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The environmentally-sound management of agricultural phosphorus

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Abstract

Freshwater eutrophication is often accelerated by increased phosphorus (P) inputs, a greater share of which now come from agricultural nonpoint sources than two decades ago. Maintenance of soil P at levels sufficient for crop needs is an essential part of sustainable agriculture. However, in areas of intensive crop and livestock production in Europe and the U.S.A., P has accumulated in soils to levels that are a long-term eutrophication rather than agronomic concern. Also, changes in land management in Europe and the U.S.A. have increased the potential for P loss in surface runoff and drainage. There is, thus, a need for information on how these factors influence the loss of P in agricultural runoff. The processes controlling the build-up of P in soil, its transport in surface and subsurface drainage in dissolved and particulate forms, and their biological availability in freshwater systems, are discussed in terms of environmentally sound P management. Such management will involve identifying P sources within watersheds; targeting cost-effective remedial measures to minimize P losses; and accounting for different water quality objectives within watersheds. The means by which this can be achieved are identified and include developing soil tests to determine the relative potential for P enrichment of agricultural runoff to occur; establishing threshold soil P levels which are of environmental concern; finding alternative uses for animal manures to decrease land area limitations for application; and adopting management systems integrating measures to reduce P sources as well as runoff and erosion potential.

Introduction

Since the 1970's point sources of water pollution have been to large extent controlled, due to their easy identification [50]. Even so, there are still water quality problems [31, 59, 96]. One of the current concerns is the accelerated eutrophication of surface waters from increased nutrient inputs stimulating algal and rooted aquatic plant growth. Controlled eutrophication is beneficial to the fisheries industry. However, excessive eutrophication restricts water use for recreation, industry, and drinking due to the increased growth of undesirable algae and aquatic weeds, which by their senescence and decay, can cause oxygen shortages and fish kills. In addition, potentially carcinogenic toxins produced by some blue-green algal blooms (dominantly cyanobacteria), can pose acute health risks to humans and animals if consumed [35, 37, 55]. These toxins also contribute to unpalatibility of drinking water via trihalomethane formation during water dechlorination [61]. Thus, eutrophication can create serious local and regional economic problems.

Nitrogen (N), carbon (C) and phosphorus (P) are the major nutrients required for freshwater eutrophication. However, most attention has focused on controlling P inputs, because of the free air-water exchange of N and C and fixation of atmospheric N by some blue-green algae. Irrespective of whether point sources (e.g., municipal and industrial discharge) are controlled or not, the nonpoint input of P in agricultural runoff can sustain further eutrophication of freshwaters in Europe [8, 23, 36, 41, 97, 98], North America [16, 40, 65, 67], and Oceania [100, 101, 102]. There is little reason to believe that these environmental concerns will be different in other regions of the world, where agricultural systems involve increased P inputs.

Current concerns facing the environmentally-sound management of P in agriculture are similar world-wide and revolve around agricultural, economic, and environmental compromises associated with balancing productivity with environmental values. For example, if agricultural P inputs are based on environmental rather than agronomic criteria, the generally lower inputs may compromise crop productivity [104]. Similarly, if manure applications are based on P rather than N input, the resulting lower rates of application will force many farmers to find alternative ways of disposing of excess manure and to buy needed inorganic N.

Phosphorus inputs are required for profitable crop production, especially in areas with P deficient soils. Thus, balancing P inputs and outputs is one of the main challenges facing modern farming systems which need to be both economically and environmentally sound. To meet these future challenges, we must be able to identify sites, soils or management systems that are vulnerable to P loss so that appropriate remedial measures can be effectively targeted. To achieve this, environmental assessments are required at the farm and watershed level; for example, soil tests are needed to assess a soil's potential to release P to runoff rather than its availability for plant uptake. Also, economically viable practices that minimize P loss in drainage and runoff should be identified and the means for their effective implementation developed. Effective implementation will involve education programs to overcome the common perception among end-users of water that it is often much cheaper to treat the symptoms of eutrophication rather than control the diffuse or nonpoint sources.

This paper discusses the major sources, forms, and pathways of P loss from agriculture in Europe and the U.S.A., how we can overcome current concerns and meet future challenges facing P management, and the development of sustainable farming systems that maintain agricultural productivity, minimize environmental degradation, and promote short- and long-term economic viability and stable farming communities.

Agricultural phosphorus

An assessment of the agricultural contribution to eutrophication in various European countries has been attempted by Vighi and Chiaudani [98]. This assessment, which was based upon a detailed questionnaire sent to participating countries, shows that agriculture contributes between 24 and 71% of the total P (TP) loadings to surface waters in Europe, although these estimates include both point (10–53% of total P load) and nonpoint sources (8–30% of total P load). Point sources of P loss from agriculture include concentrated discharge of livestock manure, accidental discharge from manure stores or direct contamination during broadcast applications of fertilizer and manure. Such point sources are best controlled by appropriate legislation relating to codes of good agricultural practice [50]. The contribution of the diffuse sources of P from agricultural land is a function of the P loading to soil and land management practices which affect the ease with which accumulated P is lost.

In the Republic of Ireland, a balance sheet study of P inputs and outputs indicated that inputs are more than double outputs, although inorganic P fertilizer use has remained constant over the last 10 years [94]. The available P content of soils have consequently shown a steady, almost linear, eight fold increase since 1950. The positive balance represents the fertilization with inorganic P in excess of crop requirements, because the manurial value of P inputs from livestock are often ignored by the farming community. A large proportion (75%) of the TP ingested by livestock in concentrate and forage is excreted [1, 22]. The P excreted from housed livestock requires storage and is often applied to a relatively small land area.

In the U.K., although the consumption of inorganic fertilizer has remained fairly constant over the last 30 years and national soil surveys in England and Wales have indicated no substantial increase in available soil P over the period 1969–1988 [88], there is still a large percentage of arable (56%) and grassed fields (30%) with moderate (26 to 45 mg kg^{-1}) to high ($>$ 45 mg kg^{-1}) Olsen extractable soil P levels (Table 1). In reviewing the significance of agriculture as a source of P to inland and coastal waters in the U.K., Withers [103] concluded that recent changes in land management practice (e.g., increase in winter cereals, slurry based livestock systems and land underdrainage) rather than changes in agricultural P inputs had increased the potential for P loss in surface and sub-surface flow.

In the Nordic countries (Denmark, Norway, Finland and Sweden) the main reason for the significant loss of P from agricultural land is considered to be the high net input of P to the soil (calculated as 20 kg ha^{-1} yr^{-1}) in recent decades [91]. Iserman [28] reports P surpluses of between 55, 71 and 88 kg ha^{-1} yr^{-1} for West Germany, East Germany and The Netherlands, respectively. For agricultural soils in the Netherlands,

Table 1. Percentages of soils in England and Wales with given Olsen extractable P contents (data from Skinner *et al.* [88])

Management	Percent soils with extractable P range (mg kg^{-1})					
	< 9	10–15	16–25	26–45	46–70	> 71
			%			
Arable						
1969–73	7	14	24	30	16	10
1974–78	4	13	26	36	14	7
1979–83	3	11	28	35	16	7
1984–88	3	11	31	34	16	6
Ley-arable						
1969–73	10	18	30	30	8	4
1974–78	9	22	31	26	7	6
1979–83	10	21	30	28	8	3
1984–88	10	18	34	28	8	3
Grassland						
1969–73	16	27	25	19	7	5
1974–78	15	22	30	24	8	2
1979–83	16	25	27	22	7	3
1984–88	17	23	30	22	6	2

Breeuwsma and Silva [8] estimated that in 1990 about 43% of those in grass and 82% of those in maize were P-saturated due to over-fertilization. In 1970, only 18% of these soils were P-saturated. Dutch soils are considered saturated when more than 25% of its sorption capacity is used [8]. The potential for P loss from these saturated soils is exacerbated by high water tables.

In the U.S.A., fertilizer P use declined from 2.2 to 1.8 million tonnes yr^{-1} during 1978 to 1988 [6]. This decrease reflects efforts to reduce unnecessary applications and farmers' response to high soil P levels, policy changes, regulating price support, P fertilizer cost, removal of fertilizer subsidies, and production control measures. Even so, a large percentage of soils in areas with intensive cropping and livestock systems still have high or excessive soil test P, in terms of crop requirements [86]. However, in the U.S., high soil test P levels are a regional problem, with the majority of soils in the Great Plains for example, still requiring fertilizer P for optimum crop yields. Unfortunately, problems associated with high soil P are aggravated by the fact that many of these soils are located near P-sensitive water bodies, such as the Great Lakes, Chesapeake and Delaware Bays, Lake Okeechobee and the Everglades.

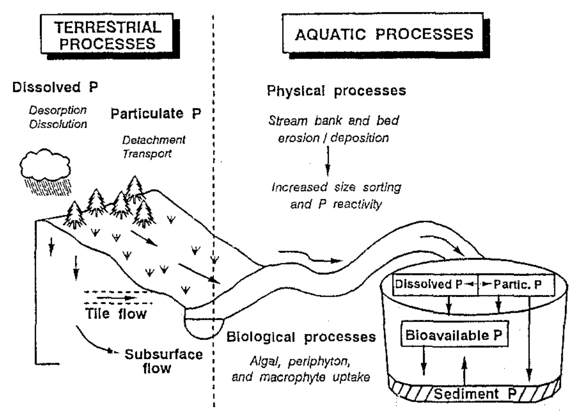

Fig. 1. Processes involved in the transport and bioavailability of P from agricultural land [adapted from 80].

Phosphorus transport in agricultural runoff

Transport processes

Phosphorus is transported in dissolved (DP) and particulate (PP) forms (Fig. 1; adapted from [80]). Dissolved P is mainly orthophosphate released from soil, vegetation, and applied fertilizer and manure and is available for uptake by aquatic biota [62]. Particulate P is comprised of P sorbed by soil material, mineral P, and organic matter eroded during runoff, which can provide a long-term source of P to aquatic biota [83].

In contrast to runoff, sorption of P by P-deficient subsoils generally results in lower concentrations of DP in subsurface flow [5, 9, 68, 71, 79]. However, in organic or peaty soils, organic C may accelerate the downward movement of P together with organic acids and/or Fe and Al [14, 17, 26, 48, 87]. Similarly, P is more susceptible to movement through sandy soils with low P sorption capacities [2, 60, 71, 90] and in soils which have become waterlogged, where a decrease in Fe (III) is reduced to Fe (II) [19, 32, 63]. The migration of particulate P through fissured soils in summer and early autumn, in association with the dispersion of clay particles by percolating water, can also occur [29].

Once in stream flow, transformations between DP and PP can occur depending on relative DP and PP concentrations [91] (Fig. 1). These transformations are accentuated by the selective transport of fine material, which has a greater capacity to sorb or desorb P and will thus, be important in determining the bioavailability of P transported [74]. In addition, DP may be removed by stream macrophytes [24, 43, 99] and PP deposited or eroded from the stream channel with a change in flow velocity. Thus, changes in DP, PP, and resultant P bioavailability during channel flow, must be considered in assessing the impact of P loss from agricultural land on the trophic state of receiving water bodies.

Amounts transported

Runoff from uncultivated and agriculturally unimproved or pristine land is considered the background loading, which cannot be reduced. This source determines the natural trophic status of a lake or river. As we try to assess the impact of agricultural management on P loss in runoff, it becomes evident that little quantitative information is available on background losses of P from a given location prior to cultivation. Consequently, it is still difficult to quantify any increase in P loss following cultivation. These problems result mainly from the expensive and labor intensive nature of water quality monitoring studies, which are site-specific and impossible to replicate, due to spatial and temporal variations in climatic, edaphic, and agronomic conditions. Despite these problems, an investigation of published studies enables generalizations regarding

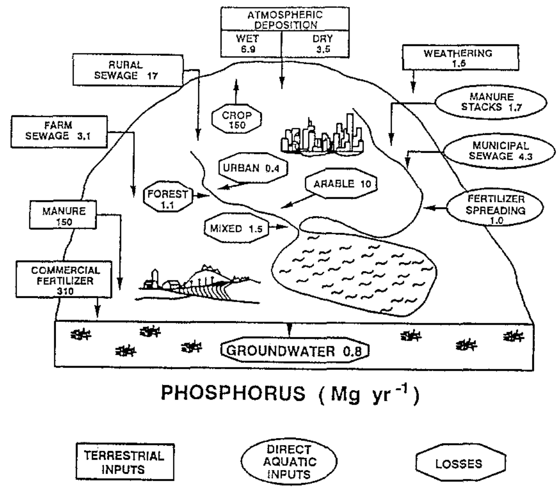

Fig. 2. Annual P inputs and losses from the drainage basin of Lake Ringsjon, Sweden [adapted from 70].

P transfer within and between ecosystems to be made. The complex nature of P transfers within terrestrial and aquatic ecosystems is shown in Fig. 2, which gives average annual P fluxes in the drainage basin of Lake Ringsjon, Sweden, as reported by Ryding *et al.* [70]. This information summarizes measured and calculated data collected over the last decade (1980–1990) by several Swedish scientists.

The atmospheric input of P to agricultural land is generally small compared to fertilizer and manure inputs (Fig. 2). However, the direct input of rainfall P to surface waters may be sufficient to enhance algal growth in certain situations. For example, Elder [15] estimated that rainfall P may account for up to 50% of the P entering Lake Superior. Since 25–50% of the TP in rainfall is dissolved, it is directly available to organisms in the lake [12, 53]. As a result, Schindler and Nighswander [72] attributed most of the enrichment of Clear Lake, Ontario, to rainfall and similar observations have been made for several Wisconsin lakes by Lee [38]. Ryding and Rast [69] report that the amount of P deposited from the atmosphere was dependent on the land-use of the surrounding area, emphasizing the often particulate nature of atmospheric P. Clearly, atmospheric inputs of P will be difficult to control, mainly because the source may be some distance from the impacted area. Also, political and regional boundaries can be crossed, and transfer pathways difficult to identify.

Increases in P loss in surface runoff have been measured after the application of fertilizer P (Table 2). Fertilizer P losses are influenced by the rate, time,

Table 2. Phosphorus loss from selected watersheds in the U.K. and the proportion attributable to agriculture

Watershed	Area (km^2)	Land use	P loss (kg ha^{-1}) yr^{-1}	Estimated agricultural contribution	Reference
				– % –	
Lough Neagh (1971–1979)	4453	74% grassland	0.84 TP (mean)	–	Foy *et al.* [18]
		19% rough grazing	0.57 DP	40	
		7% arable			
		Urban inputs			
R. Main, Co Antrim	709	10% arable	1.08 TP	55	Smith [89]
		52% grassland	0.65 DP	38	
		24% rough grazing			
		10% woodland			
		4% urban			
Loch Leven	145	65% arable	0.65 TP	51	Bailey-Watts and Kirika [4]
		Urban and industrial input	0.25 DP	34	
R. Wye – Frome	144	58% grassland	0.47 DP	51	Houston and Brooker [25]
		35% arable			
		5% forestry			
		1% rough grazing			
		Urban inputs			
R. Wye – Trothy	142	81% grassland	0.22 DP	86	Houston and Brooker [25]
		14% arable			
		3% woodland			
		2% rough grazing			
		Urban inputs			
Loch Lowes	14.9	3% arable	0.18 DP	26	Harper and Steward [21]
		7% grassland			
		10% rough grazing			
		80% forest and heath			
		No urban			
Loch Balgavies	24	75% arable	0.27 DP	93	Harper and Steward [21]
		12% grassland			
		1% rough grazing			
		12% forest and heath			
		No urban			
Loch Forfar	15.4	60% arable	8.9 DP	4	Harper and Stewart [21]
		14% grassland			
		1% forest and heath			
		25% urban			

and method of fertilizer application; form of fertilizer; amount and time of rainfall after application; and vegetative cover. The proportion of fertilizer P transported in runoff from undrained soils for the studies reported in Table 2, was generally greater from conventional compared to conservation tilled (no or zero till) watersheds. A greater proportion of fertilizer P was transported as PP than DP from the conventional compared to no till and grassed watersheds (Table 2). However, fertilizer P application to no till corn reduced PP transport [46], probably due to an increased vegetative cover afforded by fertilization. Although it is difficult to distinguish between losses of fertilizer and native soil P without the use of expensive and hazardous radiotracers, the loss of fertilizer P in surface runoff is generally less than 5% of that applied.

Table 3. Effect of fertilizer P application on the loss of P in surface runoff

Land use	P applied	Concentration Soluble	Concentration Partic.	Amount Soluble	Amount Partic.	Fertilizer loss Soluble	Fertilizer loss Partic.	Reference
	kg ha^{-1} yr^{-1}	mgL^{-1}		kg ha^{-1} yr^{-1}		%		
Contour corn	40	0.19	0.71	0.12	0.45			Burwell *et al.* [9],
	66	0.25	1.27	0.15	0.76	0.1	1.2	Minnesota
Grass	0	0.01	0.06	0.01	0.20			McColl *et al.* [44],
	75	0.03	0.14	0.04	0.29	0.04	0.1	New Zealand
No till corn	0	0.23	0.43	0.70	1.30			McDowell and
silage	30	0.39	0.49	0.80	1.00	0.3	*+23.1*[a]	McGregor [46],
								Mississippi
No till corn	0	0.23	0.46	1.10	2.20			McDowell and
grain	30	0.57	0.51	1.80	1.60	2.3	*+27.3*[a]	McGregor [46],
								Mississippi
Wheat –	0	0.30	1.80	0.20	1.40			Nicholaichuk and
summer fallow	54	3.70	7.40	1.20	2.90	1.9	2.8	Read [56],
								Western Canada
Grass	0	0.18	0.24	0.50	0.67			Sharpley and Syers
	50	0.98	0.96	2.80	2.74	4.6	4.1	[78], New Zealand

[a]Percent decrease in P loss from fertilizer compared to check treatment.

The loss of P from several mixed land-use watersheds in the British Isles is generally less than 1 kg P ha^{-1} yr^{-1} (Table 3). The estimated contribution of nonpoint sources from agriculture to these losses is variable (5 to 90%) but can be the major contributor (Table 3).

In small watershed studies, greater P concentrations have been measured in runoff from heavily stocked watersheds compared to lightly stocked watersheds [103]. The amount of P lost in surface runoff from land receiving surface application of livestock manures has been shown to depend not only on the rate and timing of the manure application but also on the time interval between application and the runoff event [84]. Highest P losses, representing up to nearly 20% of the P applied, have occurred on sloping, poorly drained and/or frozen soils [33, 34, 95]. Phosphorus concentrations as high as 30 mg L^{-1} were recorded soon after pig and cattle slurry applications to grassland in Ireland and were greater than 1 mg L^{-1} even six weeks after application [85].

The loss of P in subsurface runoff is appreciably lower than that in surface runoff because of P sorption from infiltrating water as it moves through the soil profile (Table 4). Subsurface runoff is discussed as accelerated and natural subsurface runoff, where accelerated flow is percolating water intercepted by artificial drainage systems, such as tile or mole drain, which accelerate its movement into streams. In general, P concentrations and losses in natural subsurface runoff were lower than in tile drainage (Table 4). A longer time of contact between the subsoil material and natural subsurface runoff compared to tile drainage will result in a greater retention of P by soil and lower DP in natural subsurface runoff. Increased sorption of P from percolating water also accounted for lower P loads from 1.0 m deep (0.32 kg ha^{-1} yr^{-1}) than from 0.6 m deep (0.83 kg ha^{-1} yr^{-1}) tiles draining a Brookston clay soil under alfalfa in Ontario, Canada [11]. For the shallower drains, TP loads were about 1% of fertilizer P applied (30 kg P ha^{-1} yr^{-1}) whereas 1 m deep tiles exported about 0.6% of that applied.

Significant increases in P concentrations in drainage water (up to 10 mg L^{-1}) have also been observed where diluted livestock slurries have been applied to cracking clay soils or to land which is intensively underdrained with permeable backfill [42]. Also, Sharpley and Syers [79] found that, in 4 weeks following grazing, DP loss in drainage from 45- cm deep tiles (68 g ha^{-1}) was 50% greater than from ungrazed plots (45 g ha^{-1}). The response of DP in tile drainage to grazing was rapid with maximum concentrations (0.25 mg L^{-1}) occurring only 1 week after grazing [79].

Table 4. Effect of fertilizer P application on the loss of P in subsurface runoff

Land use	P applied	Concentration		Amount		Fertilizer loss		Reference
		Soluble	Partic.	Soluble	Partic.	Soluble	Partic.	
	$kg\ ha^{-1}\ yr^{-1}$	mgL^{-1}		$kg\ ha^{-1}\ yr^{-1}$		%		
Alfalfa	0	0.180	–	0.12	0			Bolton *et al.* [7],
(tile drainage)	29	0.210	–	0.19	–	1.0	–	Canada
Continuous corn	40	0.007	–	0.03	–	–	–	Burwell *et al.* [9],
	66	0.009	–	0.04	–	–	–	Iowa
Terraced corn	67	0.028	–	0.17	–	–	–	Burwell *et al.* [9], Iowa
Bromegrass	40	0.005	–	0.03	–	–	–	Burwell *et al.* [9], Iowa
Continuous corn	0	0.20	0.100	0.13	0.29			Culley *et al.* [11],
(tile drainage)	30	0.110	0.360	0.20	0.42	0.2	0.4	Canada
Blue grass sod	0	0.02	0.15	0.06	0.09	–	–	Culley *et al.* [11],
(tile drainage)	30	1.01	3.29	0.16	0.21	0.3	0.4	Canada
Oats	0	0.02	0.09	0.10	0.19			Culley *et al.* [11],
(tile drainage)	30	0.42	1.10	0.20	0.30	0.3	0.4	Canada
Alfalfa	0	0.02	0.011	0.012	0.020			Culley *et al.* [11],
(tile drainage)	30	0.37	1.03	0.20	0.31	0.3	0.3	Canada
Corn	17	0.018	0.043	0.005	0.02	–	–	Hanway and Laflen [20],
(tile drainage)	42	0.000	0.000	0.000	0.00	–	–	Iowa
	44	0.004	0.024	0.004	0.04	–	–	
Grass	0	0.020	0.022	0.04	0.44			Sharpley and Syers [78],
	50	0.033	0.019	0.12	0.07	0.2	+7.4[a]	New Zealand
Grass	0	0.064	0.072	0.08	0.09			Sharpley and Syers [78],
(tile drainage)	50	0.190	0.161	0.44	0.37	0.7	0.6	New Zealand

[a]Percent decrease in P loss from fertilizer compared to check treatment.

Clearly, the main factors controlling these nonpoint P losses from agricultural land include the relative importance of surface and subsurface runoff in a watershed; fertilizer and manure inputs of P; and runoff and erosion potential as influenced by land management. These losses are often small (generally < 2 kg P ha $^{-1}$) and represent a minor proportion of fertilizer or manure P applied (generally < 5%). Thus, these losses are not of economic importance to farmers in terms of irreplaceable fertility. However, they may contribute to the P related eutrophication of surface waters and are, thus, of environmental and off-site economic importance. In as much, environmental impacts of agricultural P loss raise several concerns that must be addressed.

Current concerns

The main concerns currently facing the environmentally sound management of agricultural P involve (1) the accumulation of soil P in excess of crop requirements, which increases the potential for P loss in runoff or drainage water, and (2) land management practices which affect the ease with which P enters water courses. In most cases, the accumulation of soil P has occurred in areas of intensive crop and livestock production [8, 16, 30]. Thus, current environmental P concerns revolve around soil P fertility, animal manure, and land management.

Fertility management

Continual long-term application of fertilizer and manures at levels exceeding crop requirements can raise soil test P above those levels required for economically optimum crop yields in the runoff-sensitive portion of surface soil (0 to 2 cm). The build-up of P in soil is accentuated by the poor efficiency with which P, added as fertilizer or manure, is utilized by agricultural crops. This build-up can be rapid where there is an economic gain to large applications of fresh P fertilizer (eg., to potatoes) (Table 5). Where animal manures

Table 5. Potential input and removal of P by different crops receiving recommended rates of fertilizer P in the United Kingdom (from Mininstry of Agriculture, Fisheries, and Food [50])

Crop	Potential input	Potential removal[a]	Balance
		kg P ha^{-1} yr^{-1}	
Winter wheat	28	27 (7)	+1
Spring barley	19	19 (5)	0
Potatoes	91	17 (40)	+74
Sugar beet	30	14 (40)	+16
Oilseed rape	27	21 (3)	+6
Peas	26	14 (3.5)	+12
Beans	27	14 (3)	+13
Cabbage	39	20 (50)	+19

[a] Number in parenthesis is average crop yield in t ha^{-1}.

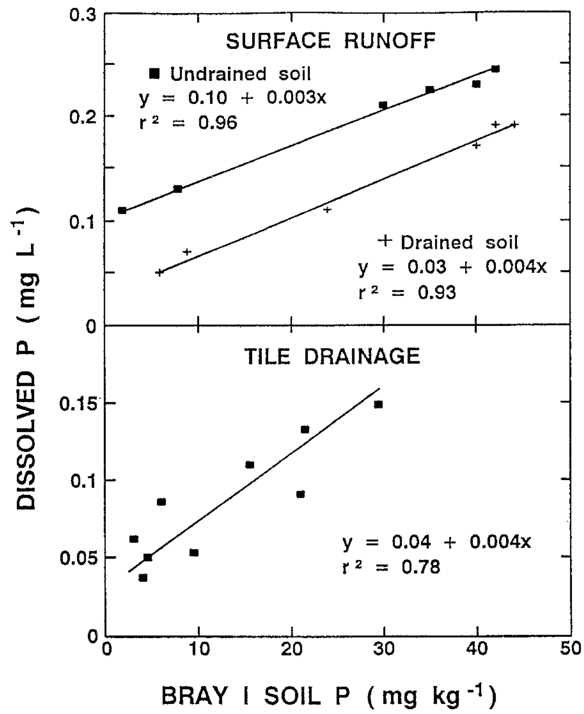

Fig. 3. Relationship between the Bray-1 P content of surface (0–5 cm) and subsurface (40–50 cm) soil and the dissolved P concentration of surface runoff and tile drianage, respectively, from several unfertilized and fertilized soils in New Zealand [adapted from 79, 82].

are also applied, potential accumulation of P is even greater (Table 6). Clearly, P inputs of up to 190 kg ha^{-1} yr^{-1} greater than crop removal can quickly create environmental problems. However, considerable time is required for significant depletion of excessive soil test P. Johnston [30] and McCollum [45] found half-lives of about 9 years for Olsen P contents of a clay loam soil and Mehlich III contents of a sandy soil, respectively.

Once soil test P levels become excessive, the potential for P loss, if runoff and erosion occur, is greater than any agronomic benefits of further P applications. This is due to the dependence of P loss in runoff on surface soil P content. A highly significant linear relationship was obtained between the soil test P content (Bray I) of surface soil (5 cm) and the DP concentration of runoff from drained and undrained field plots in New Zealand (Fig. 3; from [82]). The consistently higher DP concentration in surface runoff from undrained than drained fields reflects the desorption of P from the higher sediment loads found in these waters. Several other studies have also reported a close dependence of the DP concentration of runoff on soil test P [58, 66, 73].

Because of the variable path and time of water flow through a soil with subsurface drainage, factors controlling DP in subsurface waters are more complex than for surface runoff. However, the DP concentration of tile flow in New Zealand was related to the Bray-1 P content of soil at the tile drain depth (40 to 50 cm) (Fig. 3; from [82]). A similar dependence of DP concentration in tile drainage on the P sorption-desorption properties of subsoil material was found for Histosols in Florida [26], New York [10, 14], and Ontario [57], and for Haploquolls in Ontario and Michigan [11].

Manure management

Excessive soil P has occurred to a greater extent in livestock systems, which on economic grounds need to operate on less land area. Thus, development of manure management plans that are environmentally sound is a concern facing an increasing number of landowners.

Animal manure can be a valuable resource integrated in cost-effective Best Management Practices (BMPs). In many areas, manure applications have improved soil structure and increased vegetative cover, thereby reducing runoff and erosion potential. However, in areas where a large number of confined animal operations are located, the amount of nutrients in manure often exceeds local crop requirements and the area of land available for application. Clearly, economics is the crucial issue facing efficient utilization of manure. This involves applying manure on a P

Table 6. Potential input of P in fertilized and animal manures in areas of intensive livestock production in Italy (Po Basin) and the Netherlands (Sand districts) and removal in maize and wheat [8]

Region	Potential input		Potential removal[a]		Balance	
	Fertilizers	Manures	Maize	Wheat	Maize	Wheat
			kg P $ha^{-1}yr^{-1}$			
Italy						
Piemonte	22	16	40	30	−2	+8
Lombardia	31	30	40	30	+21	+31
Veneto	35	26	40	30	+21	+31
Emilia-Romagna	27	19	40	30	+6	+16
Netherlands						
Salland-Twente	15	85	40	30	+60	+70
West Veluwe	15	174	40	30	+149	+159
Meijerij	15	130	40	30	+105	+115
South Peel	15	204	40	30	+179	+189

[a]Maize and wheat yields of 10 and 5 t ha^{-1} yr^{-1}, respectively.

rather than N basis, limiting the area of land available for application, transporting manure to non-producing areas, and linking the number of animals to the area of land available for application of manure. Thus, we can develop BMPs for manure but should we expect farmers to bear the total cost of these programs?

In Europe and the U.S., rates for application of animal manure have been based on the N needs of the crop in order to minimize nitrate losses by leaching and the potential for ground water contamination. In most cases, this strategy has led to an increase in soil P levels in excess of crop requirements due to the generally lower ratio of N:P added in manure (4:1) than taken up by crops (8:1).

Site hydrology will also be important in determining manure application strategies. If the potential for nitrate leaching from an application site exists, N should be a priority management consideration. However, if runoff and erosion potential exceeds leaching potential then P should be the main element driving application rates, as this strategy will mitigate the excessive build up of soil P and at the same time lower the risk for nitrate leaching to ground water. A soil P-based strategy could eliminate much of the land area with a history of continual manure application from further additions, since many years are required to lower soil P levels once they become excessive. This would force farmers to identify larger areas of land on which to utilize the generated manure, further exacerbating the problem of local land area limitations. In addition, farmers relying on manure to supply most of their crop N requirements may be forced to buy fertilizer N to supplement foregone manure N. Using a P-based strategy may resolve potential environmental issues but could place additional economic burdens on farmers.

Options for efficient utilization of manure include basing application rates on site susceptibility to runoff (P-based strategy) or leaching (N-based strategy); linking the number of animals to area of land available for manure utilization; formation of co-operatives that can more economically compost or concentrate manure to increase the economic distance it can be transported from its source, thus increasing the area of land for application; establishment of cost-sharing programs so that both the consumer and producer share the economic burden of environmental sustainability; and expansion of education and extension programs highlighting the nutritive and mulching value of manure to non-producing farmers.

Land management

Although land management encompasses both fertility and manure management, additional broader land management issues must be considered. For example, conservation tillage may increase crop yields by enhancing soil moisture, while in some cases weeds may reduce crop yields and quality [83]. Further, conservation tillage may reduce erosion and TP loss in runoff compared to conventional tillage but increase the potential for DP loss and nitrate leaching [78, 83, 93]. Other land management changes such as set-aside land, residue burning, wetland classification, animal manure incorporation, and weed management will also impact environmental issues.

Clearly, changes in land management must be considered not only in terms of whether they improve productivity but if they positively or negatively influence environmental sustainability. As a result, land management policy decisions will be required to address the potential for severe water quality problems. This will be of particular relevance to management systems involving manural inputs of P. Fertilizer inputs can be easily adjusted to accurately balance crop uptake of P, however, manure often provides excess P. For example, confined animal operations should develop a comprehensive waste management plan tailored to local land limitations, involving several options discussed in the previous section. Thus, land management planning will have to address the potential for water quality issues as well as maximizing profitability. However, if the cost of the environmental effects of P loss in runoff are included in land management decisions, this may lower economically optimum crop yields compared to traditional yields. Even so, it is possible that land management will only change if there are clear economic (or legislative) incentives for them to do so. We hope targeting flexible, cost-effective BMPs will minimize P loss in runoff and lead to environmentally sustainable land management through recommendation rather than regulation.

Future challenges

To achieve environmentally-sound P management in agriculture, we must be able to identify soil P levels that are of environmental concern; assess sites and management practices within a watershed that are vulnerable to P loss; and target remedial measures to minimize P loss in runoff and erosion. However, in doing this we must ensure the economic viability of farming.

Environmental tests for soil phosphorus

Soil P tests have provided farmers with an indication of how much plant available P is present in a soil and consequently how much fertilizer to apply to obtain the desired crop yields. However, as we move from agronomic to environmental concerns with soils containing P levels in excess of crop requirements, will current soil test P methods assessing plant availability, estimate P forms that can accelerate eutrophication? If not, are appropriate methods available? Environmental soil tests for P must estimate the bioavailability of soil, sediment, or runoff P to aquatic organisms and the long-term capacity of a soil to retain P against leaching.

The amount of P in soil, sediment, or runoff that is potentially available for algal uptake can be quantified by algal assays, but these require up to 100-d incubations [47]. Thus, more rapid chemical extractions, such as NaOH [13], NH_4F [64], and ion exchange resin [27] have been developed. More recently, Sharpley [76] showed that the amount of P removed from runoff sediment by iron oxide-impregnated filter paper (Fe-oxide strip) was related (r^2 = 0.92–0.95) to the growth of several algal species incubated with runoff as the sole source of P. As the strips act as a P-sink, they simulate P removal from soil or sediment-water samples by plant roots and algae. Thus, use of the Fe-oxide strip method has a stronger theoretical justification to estimate bioavailable P than do chemical extractants. The method may have potential use as an environmental soil P test to identify soils liable to enrich runoff with sufficient P to accelerate eutrophication.

In addition to bioavailable P, environmental soil tests will need to estimate the long-term capacity of a soil to retain P against leaching. For example, estimates of the P-loading capacity of soils receiving continual applications of P in manure or waste water will aid development of sustainable management systems. This capacity is commonly estimated by sorption isotherms that can be used to derive sorption maxima for soil horizons. These isotherms require equilibration of soil with a solution of P for up to 6 d, and are, thus, not appropriate for routine soil testing. However, Bache and Williams [3] suggested that a single-point isotherm can provide a reasonably accurate estimate of soil P sorption maxima.

The additional analytical workload for a soil test laboratory to conduct environmental tests for P, along with a lack of rigorous field testing to determine critical P levels associated with eutrophication, will limit their widespread adoption in the near future [85]. However, several studies have shown the amounts of P extracted by standard soil tests (Bray, Mehlich, and Olsen) are related to bioavailable P estimated by either Fe-oxide strip or NaOH methods [75, 105]. Also, P sorption parameters can be approximated by simpler water extractions [52, 81]. Consequently, in areas with P-related water quality problems, soil test laboratories could use routine soil tests as surrogates to provide preliminary rankings of the algal available P content and identify those on which environmental tests should be conducted.

Assessing site vulnerability to phosphorus loss

Soil testing alone cannot assess the potential for soil P from an individual site or watershed to play a significant role in surface water eutrophication. Any environmental soil P test must be linked to site assessment of drainage, runoff and erosion potential and management factors affecting the vulnerability for P transport from a site. Strategies to minimize P loss in runoff will be most effective if they are targeted to sensitive or source areas identified within a watershed rather than through widespread implementation over broad areas.

Lemunyon and Gilbert [39] developed a P indexing system to identify sites vulnerable to P loss in runoff. The index rates source (soil test P and fertilizer and manure management) and transport factors (runoff and erosion potential) of a site to provide a numerical value, ranking site vulnerability to P loss in runoff [84]. The index is intended for use as a tool for field personnel to easily identify agricultural areas or practices that have the greatest potential to accelerate eutrophication [84]. It is hoped that this will identify management options available to land users that will allow them flexibility in developing remedial measures.

Minimizing phosphorus losses

Minimizing the loss if agricultural P in runoff can be accomplished by P-source management and erosion and runoff control. Source management of P includes basing application rates on eutrophic rather than agronomic soil test P guidelines and the possible use of slow-release P fertilizers. In addition, subsurface placement of P away from the zone of removal in runoff will reduce the potential for P loss. Where practical and economically viable, subsurface placement may also increase crop yield response to P additions.

The most effective measure to reduce total P losses in runoff involves the implementation of conservation or reduced tillage, although DP losses can be increased compared to conventional cultivation [77, 83]. The surface soil accumulation of added P and crop residues can be a source of P to runoff that would otherwise be reduced by tillage incorporation [83]. Thus, it may be necessary to incorporate surface accumulations of P in the soil profile by occasional plowing. Conservation tillage has also been shown to enhance nitrate movement to ground water compared to conventional tillage [77, 93]. Clearly, the potential for enhanced DP loss and nitrate leaching should be accounted for in assessing the effectiveness and potential water quality benefits (reduced soil erosion and total P loss) of conservation tillage measures.

The loss of P by erosion and runoff may also be reduced by terracing, contour tillage, cover crops, grassing of valley floors, and creation of targeted riparian zones [51, 54]. These practices efficiently reduce PP losses, and thereby the long-term potential for eutrophication, due to recycling of deposited PP. However, these practices are less efficient at reducing DP loss and in many cases the bioavailability of P transported is increased [83]. Often measures to reduce P inputs to aquatic systems have had less effect on the degree of eutrophication than expected, due to an increased bioavailability of P entering the system as well as internal recycling of P. Thus, the environmentally-sound management of agricultural P will involve both P-source management as well as erosion and runoff control. Clearly, a combination of remedial measures will be necessary to reduce eutrophication to acceptable levels.

Research priorities

The benefits of remedial measures on freshwater eutrophication may not be immediately visible. Thus, further research should emphasize the long-term economic and environmental benefits of these measures. Further development of procedures to estimate the potential of soils to enrich the P content of runoff or retain P in the profile during drainage is needed. Even if current soil test procedures are used as surrogates for environmental tests until improved methods are available, field calibration is essential. In other words, site specific threshold soil P levels are needed above which the potential for eutrophication exceeds any agronomic benefit of P application; and above which it is recommended that either no P be applied or that the rate be less than crop removal rates.

Further development of P indexing procedures to target source areas within watersheds must address the ability of P losses to cause eutrophication. This will involve evaluation of the proximity of a P source to a water course or body, biosensitivity of a water body to

P inputs, and the major use of affected water bodies and desired trophic status.

In many cases, P-related eutrophication is accelerated by the land application of excessive amounts of animal manure in localized areas. Consequently, future research must address the technical and economic feasibility of reducing P solubility in manures and treated soils, reducing transportation costs, and developing alternative uses for manure. Alternatives include power generation, livestock feed, and market garden or home use of composted material.

Finally, in the past we have tended to assess the effectiveness of individual practices to reduce P loss from agricultural land. Future field research should evaluate remedial systems which incorporate several measures to minimize soil P accumulations, runoff and erosion potential, and delivery of P from its source to water body. Land use and management practices are constantly changing in Europe and the U.S.A. For example, conservation tillage, set-aside land, land-burning bans, and irrigation are all new developments which will impinge on P transport from agricultural land. Thus, the effect of these changes on the development of environmentally-sound management systems for agricultural P should be considered.

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