize erosion and runoff
Grazing (pasture and range) management to minimize erosion and runoff
Install and maintain manure handling systems (houses/lagoons)
Barnyard storm water management
Install and maintain milkhouse waste filtering systems
Implement nutrient management plan for farms
Water Body Treatment BMPs - practices designed to correct problems associated with excess P in the water
Dredge lakes and ponds to remove P-rich sediments
Inactivation of sedimentary P by addition of alum, straw
Aeration to minimize reducing conditions, which favor sediment P release
Encourage vegetative growth in littoral zones to decrease water column mixing, which brings P released from sediment to surface photic zone
Vegetative mining of sedimentary P
Harvesting aquatic vegetation

limiting the quantity of P in manure that must be applied to land, and controlling the amount of P that is applied in a localized area. Several techniques for doing so will be described next: (1) manipulating animal intake of dietary P, (2) managing inorganic and protein supplements that contain P, (3) using enzyme additives for animal feed, (4) using corn hybrids with less phytate P, (5) before the land application of manure, determining the P content of both manure and soil, (6) using commercially available manure amendments, (7) physical treatment of manure to separate solids from liquids, (8) facilitating the movement of manure from surplus to deficit areas, (9) using innovative methods to transport manure, (10) composting manure, (11) using some manures as "bioenergy" sources, and (12) carefully manage the timing and method of P applications.

Manipulation of dietary P intake by animals will help balance farm P inputs and outputs in animal operations, once feed inputs are often the major cause of P surplus. Feeding beef, poultry, and swine more P than minimum dietary requirements does not seem to confer any growth, reproduction, or health advantage and is in fact, excreted (Cromwell, 2005; National Research Council, 2001; Patterson et al., 2005). Thus, carefully matching dietary P inputs to animal requirements, which means having more than one feeding management group and P level across the life cycle of

an animal can reduce the amount of P animals excrete (Cerosaletti et al., 2004). For example, Hostetter et al. (2000) stated that the introduction of ration P levels tailored to a life cycle of a sow has lowered on-farm P use by 43% between 1981 and 1999. While this had no disadvantage to sow performance, profitability increased and the environment benefited from decreased excretion of P (Hostetter et al., 2000). 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. For example, a survey of dairy farms in Wisconsin by Powell et al. (2002) showed that on farms where manure P exceeds crop P requirements, reducing dietary P to the NRC recommendation would reduce the number of farms and acreage with excess P balance by approximately two-thirds.

In addition to inorganic P supplementation of animal feed, some protein supplements can contribute substantial amounts of P to animal diets (National Research Council, 2001). Common protein supplements vary greatly in cost and P content (0.3 to 4.7% 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.

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 monogastric animals such as swine and poultry. 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 monogastric animals, can be added to feed to increase the efficiency of grain P absorption by swine and poultry (Federation of Animal Science Societies, 2001). Such enzymes reduce the need for P supplements in feed and potentially reduce the total P content of manure.

Another approach to better balance farm P inputs and outputs is to increase the quantity of P in corn that is available to swine and poultry (Cromwell, 2005; Patterson et al., 2005). Corn hybrids are available which contain low amounts of indigestible phytate P. Swine and poultry fed "low-phytic acid" corn grain excreted 10 to 40% 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. Combining use of phytase feed amendments and low-

phytate corn resulted in a 60% reduction in P excreted by swine (Baxter et al., 1998).

Farm advisors and resource planners should recommend that the P content of both soil and manure be determined by soil test laboratories before land application of manure. Without these determinations, farmers and their advisors tend to underestimate the fertilizer value of manure and may therefore over-apply them in regard to P.

Commercially available amendments, such as slaked lime or alum, which are applied to animal bedding material, can reduce ammonia (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 et al., 2000; Vadas et al., 2004). 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 P in the manure and N loss because of NH_3 volatilization. An increased N:P ratio of manure would more closely match crop N and P requirements.

Swine and dairy operations commonly rely on flush-water system for managing their manure. While such systems are very efficient, 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. Separating the solids from the liquids during slurry storage produces a solid fraction that could be more easily transported than the bulkier slurry. Solid - liquid separation also leaves large proportion of the available N in the liquid fraction and a larger proportion of the P will be in solid fraction. Coagulant and flocculent techniques commonly used by municipalities are being used to solve such problems (Timby et al., 2000). For example, use of a metal coagulant, such as aluminum in combination with commercial polymers (polyacrylamide), not only doubles the removal of solids but can dramatically reduce the soluble P in the effluent. It must be remembered, however, that manure treatment does not change the total amount of P that must be handled.

At the moment, manures are rarely transported more than 15 km from where they are produced. A program should be established to facilitate movement of manures from surplus to deficit areas. However, mandatory transport of manure from farms with surplus nutrients to neighboring farms where nutrients are needed faces several significant obstacles. First, it must be shown that manure-rich farms are unsuitable for

manure application, based on soil properties, crop nutrient requirements, hydrology, actual P movement, and sensitive water-bodies. Conversely, it must be shown that the recipient farms are more suitable for manure application. The greatest success with re-distribution of manure nutrients is likely to occur when the general goals of nutrient management set by state governments are supported by consumers, local governments, the farm community, and the animal industry involved.

Composting, another potential tool, may also be considered as management tool to improve manure distribution. Because there is a wide range of composting methods, there is little consistency in the change of manure P form during composting, in terms of its availability or stability. However, as manure volume generally decreases during composting, P becomes more concentrated and transportation costs are reduced.

There is interest in using some manure as sources of "bioenergy." For example, dried poultry litter can be burned directly or converted by pyrolytic methods into oils suitable for use to generate electric power. Liquid manures can be digested anaerobically to produce methane, which can be used for heat and energy. As there is little change in the amount of total P, an important part of any manure to energy approach must include a plan for utilizing the nutrient-rich residue.

Consideration of the rate, timing, and method of P applications can reduce the potential for P loss in runoff. As we have shown, P loss in runoff increases with greater rates and frequency of applied mineral fertilizer or manure (Edwards & Daniel, 1993; Sharpley et al., 1998). Several studies have shown a decrease in P loss with an increase in the length of time between manure application and surface runoff (Djodjic et al., 2000; Sharpley, 1997; Westerman et al., 1983). This decrease can be attributed to the reaction of added P with soil and dilution of applied P by infiltrating water from rainfall that did not cause surface runoff. For instance, in field-based rainfall simulation studies, Sharpley et al. (2001) observed that the dissolved P concentration of surface runoff from the Berks silt loam (Typic Dystrochrept) decreased from 2.75 to 0.40 mg L^{-1} when rainfall occurred 35 days rather than two days after a surface broadcast application of 100 kg P ha^{-1} as poultry manure.

Incorporation of manure into the soil profile either by tillage or subsurface placement decreases the potential for P loss in runoff by lowering the concentration of P at the soil surface and a reducing runoff volume (Mueller et al., 1984; Pote et al., 1996;

Tarkalson & Mikkelsen, 2004b). The relative solubility of fertilizer P can also influence the amount and form of P transported in runoff (Hart et al., 2004). For instance, Sharpley et al. (1978) observed a slightly greater dissolved P loss in runoff following the application of monocalcium P (MCP - the main component of superphosphate) to a permanent pasture in New Zealand (2.80 kg ha^{-1}), compared to that with dicalcium P (DCP) (2.17 kg ha^{-1}), a slow release fertilizer. The difference was attributed to more rapid dissolution of MCP than DCP at the soil surface. However, an appreciably greater loss of sediment-bound P with DCP (4.92 kg ha^{-1}) than MCP (2.63 kg ha^{-1}), resulted from an increased loss of P by transport of the less soluble DCP particles in runoff.

Transport Management - Transport management refers to efforts to control the movement of P from soils to sensitive locations such as bodies of fresh water (Figure 5). Phosphorus loss via surface runoff and erosion may be reduced by conservation tillage and crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops and impoundments (e.g., settling basins) (Table 4). These practices tend to reduce rainfall impact on the soil surface, reduce runoff volume and velocity, and increase soil resistance to erosion. Techniques for reducing the potential for transport to occur include: (1) conservation tillage, (2) cover crops, (3) grassed waterways, (4) conservation buffers, (4) barnyard runoff management, (5) stream-bank protection, and (6) constructed wetlands and sediment basins.

Conservation tillage practices are designed to reduce runoff and erosion and associated P losses. However, if manures are surface applied to maintain no-till residue compliances, the potential for P loss, particularly in the dissolved form, can be greater than for conventional tillage (Gaynor & Findlay, 1995; Sharpley & Smith, 1994). Thus, the subsurface application of manures by injection, for example, should be considered as part of conservation tillage, particularly no-till, in order to minimize runoff P losses. Injection techniques that minimize surface disturbance are important so that erosion is not increased.

Cover crops serve to protect the soil surface from raindrop impact, improve infiltration relative to bare soil and trap eroded particles (Sharpley & Smith, 1991). In areas where dissolved P transport is the primary concern, cover crops may reduce runoff, and, consequently, runoff P load (mass), but are unlikely to impact dissolved P in runoff.

Grassed waterways are designed to reduce runoff velocity and reduce channel erosion. In some cases,

grass diversions may be installed across a slope to intercept runoff and break up effective slope length (Chow et al., 1999). Riparian areas or in-field buffers can reduce erosion and P losses, as well as increase wildlife diversity and numbers and aquatic habitat (Lowrance et al., 1985; Peterjohn & Correll, 1984; Uusi-Kämppä et al., 2000). In addition to acting as physical buffers to sediment-bound nutrients, plant uptake captures P, resulting in a short-term and long-term accumulation of nutrients in biomass (Clausen et al., 2000; Jokela et al., 2004). However, the effectiveness of conservation buffer areas as nutrient buffers can vary significantly. For instance, the route and depth of subsurface water flow paths through riparian areas can influence nutrient retention. Conservation buffers are most efficient when sheet flow occurs, rather than channelized flow, which often bypass some of the retention mechanisms. Thus these areas must be carefully managed to realize their full retention and filtration capabilities.

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

Stream-bank protection and fencing (for animal exclusion) can reduce erosional inputs of P and direct deposition of manure in streams, respectively. However, stream-bank protection and fencing have not been a popular practice with many farmers and thus, not widely implemented, due to high costs, maintenance needs, and removal of a cheap and readily available drinking water source for animal.

Constructed wetlands and sediment basins both serve to reduce particulate P by intercepting sediment-laden flow. Certain wetland plant species (e.g. *Phragmites* spp.) can substantially improve P removal efficiency from surface flow.

Despite these advantages, any one of these measures should not be relied upon as the sole or primary means of reducing P losses in agricultural runoff. These 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 even after inputs from agriculture have been reduced. Thus, the effect of remedial measures in the contributing watershed will be slow for many cases of poor water quality. Therefore, immediate action may be needed to reduce future problems.

CONCLUDING REMARKS

Major changes in crop and animal production systems have taken place over the last 10 to 20 years on a global scale. Both crop and animal production became more intensive and specialized to meet population demands for low-cost yet high quality grain and protein sources. These systems now exist in spatially-separated areas because of cheap and effective transport networks that operate across regions and even countries. This has led to the one-way transfer of P from areas where rock P deposits are mined to areas of grain production to animal rearing facilities, where there is a consequent accumulation of P in manures. As this manure is land applied, soil P builds to levels that exceed crop needs and increases the potential for P in runoff. The potential for P loss and associated water quality impairment is exacerbated by the growth of animal operation in areas with inherently low soil productivity, where farmers have turned from growing crops to rearing animals to be economically viable (i.e., to continue being able to make a living from farming).

Brazil is no exception, with the major proportion of the country's swine and poultry production now occurring in the South and Southeast regions (75%). We estimate that these animals produce 2.5 million tones of P in manure each year, nationally. Although there have been many studies on the effects of land applying manure and P on soil fertility and crop production, some of which we have presented, little information exists on resulting water quality impacts. We have demonstrated that this information is clearly needed to develop conservation practices that will minimize the potential for P runoff under Brazilian farming conditions. Although lessons can be learnt from other regions of the world, conservation practices must be tailored to local land and economic constraints.

There are several measures available to minimize the potential for P loss in agricultural runoff, which address sources and transport of P. The main measures that should be considered are those that attempt to decrease the surplus of P in localized areas through dietary P reduction, feed additives that enhance P utilization by animals, alternative uses for manure other than land application, and transporting manure to P-deficient areas. Other measures, which attempt to reduce the loss in runoff, will only provide short-term benefits unless P surpluses are diminished. These measures include the use of soil P tests that estimate environmental rather than agronomic thresholds, manure application rates based on soil P and crop needs, as well as adopting conservation tillage and buffer zones that limit soil and associated P entering

streams. Even so, these measures should be targeted to critical source areas where most of the runoff originates. Finally, a financial infrastructure needs to be established that will support implementation of the above remedial measures, as well as the dissemination of technically sound advice to all farmers, policy makers, and affected public. Water quality impairment is extremely difficult to reverse and the longer we wait to address the sources of P (e.g., agriculture, municipal, urban), the more expensive remedial measures will become.

Research to address agricultural P-related should fall into four general areas: (1) assess the extent of P related water quality problems - is this a widespread or localized problem?; (2) evaluate farm P budgets (how much P input in feed and fertilizer minus output in produce) to determine the extent to which P surpluses occur - is this a small or large farm problem?; (3) determine the level of P in soils of impaired areas and how easily this is released to runoff water - is this a land use problem?; and (4) evaluate conservation or BMP measures on P loss (e.g., conservation tillage, buffers, and manure management) – what can be done?

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