Phosphorus fertilisation and environmental effects in The Netherlands and the Po region (Italy)

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ABSTRACT

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In the intensive husbandry areas in The Netherlands amounts of phosphate produced by animal waste significantly exceed crop requirements. This leads to high loadings of the soil. The soils in these areas are particularly vulnerable to saturation and leaching due to their sandy texture and shallow groundwater levels. Locally, agriculture is the major source of the phosphate pollution of surface waters. A tentative analysis of the phosphate loadings and soil vulnerability in the Po region in Italy indicates that similar problems may arise here, although to a lesser extent. The area with vulnarable sandy soils is relatively small and the potential loads are lower. The relative contribution of surface runoff to the loadings of surface waters is expected to be higher in the Po region than in The Netherlands.

Keywords: phosphate (ad)sorption, phosphate saturated soils, phosphate leaching, fertilisation, agriculture, surface waters, sandy soils

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PREFACE

In 1990, the chamber of Commerce of Mantova, on behalf of the Higher National Authorities of Italy, initiated an international study on the safe use of animal waste in agriculture. A number of experts from abroad were invited to report the state-of-the-art on various topics concerning the use and processing of animal waste. Each rapporteur had an Italian co-rapporteur to ensure the use of all information available on the situation in the Mediterranean area. In view of their expertise with phosphate-contaminated soils the DLO Winand Staring Centre was invited to report on this topic.

The study was made in commission of the Organizing Committee of the European Conference on Environment, Agriculture and Livestock Farming and supported by the Commission of the European Communities. The results were reported at a scientific colloqium held in Mantova, 12-14 November 1991. The reports will be used as a scientific basis for the discussions on the setting-up of regulations at the Conference.

SUMMARY

Application of animal manure and slurry can cause pollution of surface waters with phopsphate by leaching and surface runoff. This review addresses the behaviour of phosphate in soils, the loadings to the soil and observed and potential environmental effects for areas with intensive animal production in The Netherlands and Italy (Po region). The report is primarily based on earlier studies by the DLO Winand Staring Centre, Wageningen, The Netherlands.

Dissolved and solid phosphates in animal waste are transformed into Al- en Fe-phosphates in non-calcareous soils and Ca-phosphates in calcareous soils. The reaction with the soil is primarily attributed to sorption by Al- en Fe-oxides and Ca-carbonates, respectively. The sorption capacity of the soil may become "saturated" if phosphorus applications continuously exceed crop requirements. According to a Dutch definition a soil is considered saturated when more than 25% of the sorption capacity has been used. The concentration of phosphate in groundwater will then exceed a critical limit of 0.1 mg l^{-1} ortho-P at high water levels.

The surplus of phosphate from animal waste and fertilisers, expressed per unit agricultural area, is ca. 160-430 kg ha^{-1} P_2O_5 in areas with intensive livestock farming in The Netherlands and ca. 10-60 kg ha^{-1} P_2O_5 in the Po region. In 1990 it was estimated that in The Netherlands about 43% of the grassland and 82% of the maizeland was saturated due to overfertilisation. For the Po region these data are not available, but it is expected that the (calcareous) sandy soils in this region may also become saturated.

Leaching of phosphate from saturated soils was studied in a catchment area in one of the sand districts in The Netherlands (Gelderse Vallei). The load from agricultural soils was ca. 2.5 kg ha^{-1} P and the mean annual concentration in surface waters 1 mg l^{-1} P. In the Po region leaching was studied by lysimeter experiments on samples with unknown degree of phosphate saturation. Significant losses of phosphate occurred only at high application of slurry.

Surface runoff also contributes to the pollution of surface waters by agriculture. Annual losses of ca. 2 kg ha^{-1} P have been reported for slurry applications on poorly drained soil. Surface runoff is taken to play a more significant role in the Po region than in the sand districts of The Netherlands due to the presence of more vulnerable clay soils.

Phosphate losses to the environment can be prevented or reduced by various measures. Leaching above the background level is prevented by keeping the soil unsaturated. In soils with a sufficient P status, applications should not exceed the removal of phosphate by harvesting and leaching. Saturated soils require lower applications and technical measures, for example hydrological measures and addition of chemicals to the soil. Leaching can also be reduced by adding chemicals (Fe-salts)

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to the slurry. Surface runoff is reduced by ploughing in or injection of slurry and by applications in late spring rather than in the autumn or early spring.

1 INTRODUCTION

Utilisation of animal wastes can induce pollution of groundwater and surface waters not only with nitrate, but at a lower concentration level, also with phosphate.

Sofar, the possible adverse effects of phosphate fertilisation on the environment have been primarily attributed to (surface) runoff. However, there is another, somewhat disregarded effect, caused by application rates exceeding crop requirements. Overdoses have become common practice in agricultural areas with intensive agriculture and, more specifically, livestock farming. The overdose may be small, and in accordance with recommended rates, but also very high on farms with a manure surplus. The sorption capacity of the soil may not always be sufficient to prevent enhanced leaching of phosphate, as shown by recent studies in The Netherlands.

It is the purpose of this study to assess the possible losses of phosphate to the environment by leaching and runoff and to indicate ways to reduce the losses. Special reference is being made to the situation in The Netherlands, based on studies by the DLO Winand Staring Centre, and Italy.

We will first discuss the behaviour of phosphate in the soil to provide the reader with some background information on the processes that govern the abiotic environmental effects, that is the effects on soil and water quality (Chapter 2). Then some figures will be presented to illustrate the order of magnitude of the overdose for various agricultural crops and systems (Chapter 3). The environmental effects on soils and ground- and surface waters are discussed in Chapter 4 and possible ways to reduce these effects in Chapter 5. The most relevant conclusions have been summarized in Chapter 6.

2 BEHAVIOUR IN THE SOIL

2.1 Phosphate compounds and transformations

Solid phosphate compounds applied to the soil by fertilisers and animal waste are usually unstable in the soil environment. Mineral fertilisers containing monocalcium phosphate (e.g. super phosphate) are well soluble and transformed into less soluble species (Lindsay, 1979) or adsorbed on the surface of soil particles (par. 2.2). Less soluble phosphates, e.g. rock phosphates that contain hydroxyapatite, dissolve more slowly and only in acid soils (pH < ca. 5). Polyphosphates are also unstable in soils and converted into orthophosphate. Animal waste slurries primarily consist of well soluble inorganic phosphates such as struvite (Bril and Salomons, 1990). The organic phosphates in slurries are also readily transformed into orthophosphate and do not leach to the subsoil except in small amounts in sandy soils and at high application rates (Gerritse, 1981). The behaviour of (inorganic) orthophosphate in soils is therefore of prime importance.

Orthophosphate is transferred into mineral forms and organic compounds. The most important mineral products determined by the selective dissolution method of Chang and Jackson (1957) are:
Al and Fe phosphates : in non-calcareous soils
Ca phosphates   : in calcareous soils

At intermediate pH, between about 6 and 7, both forms are commonly present (Scheffer and Schachtschabel, 1979). This is also illustrated by data for calcareous soils in the Po region that have received pig slurry in various rates (Table 1). Except for the sandy loam, which is low in carbonate, most of the phosphate is Ca-bound. The table also includes data on occluded forms containing Al- and Fe-bound phosphates that are more difficult to dissolve by extractants. Except for the sandy soil, these data show another commonly observed phenomenon, that is the decrease in solubility of soil phosphate with time (compare 1980 and 1983). The sandy soil shows a transformation of organic P into mineral P in the same period due to mineralisation of organic matter (Spallacci, 1991). In non-calcareous sandy soils in The Netherlands, mineral P as estimated by an oxalate extraction is commonly about 90% of total P (Lexmond et al., 1982).

2.2 Sorption mechanism and capacity

The mechanism that governs the supply of P to the plant as well as the leaching potential has been extensively studied. These studies have revealed that adsorption cannot be described by a single Langmuir or Freundlich isotherm due to a slow reaction that is superimposed on the normal (fast) reaction with the surface of an adsorbent. The major adsorbents are oxides of aluminium and iron (in non-calcareous soils), carbonates (in calcareous soils) and clay minerals.

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Table 1 *Phosphorus forms as percentage of the total content in different soils treated with increasing rates of pig slurry in lysimeters from 1976 to 1979 (upper 20 cm of the soil) (Papini et al., 1991)*

Soil type[1]	Slurry rate	Soluble 1980	Soluble 1983	Organic 1980	Organic 1983	Fe-bound 1980	Fe-bound 1983	Ca-bound 1980	Ca-bound 1983	Occluded 1980	Occluded 1983
Sand	0	0.8	1.2	14.9	9.8	0.3	5.4	61.2	71.3	22.8	12.2
	1	4.3	4.0	19.5	6.6	4.2	13.4	44.7	69.2	27.2	6.8
	2	5.6	8.4	27.2	9.0	5.2	11.4	39.0	63.8	23.0	7.4
	3	7.0	7.8	20.2	9.0	8.0	9.3	48.3	73.6	16.5	1.3
Sandy loam	0	0.7	2.1	38.6	34.0	12.9	18.7	17.3	14.0	30.5	31.2
	1	1.6	2.0	35.7	31.2	26.4	24.8	13.9	12.1	22.5	29.8
	2	3.2	2.5	25.0	25.7	31.0	28.5	14.9	14.8	26.0	28.3
	3	4.5	2.6	22.3	20.4	35.8	33.1	8.5	12.8	28.9	31.0
Sandy clay	0	0.4	0.3	34.5	25.2	3.2	2.3	61.8	59.9	0.0	12.3
	1	1.5	0.9	30.3	23.7	7.6	2.7	53.2	56.1	7.3	16.6
	2	4.7	2.1	20.2	22.6	8.4	1.3	54.2	53.5	12.5	20.5
	3	4.5	3.7	16.0	21.1	9.7	1.2	50.6	48.9	19.2	25.0
Clay	0	0.4	0.3	31.2	24.7	2.2	1.7	64.3	52.4	1.9	20.9
	1	1.4	1.0	26.4	17.4	5.0	1.7	65.3	52.9	1.9	27.1
	2	1.6	1.4	17.7	17.5	7.4	1.9	62.9	56.9	10.4	22.3
	3	4.2	1.7	17.9	16.7	9.0	1.0	55.2	58.2	13.7	22.3

[1] The $CaCO_3$ percentage in these soils is 6.0, 0.6, 14.4 and 14.6 respectively.

The slow reaction can be described as a diffusion controlled process (Enfield et al., 1981; Barrow, 1983; Van Riemsdijk et al., 1984).

The most important conclusion from these studies is that the fast reaction with the soil is a reversible proces, whereas the slow reaction is practically irreversible, at least in non-calcareous soils (Van der Zee and Van Riemsdijk, 1986). The reversibly adsorbed P controls the supply to the soil solution and, thereby, plant growth and leaching. The irreversibly retained P is responsible for the well-known fixation phenomenon.

For the non-calcareous soils, that have been studied most intensively, the reversible adsorption can be described by the Langmuir equation:

$$Q = \frac{k\,c\,Q_m}{1 + k\,c} \tag{1}$$

where

Q = the reversibly adsorbed phosphate (mmol kg^{-1})
Q_m = the adsorption maximum (mmol kg^{-1})
k = the adsorption constant (l $mmol^{-1}$)
c = the concentration of phosphate in the solution (mmol l^{-1})

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The reversibly adsorbed amount of phosphate Q can be readily determined by a desorption technique (Van der Zee et al., 1987). The irreversibly adsorbed amount can be obtained by difference of the totally sorbed amount and the reversibly adsorbed amount. The total sorption has been calculated in numerous ways depending on the model used to describe the kinetics of the slow reaction (see e.g. Bolan et al., 1985). An empirical relation obtained by combining the equations of Freundlich and Elovich was found to describe both the effects of concentration and time fairly well (Schoumans et al., 1987):

$$S_{c,t} = S_r \, (1 + a \, \ln t) \, (c/c_o)^n \qquad (2)$$

where

$S_{c,t}$ = the available phosphate sorption capacity (mmol kg^{-1})
S_r = the phosphate sorbed at a reference concentration (c_o) and time (t_o) (mmol kg^{-1})
a = a dimensionless constant in the Elovich equation
n = a dimensionless constant in the Freundlich equation
c = the concentration of phosphate (mg l^{-1})
t = the reaction time (days)

This equation is used to extrapolate sorption measurements at standard laboratory conditions for c and t (e.g. c_o = 50 mg l^{-1} P and t_o = 1 day) to standard field conditions (e.g. c = 90 mg l^{-1} P and t = 5 years). Finally the total sorption capacity of the soil is obtained from

$$PSC_m^t = S_{c,t} + P_{ox} \qquad (3)$$

where
PSC_m^t = the (massic) total phosphate sorption capacity (mmol kg^{-1} P)
P_{ox} = the oxalate-extractable phosphate in the soil (mmol kg^{-1} P)

The total sorption capacity of non-calcareous sandy soils is well correlated with oxalate-extractable Al and Fe (Fig. 1).

Similar results have been obtained using other extractants (e.g. Borggaard, 1983). The slope of the line in Fig. 1 varies between 0.4 (Schoumans et al., 1987) and 0.6 (Van der Zee and Van Riemsdijk, 1988) when residual sorption, at $Al_{ox}+Fe_{ox}=0$, is ignored. The mean total phosphate sorption capacity can therefore be calculated from:

$$PSC_m^t = 0.50 \, (Al_{ox} + Fe_{ox}) \qquad (4)$$

where Al_{ox} and Fe_{ox} represent the oxalate-extractable Al and Fe content of the soil.
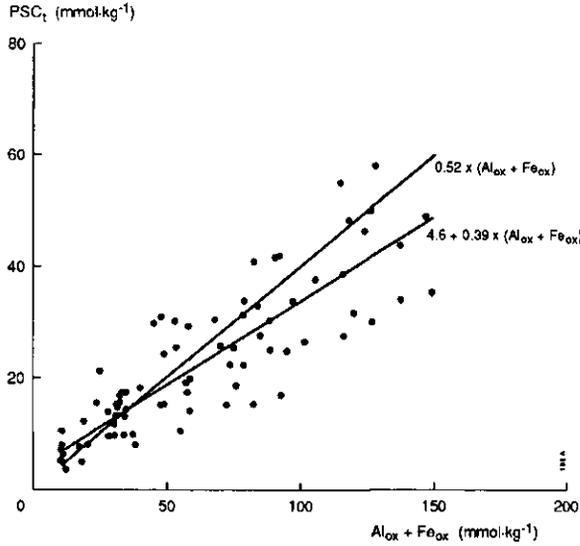
Fig. 1 *The total phosphate sorption capacity of non-calcareous sandy soils as a function of oxalate-extractable aluminium (Al_{ox}) and iron (Fe_{ox})*

The reversibly adsorbed maximum amount is about ⅓ of the total sorption capacity (Van der Zee et al., 1987) and can therefore be derived from

$$Q_m = 0.16 \ (Al_{ox} + Fe_{ox}) \tag{5}$$

The sorption capacity and P content of the soil are often expressed per unit surface area using the following equations:

$$PSC_a^t = PSC_m^t \ x \ T \ x \ d \ x \ 7.1 \tag{6}$$

$$P_{act} = P_{ox} \ x \ T \ x \ d \ x \ 7.1 \tag{7}$$

where
PSC_a^t = the (areic) phosphate sorption capacity
P_{act} = the (areic) oxalate-extractable P content (kg ha^{-1} P_2O_5)
T = the thickness of the soil layer considered (cm)
d = the density of the soil (g cm^{-3})
7.1 = a factor to convert mmol kg^{-1} P into kg ha^{-1} P_2O_5.

2.3 Role of pH and organic components

The sorption of phosphate depends not only on the concentration of phosphate but also on other factors such as pH and organic matter.

The behaviour of phosphorus in soils is essentially governed by pH. In acid soils phosphorus retention is governed by the high affinity of P for Fe and Al oxides and clays as described above. Phosphate reactions with Ca are frequent in soils typical of the Mediterranean region where alkaline, neutral and subacid soils occur.

It is important to emphasize that organic matter plays an essential role in affecting phosphorus behaviour in soils by slowing down its kinetics of fixation. Therefore, organic matter is likely to have the important role of hindering phosphate immobilization in soils (Fardeau et al.,1977; Gaur, 1969; Gessa et al., 1978; Manojlovic, 1965; Silva et al., 1987; Gatti et al., 1991). Low molecular weight organic ions as bi- and tri-carboxylic acids (citrate, tartrate, oxalate etc.) and high molecular weight ions as humic and fulvic acids may preserve phosphates from insolubilization processes in soils and may have a favourable influence in maintaining the availability of P to plants for long periods of time (Stevenson, 1986).

It has been proved that plants grown in conditions of phosphorus deficiency increase the concentration of chelating substances in the rizosphere. Such substances could remove, by a chelation mechanism, the metals which behave like a bridge between organic matter and phosphates which are then incorporated in the soil solution and become available to root systems.

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3 LOADINGS TO THE SOIL

3.1 Fertiliser recommendations

Recommended fertiliser rates based on crop response generally aim at obtaining optimum yields from an economic point of view. For phosphorus recommendations depend on the P status of the soil, as determined by soil testing. For P demanding crops, for example potatoes, recommended rates in The Netherlands exceed the net uptake by the crop except when the P status is "high" (Breeuwsma and Ehlert, 1991). For grains in a crop rotation with potatoes fertilisation rates can be lower than the net uptake. The mean application rate for a given rotation of arable crops equals the average crop requirement at a P status "amply sufficient" (Table 2) (Ris and Van Luit, 1978).

Table 2 Comparison of the average uptake and recommended rates of application of P over a 4 year period for arable crops on sandy soils in The Netherlands[1]

Soil P status	P_w[2] (mg l^{-1} P_2O_5)	Mean recommended rate	Mean uptake
		kg ha^{-1} yr^{-1} P_2O_5	
low	15	142	
sufficient	25	102	
amply sufficient	35	77	70
ibid	40	67	
high	80	0	

[1] crop rotation: potatoes, barley/grass, sugar beet, wheat (example)
[2] water extraction (Van der Paauw, 1971; Sissingh, 1971)

If the P status is low, higher rates are needed for an optimum production. In fact, in The Netherlands it is recommended to apply large amounts of phosphate for some years to "repare" the soil fertility if the soil is not phosphate-fixing (reparation fertilisation). At a high soil P status the recommended rates are substantially lower than the uptake by the crop, or even nil (Table 2).

3.2 Maximum and "optimum" rates of application

Locally, loadings of P to the soil can be much higher than the mean potential input for the whole region. This holds particularly for farms with a high livestock density where animal waste is applied in addition to (or as replacement of) fertilisers. Some crops, like forage sorghum and silage maize can tolerate very high applications of slurry but most crops suffer from very high loadings. Boschi et al. (1982) have indicated the amounts of slurry that produce a maximum yield in Italy (Table 3). The maximum amounts of N are between 200 and 500 kg of kg ha^{-1} yr^{-1} total N. The

accompanying rates of P are 150-300 kg ha^{-1} yr^{-1} P$_2$O$_5$ when pig slurry is used (with 0.3% P$_2$O$_5$ and 0.6% N) and 88-176 kg ha^{-1} yr^{-1} P$_2$O$_5$ when cattle slurry is used. Spallacci and Boschi (1980) have defined "optimum" rates of total N as the rates that show "the highest difference between uptake and leaching". The accompanying rates for P are in the order of 100-285 kg ha^{-1} yr^{-1} P$_2$O$_5$ depending on the soil type (Table 3). For most crops, this can lead to an accumulation in the soil of about 20 kg ha^{-1} yr^{-1} P$_2$O$_5$ in sandy soils to about 200 kg ha^{-1} yr^{-1} P$_2$O$_5$ in clay soils.

Table 3   Maximum and "optimum" rates of slurry N (kg ha^{-1} yr^{-1}) and accompanying rates for P in pig slurry (kg P$_2$O$_5$ ha^{-1} yr^{-1}) in Italy

Crop	Maximum rates[1]		"Optimum" rates[2]		
	total N	P	soil type	total N	P
wheat	400	200	sand	200	100
feeding barley	500	250	sandy loam	350	175
grain barley	200	100	sandy clay	470	235
grain sorghum	300	150	clay	570	285
forage sorghum	-	-			
grain maize	500-600	250-300			
silage maize	-	-			
Italian rye grass	300	150			

[1] Boschi et al. (1982)

[2] for sorghum followed by Italian rye grass: Spallaci and Boschi (1980)

The maximum and "optimum" rates are commonly below the maximum rates allowed by Italian regulations (Table 4). These regulations primarily restrict the overdosing for forage sorghum and silage maize, which have no maximum rate, and do not lead to a reduction of agricultural production. The maximum amounts annually allowed exceed the removal by arable crops with about 170 and 350 kg ha^{-1} P$_2$O$_5$ for cattle and pig slurries.

Table 4   The maximum amount of P that can be applied in slurries according to Italian regulations[1]

Type of slurry	Slurry (ton ha^{-1} yr^{-1})	P$_2$O$_5$ (kg ha^{-1} yr^{-1})
cattle	136	250
pigs	144	428
poultry	132	2116
sheep/goats	104	309

[1] amounts corresponding to 4 tons (live weight) of livestock per hectare

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3.3 Net annual input

Mean loadings of P to the soil vary substantially between and within countries of the EC (Lee and Coulter, 1990). This is primarily due to the variations in livestock density. In Italy the annual production of P by animal waste is about 1/6 of that in The Netherlands (16 versus 101 kg ha^{-1} P$_2$O$_5$ utilised agricultural area). The same holds for the areas in these countries that have concentrations of livestock farming. In the Po region the annual production of P is 40-70 kg ha^{-1} P$_2$O$_5$ and in sandy areas in the central and southern part of The Netherlands 195-467 kg ha^{-1} P$_2$O$_5$ (Table 5). The use of fertiliser is lower in the latter case. The total potential input of P in the Po region is about 1/3 of that in the Dutch areas. Because the Dutch manure surplus is partially transported to other areas the ratio will be somewhat lower for the actual input of P to the soil than for the potential input (probably around 0.4).

Table 5 Annual production of P by animal waste and input from fertilisers in areas with intensive livestock farming in Italy (Po basin) and The Netherlands (Sand districts)

Country	Region	Animal waste	Fertilisers	Potential input
		kg ha^{-1} P$_2$O$_5$		
Italy[1]	Piemonte	37	50	87
	Lombardia	69	71	140
	Veneto	60	80	140
	Emilia-Romagna	43	62	105
Netherlands[2]	Salland-Twente	195	34	229
	West Veluwe	398	34	432
	Meijerij	298	34	332
	South Peel	467	34	501

[1] 1985 (ISTAT)

[2] 1986 (CBS) and 1985 (LEI) for animal waste and fertilisers, respectively.

Despite the relatively low potential input of P in the Po region compared to the Dutch regions considered, the mean input exceeds the removal by the crop in most cases also in the former region (compare Table 6 and 5). The net annual input in the Po region is of the order of 10-60 kg ha^{-1} P$_2$O$_5$.

Table 6 Annual yield and removal of P by crops in Italy

Crop	Yield (kg ha^{-1} yr^{-1})	P$_2$O$_5$ (kg ha^{-1} yr^{-1})
maize	10,000	92
wheat	5,000	69
alfalfa	10,000	69
Italian rye grass	10,000	92
sugar beet	50,000	92
apple		23
Grape		23
mean		64

3.4 Net cumulative input

Sofar, we have focussed on the present loadings of P to the soil. However, to enable the assessment of environmental effects we need also information on the oxalate-extractable P content of the soil, or if unknown, the input of P in the past.

The oxalate-extractable P and the reversibly adsorbed amount have not been measured routinely, as available or soluble P. However, the latter entities, as measured by soil testing methods, form only a fraction of oxalate-extractable P. An indirect way to assess the P content of agricultural soils is to calculate this content from the natural content and loadings in the past. In The Netherlands, agricultural statistics enable the calculation of the potential input from animal wastes on a farm level from 1970 onwards. Using these data and maximum rates of application for grassland and arable crops, except maize, Breeuwsma et al. (1990) estimated a mean net input of P (total input minus uptake by the crop) of 200-300 kg ha^{-1} yr^{-1} P_2O_5 for maize in the total sand area and about 50 kg ha^{-1} yr^{-1} P_2O_5 for grassland (Fig. 2).
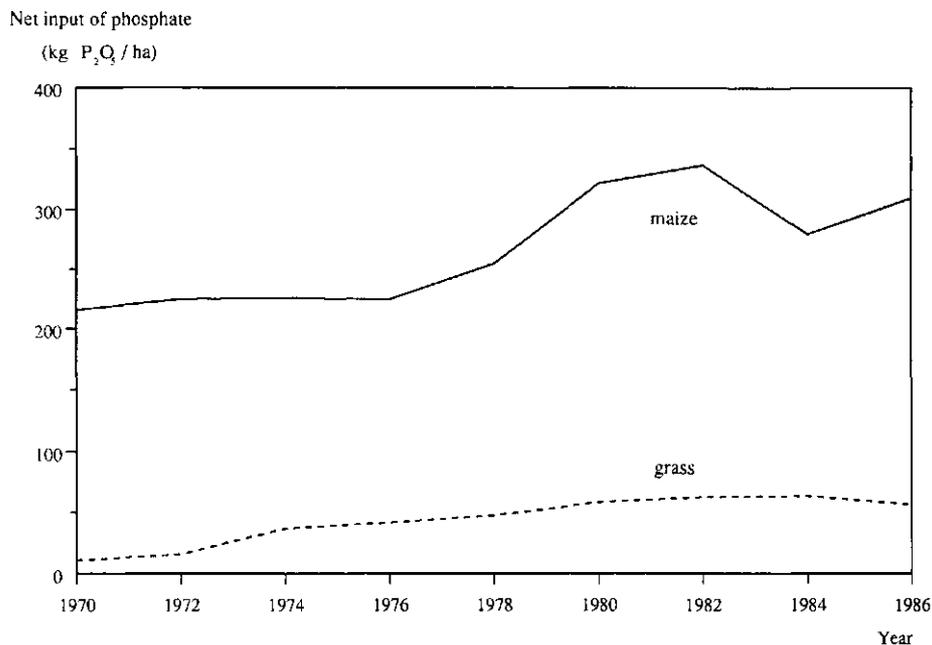
Fig. 2 Net annual input of phosphate (kg ha^{-1} P₂O₅) from animal waste to maize and grassland in areas with intensive livestock farming in The Netherlands from 1970-1986

The calculations have been tested in some subregions (Breeuwsma et al., 1990; Hackten Broeke et al., 1990). These studies showed that the model calculations underestimated the real values. This is at least partially due to the fact that there has been a net input (positive balance) of P also before 1970. This input was therefore estimated using information from farms selected for annual studies of their economic development between 1950 and 1970. This indicated that the input before 1970 varies somewhere between 12 and 33% of total P depending on the soil type (Table 7).

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Table 7 Comparison of the P content (ton ha⁻¹ P₂O₅ in 0-50 cm)
obtained by model calculations and measurements for sandy
soils under grass (Humic Gleysol) and maize (Plaggen soil)
in The Netherlands (West Veluwe)

Period	Grassland		Maize	
	calculated	measured	calculated	measured
before 1900	1.5[1]	1.5[1]	7.7[1]	7.7[1]
1900-1970	1.8	-	1.8	-
1970-1988	2.1	-	5.1	-
	5.4	5.7	14.6	16.1

[1] measured data in non-cultivated soils

3.5 Conclusions

In summary it can be said that the overall input of P to the soil in the Po region is significantly lower (about a factor 2.5) than in some of the intensive livestock areas in The Netherlands. However, the potential input generally exceeds the removal by crops. At a regional scale exceedance is less than 60 kg ha⁻¹ yr⁻¹ P_2O_5. The present Italian regulations for slurry applications allow an annual accumulation in soils of about 170-350 kg ha⁻¹ yr⁻¹ P_2O_5. Recommended rates of slurry application lead to a lower net input of about 20-200 kg ha⁻¹ ha⁻¹ P_2O_5, depending on the soil type.

4 EFFECTS ON SOIL AND WATER QUALITY

Phosphate pollution from agriculture refers mainly to surface waters, and not to groundwater. The standard for drinking water (2 mg l^{-1} P in The Netherlands) is usually much higher than the concentration in groundwater, except at shallow depth in areas with phosphate-saturated soils (par. 4.2.1). The most general and well-known cause of phosphate pollution of surface waters by agriculture is due to surface runoff. However, in areas with high loadings of phosphate accumulation may also lead to saturation of the soil and a significant increase in loadings to surface waters by leaching.

4.1 Phosphate saturation

4.1.1 Definition

Accumulation of phosphate in the soil can lead to increased leaching depending on the cumulative input, soil type and depth to the water table. To enable the calculation of a critical degree of accumulation, Dutch regulations have set critical limits to the concentration of phosphate that is tolerated in groundwater (0.1 mg l^{-1} ortho P) at a given depth (Mean Highest Water level, MHW). The degree of accumulation is related to the phosphate sorption capacity and commonly referred to as the degree of phosphate saturation. It is defined by:

$$DPS = \frac{P_{act}}{PSC_a} \ x \ 100 \tag{8}$$

where DPS is the degree of phosphate saturation (%). The critical value for DPS is 25% (Van der Zee et al., 1990).

4.1.2 Phosphate saturated soils in The Netherlands

In The Netherlands, the degree of phosphate saturation has been studied in particular in the sandy areas with a manure surplus (Breeuwsma et al., 1987 and 1990). In 1990 about 43% of the grassland and 82% of the maizeland was considered to be saturated with phosphate according to the above mentioned definition (Fig. 3).

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percentage of
soils saturated
with phosphate

degree of phosphate saturation (%)
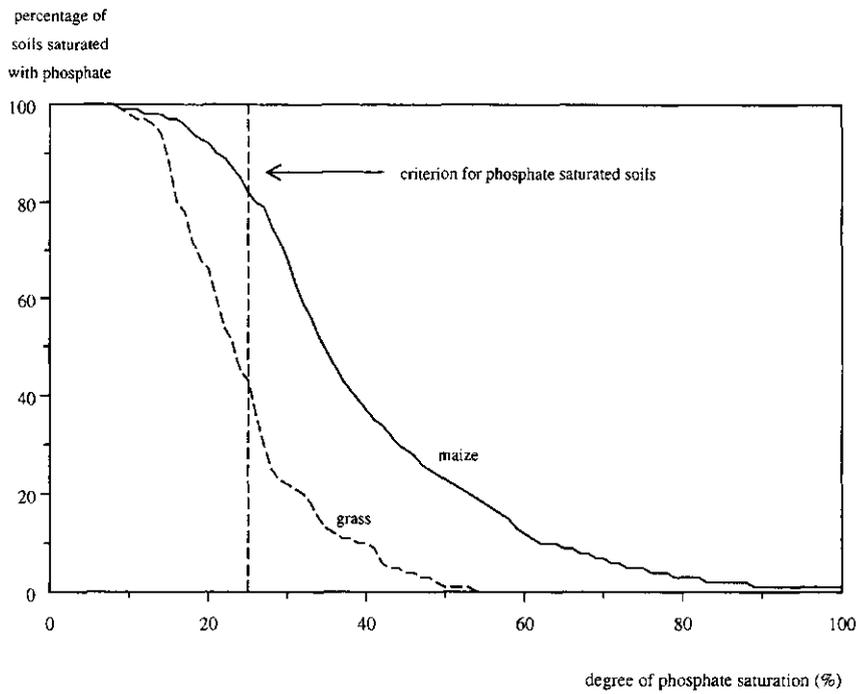
Fig. 3 Distribution of the degree of phosphate saturation of maize and grassland in areas with intensive livestock farming in The Netherlands

hectares of
phosphate saturated
maize and grassland

degree of phosphate saturation (%)
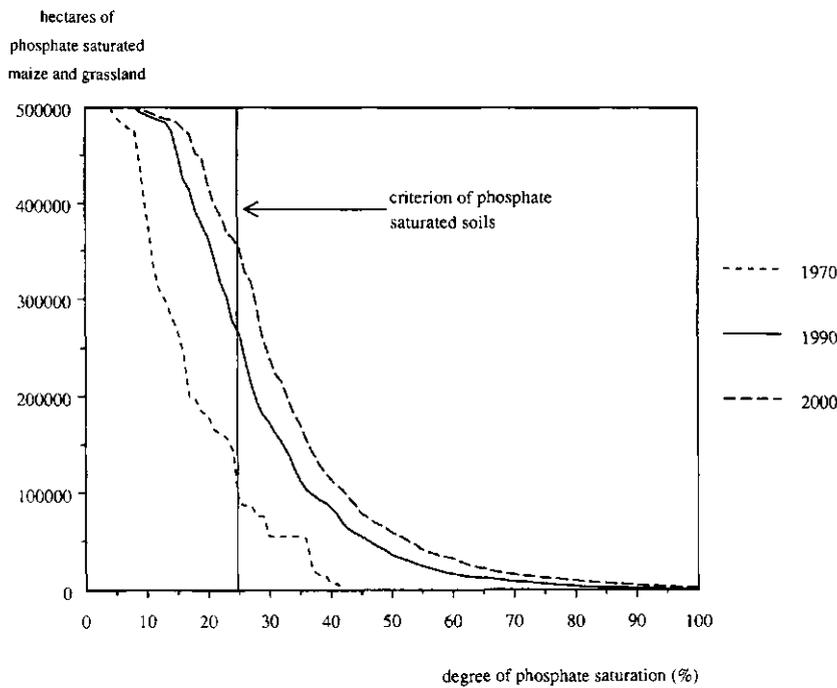
Fig. 4 Distribution of the degree of phosphate saturation of maize plus grassland as a function of time (same areas as in Fig. 2)

This amounts to 53% of the total area of maize- and grassland. Most of the soils have become saturated between 1970 and 1990 (Fig. 4).

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About 18% of the soils were already saturated in 1970. This refers mainly to Plaggen soils that received animal manure in previous centuries. Under current regulations a further increase of the saturated area to about 70% is expected.

4.1.3 Situation in the Po region

At present, phosphate saturation data are not available for Italy. However, there are at least two reasons to assume that phosphate saturation is less of a problem in the Po region than in The Netherlands. Firstly, the potential input at a regional scale is less by a factor of about 2.5 (par. 3.3). Secondly, the percentage of (calcareous) sandy soils that are most vulnerable to leaching of phosphate is relatively small (less than 10%). Nevertheless, in view of the rates allowed by Italian regulations it cannot be excluded that phosphate saturation does, or will occur, locally. Preliminary studies on calcareous sandy soils in The Netherlands have indicated a low phosphate sorption capacity of these soils (Schoumans et al., 1988; Steenvoorden et al., 1990). Whether this applies also to the sandy soils in the Po region remains to be investigated.

4.2 Leaching

4.2.1 Situation in The Netherlands

For groundwater in sandy regions the background level of total P varies between 0.05 and 0.13 mg per litre (Table 8).

Table 8 Background concentration and quality goals for phosphate (mg l^{-1} P) in groundwater and surface waters in The Netherlands

Concentration/standard	Groundwater	Surface waters
Background concentration[1]	0.05-0.13 (total P)	
General quality goal[2]		0.15 (total P)
Critical concentration for P saturated soils[3]	0.10 (ortho P)	

[1] for sandy soils
[2] Ministerie van Verkeer en Waterstaat (1989)
[3] Van der Zee et al. (1990)

The general quality goal for surface waters in these regions is 0.15 mg l^{-1} total P. This corresponds to a leaching rate of 0.45 kg ha^{-1} l^{-1} P or 1 kg ha^{-1} yr^{-1} P$_2$O$_5$ if the excess rainfall is taken to be 300 mm per year. In areas with phosphate saturated soils concentrations in the uppermost layer of groundwater can exceed the general goal particularly in the winter season at high water tables. Figure 5 shows some results for the catchment area of the Schuitenbeek where about 80% of the soils have become saturated with phosphate (Breeuwsma et al., 1989).

Percentage of
exceedance

100

80

60

40

20

0

> 0.06   > 0.15   > 0.40   > 1.00   > 2.50   > 6.00   > 15.0

Total phosphate (mg P / l)
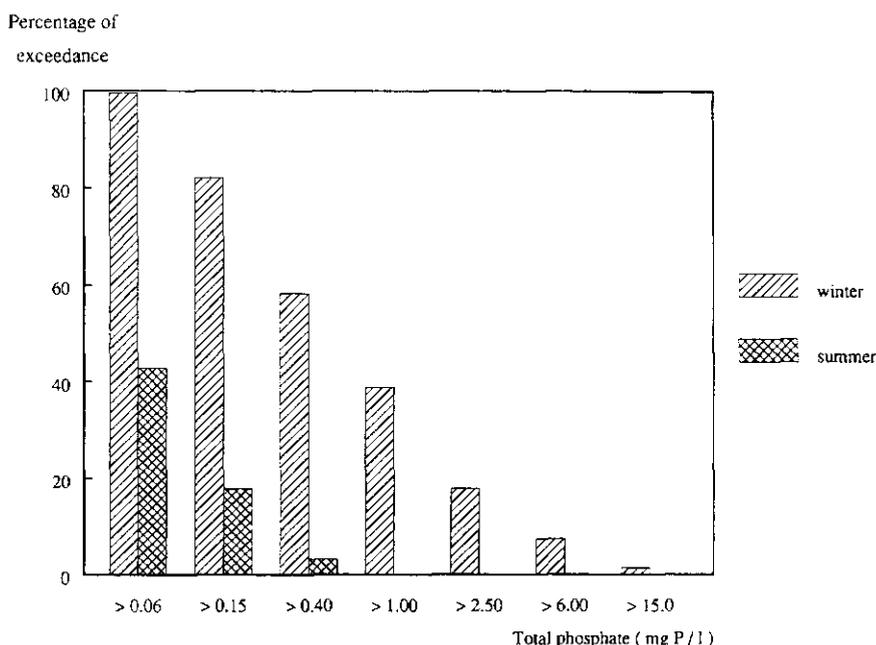
///// winter

▨▨ summer

*Fig. 5 Percentage of observations for which a given concentration of
phosphate in groundwater (upper 20 cm) is exceeded in the
Schuitenbeek area in The Netherlands at high water levels in the
winter and low levels in the summer*

The percentage of observations exceeding the level of 0.15 mg l^{-1} P decreased from
82% in the winter of 1988 to 18% in the summer, indicating a significant effect of
sampling depth.

Most of the excess rainfall is discharged into surface waters during the winter season
at shallow depth. The flux weighted mean concentration of phosphate in the surface
water of the Schuitenbeek area is about 1 mg l^{-1} total P. As the sewage water in the
region is treated to remove phosphate, agriculture has now become the largest source
(Table 9).

*Table 9 Relative contribution to surface
water loadings in a catchment area
with 80% phosphate saturated soils
in The Netherlands (Schuitenbeek
area)*

Source (%)	Relative load
farm houses	5
industry	5
natural leaching	8
agriculture	82

The overall loading to surface waters from agricultural soils amounts to about
5.5 kg ha^{-1} yr^{-1} P$_2$O$_5$ (2.5 kg P) utilised agricultural land. The contribution by surface
runoff was estimated to be about 0.7 kg ha^{-1} yr^{-1} P$_2$O$_5$, indicating that leaching has
become the major source. Steenvoorden and De Heus (1984) and Oosterloo (1986)
have estimated total P losses from agricultural areas close to the Schuitenbeek

area (in the Gelderse Vallei) varying between 10 and 18 kg ha^{-1} yr^{-1} P$_2$O$_5$ (4.4-8.1 kg ha^{-1} yr^{-1} P).

It is important to realise that phosphate transport in the soil is a very slow process. Due to differences in pathways through the soil the concentration of phosphate in surface waters will increase gradually. As a result of the loading of the soil Kroes et al. (1990) predict that the load to surface waters in The Netherlands will further increase at least till the year 2045 despite the assumption that overdosing will be prohibited by the year 2000, according to the present Dutch regulations.

4.2.2 Situation in the Po region

Some information about the situation in the Po region can be obtained from lysimeter studies by Spallacci and Boschi (1980). They found that leaching of phosphate did not increase, except for a sandy soil at high application rates of 200-480 m^3 of pig slurry per ha where the concentration of phosphate in the leachate was about 1 mg l^{-1} total P. In other studies the average concentration of phosphate in drainage water varied from 0.12-0.21 mg l^{-1} total P. Phosphate losses were always lower than 1 kg ha^{-1} yr^{-1} P (Goldberg-Federico et al., 1988).

4.3 Runoff

Phosphate pollution of surface waters by surface runoff is a more widespread phenomenon than leaching because it may occur also in situations where application rates do not exceed crop requirements. It is due to the transport of soluble P over the land surface which often occurs simultaneously with the transport of particle bound P in eroded soil. Surface runoff is primarily controlled by rainfall intensity, topography (slope), soil conditions (permeability, moisture content, depth to the water table), land use practices (contour cropping, tillage, etc.) and the time interval between fertiliser application and runoff.

Surface runoff typically occurs only in periods with heavy rainfall shortly after application of fertiliser or animal waste, and specially on soils with low permeability or water storage capacity on slopes of more then a few percent. Clay soils are generally considered to be most vulnerable with respect to surface runoff because of their low permeability. However, it should be noted that this does not hold for cracked soils where the infiltration rate may be high. Sandy soils, on the other hand, can also suffer from surface runoff if the soil is poorly wettable. Surface runoff is also not confined to hilly or mountaneous regions. It occurs also in flat areas with a slope of less than two percent provided that the soil has a low permeability or a shallow water table and, therefore, a low water storage capacity (Kolenbrander, 1977). Land use practices also play a significant role. Runoff can be reduced by remedial measures against erosion in general (Chester et al., 1978) and by special measures such as injection or ploughing-in of fertiliser or animal wastes.

The concentration of phosphate in surface runoff immediately after spreading of animal waste is of the order of 1-30 mg l^{-1} P (Sherwood and Fanning, 1981; Steenvoorden and De Heus, 1984). The concentrations steadily decrease with time, depending on the rate of application. The cumulative loss in kg ha^{-1} yr^{-1} P depends also on the annual runoff flux which varies strongly from year to year. The mean cumulative loss in experiments using 30 m^3 ha^{-1} of pig slurry during five years on a poorly drained soil was about 2 kg ha^{-1} yr^{-1} total P (Sherwood, 1990). In Italy, also significant losses have been found on clay soils in the Tuscany-Emilian Appenine region (Chisci and Spallacci, 1984).

The relative contribution of surface runoff to the loadings of surface waters is expected to be higher in the Po region than in The Netherlands. The clay soils in the Po region are more vulnerable to runoff than the sandy soils in The Netherlands, whereas leaching in more significant in the latter country due to the occurrence of phosphate-saturated soils.

In addition to runoff from cultivated fields, also runoff from farm grounds, manure storage, milking parlours, etc. has to be taken into account (Voorburg 1981). As far as we know, these "point" sources have not yet been quantified.

5 PREVENTION OR REDUCTION OF PHOSPHATE LOSSES TO THE ENVIRONMENT

Phosphate losses to the environment can be prevented or reduced in various ways.

1 Enhanced leaching from the soil can only be prevented if the soil does not become saturated. Below a given (yet to be established) degree of saturation applications can exceed the removal of phosphate by harvested crops to raise the soil fertility level. At higher degrees of saturation, and in soils with a sufficient P status, application rates should not exceed the (net) uptake by the crop and account for acceptable leaching losses ("equilibrium fertilisation").

2 If the soil is already saturated with phosphate, leaching can be reduced by applying no phosphate at all ("zero"-fertilisation) and by technical (effect-oriented) measures. Examples of technical measures are improvement of the drainage conditions and application of phosphate binding materials such as iron oxides. Technical measures should be used if the water quality has to be improved on a short term. "Zero fertilisation" is particularly effective in reducing the long term effects. It will have no, or only minor effects on the yield as long as the P status is high. When the P status has decreased to "sufficient", phosphate can be applied at rates that meet the (net) uptake by the crop.

3 Increased leaching may also be prevented by a chemical treatment of the slurry, for example with phosphate adsorbing materials such as zeolites and coccolithes (Silva and Baffi, in prep.). Addition of 1‰ of these substances reduced the soluble P content by 70%. Alternatively, $FeCl_3$ can be added to precipitate the soluble phosphate. To be effective in the long run the additions should also be sufficient to transform the solid phosphate components in slurry into less soluble iron phosphates.

4 Runoff can be reduced by applying slurries, manure and fertilisers at the beginning of the growing season (April) and not in the autumn or winter, and in adequate amounts that meet the need of the crop. Ploughing in after fertilisation and injection of slurry, further reduce phosphate losses by surface runoff.

6 CONCLUSIONS

Some general conclusions that can be drawn from this review are:

1   Dissolved and solid phosphates in animal waste are transformed into Al- en Fe-phosphates in non-calcareous soils and Ca-phosphates in calcareous soils. The reaction with the soil is primarily attributed to sorption by Al- en Fe-oxides and Ca-carbonates, respectively. The sorption capacity of the soil may become "saturated" if phosphorus applications continuously exceed crop requirements. According to a Dutch definition a soil is considered saturated when more than 25% of the sorption capacity has been used. The concentration of phosphate in groundwater will then exceed a critical limit of 0.1 mg l^{-1} ortho P at high water levels.

2   The input of P to the soil is usually higher than the uptake by the crop. Recommended rates allow a slight overdose when the soil P status is sufficient. Regulations in The Netherlands and particularly Italy allow significantly higher doses at this moment. In the Dutch regulations fertilisation rates should not exceed the uptake by the crop by the year 2000.

3   The annual net input to the soil is much larger in the Dutch areas with intensive livestock farming (160-430 kg ha^{-1} P_2O_5) than in the Po region in Italy (10-60 kg ha^{-1} P_2O_5). The non-calcareous sandy soils in the former areas are particularly vulnerable to saturation with phosphate. In 1990 it was estimated that about 43% of the grassland and 82% of the maizeland was saturated.

4   Phosphate saturation has caused an increased leaching of phosphate to surface waters. In phosphate saturated areas, the concentration of phosphate in surface waters exceeds, or will exceed, the quality goal for sandy areas of 0.15 mg l^{-1} P. Locally, the load from agricultural soils in these areas is about 2.5-8 kg ha^{-1} yr^{-1} P. The increased leaching will continue far into the next century.

5   The calcareous sandy soils in the Po region most likely have a low phosphate sorption capacity. These soils can become saturated depending on the overdose and drainage conditions. It is recommended to study the phosphate sorption capacity of these soils so that measures can be taken, if necessary, to prevent saturation, and thereby increased leaching from these soils.

6   Surface runoff is particularly occurring on the less permeable clay soils and, therefore, expected to be more important in the Po region than in The Netherlands. Annual losses of 2 kg ha^{-1} P have been reported for slurry applications on poorly drained soil.

7   Phosphate leaching can be prevented if the soil does not become saturated. In soils with a sufficient P status application rates of phosphate should not exceed the (net) uptake by the crop and an acceptable amount of leachate. Addition of chemicals

(e.g. $FeCl_3$) to slurries may also be helpfull, provide that all the phosphate (soluble and solid) is transformed into relatively insoluble phases. Surface runoff is reduced by ploughing in after application, or injection of slurry. Applications in late spring (April) will promote infiltration of phosphate into the soil and, thereby, also reduce runoff.

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