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Control and Amelioration of Phosphorus Losses from a Clay Soil Heavily Manured with Animal Slurries

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Diffuse, non-point source pollution of waterways by agricultural phosphorus is widespread in developed countries with intensive livestock-rearing sectors. This has focussed attention upon methods of assessing soil P reserves and availability, to manage pollution and increase the efficiency of utilisation of agricultural P.

A particular problem is posed by the localised intensive application of animal manures to silage swards. Downward movement of P in soils after P fertilizer application is generally thought to be small, but P can move to moderate depth (0.3-0.4m) in soil which is repeatedly treated with high loading rates of manure and animal slurries (Sharpley et al. 1984; Eghball et al., 1996). Soils in Northern Ireland, where the present work was conducted, already possess relatively high native organic matter contents, as a consequence of climate i.e. relatively high latitude combined with a position on the Atlantic seaboard (Higgins, 1997).

Whether Northern Ireland soils have properties which permit the widespread leaching of agricultural phosphate, or whether the problem is a reflection of local management practices and inadequacies, is unknown. However, the agronomically-available P in N. Ireland soils is not, in general, excessive, with average values for Olsen-P in surface layers of 20-30mg P L^{-1} (Dils et al. 1998). This fact needs to be squared with the continuing decline in water quality, in terms of elevated phosphorus status, of many of Northern Ireland's lakes and rivers.

Agricultural soils most at risk of P loss through leaching appear to be deep sandy soils, high organic matter soils and soils with high P concentration from over-fertilisation, long-term, with organic wastes (Sims et al. 1998). The sorption of phosphate by soils is affected by, among other things, soil organic matter content, content of amorphous Al and Fe oxides, of carbonates and of clay (Moshi et al., 1974; Lopéz-Hernandez and Burnham, 1982; Borggard, 1983; Brennan et al., 1994). Some account has to be taken of these characteristics in determining the susceptibility of a soil to P leaching.

The present experiment made use of the long-term slurry experiment at Hillsborough, Northern Ireland, to assess the vulnerability of local soils to P loss,

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particularly through leaching, from repeated animal slurry applications. Particular interest was focussed upon the effect of cessation of manure applications to productive silage swards as a means of reducing the risk of leachate high in dissolved P reaching local water bodies.

MATERIALS AND METHODS

Soils from a long-term slurry experiment established in 1970 and still in progress, were used in the analyses reported here. The experiment was laid down on an established perennial ryegrass sward at 120m altitude, in the Agricultural Research Institute of Northern Ireland at Hillsborough (Christie, 1987). The site is considered typical of a large area in Northern Ireland and much of the northwest of the UK. The soil is a clay loam (42% sand, 24% silt and 34% clay) overlying Silurian shale and greywacke. Two sets of treatment plots (out of eight treatments in the long-term experiment) were used in the present experiment which took place in 2000: (1) pig slurry applied at 200 m^3 ha^{-1} yr^{-1}; (2) cattle slurry applied at 200 m^3 ha^{-1} yr^{-1}. The other treatments, used in previous work on this topic (Anderson and Wu, 2001; Anderson and Xia, 2001) included a fertiliser control receiving granular fertiliser at a rate of 32 kg P ha^{-1} yr^{-1} and cattle and pig manure amended plots receiving liquid manure at 50 or 100 m^3 ha^{-1} yr^{-1}.

The high input manure treatments were chosen to determine how quickly amelioration of P loss could be achieved by cessation of manuring. Each treatment had three replicate 8.5 x 3.5m plots in which PTFE suction cup lysimeters had been installed at depths of 35cm and 85cm to sample soil micropore water. Water from the samplers was analysed for total soluble P (TSP). The samplers were installed in 1997 and were used in previous studies assessing the effect of manures upon soil P reserves and the movement of P down the soil profile (Anderson and Wu, 2001; Anderson and Xia, 2001). Control plots, three cattle and three pig, were used to assess the affect of changes in the experimental plots. Control plots received the usual dressings of manure during the experiment but lacked suction cup lysimeters. All plots were cut three times per year at the silage stage and manures applied, where appropriate, by hand in three equal dressings, first in spring and then immediately after the first two cuts of silage grass.

Soil samples of the top 10cm were taken in February 2001, before the first application of manure that year. Samples were air-dried and ground to pass a 2mm sieve. Soil pH was measured with a glass electrode in water using a 1:2.5 soil: water ratio. Total organic carbon (TOC) and nitrogen were determined on air-dried samples by combusting in a Leco FP2000 Nitrogen and Carbon Analyzer. Soils were extracted with 0.02 M acidified ammonium oxalate for analysis of oxalate-extractable Fe, Al and P and calculation of DPS (degree of P saturation = $P_{ox}/0.5 \times (Al_{ox} + Fe_{ox}) \times 100$). Extracts were digested with nitric acid/perchlorate prior to ICP analysis (Varian Liberty Series II Analyzer).

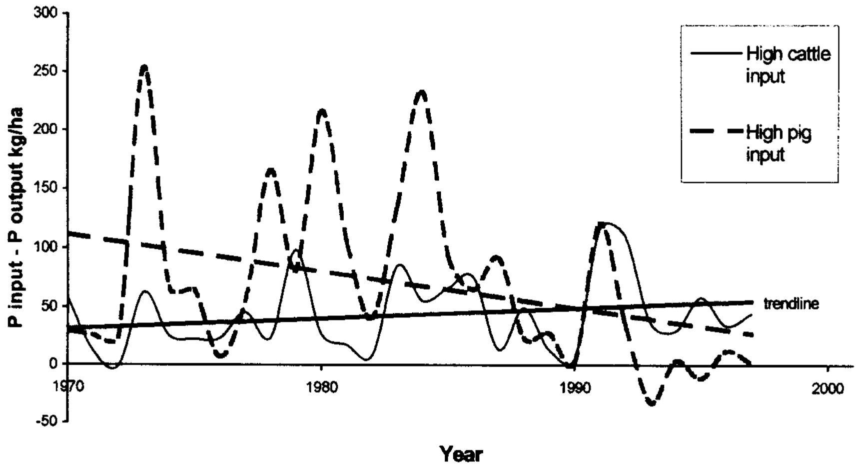

Figure 1. Phosphorus balance in high input cattle and pig slurry treatments of the Long Term Slurry Experiment. 1970 to 1997.

Sodium bicarbonate-extractable P (Olsen-P; P_{Ols}) was determined by a modification (Ministry of Agriculture, 1986) of the method of Olsen et al. (1957). Water-soluble P (P_w) was assessed by shaking soils with water at a soil/solution ratio of 1:10 for 1 hr and the filtered extract analysed for molybdate-reactive phosphorus by the method of Murphy and Riley (1962). Total soluble P (TSP) was determined in the water-soluble extracts and in soil micropore water by acidification with 30% sulphuric acid and autoclaving at 121°C for 60 minutes..

Phosphorus sorption isotherms were generated by a standard batch equilibrium technique (Nair et al., 1984). Sorption data were fitted to the Langmuir isotherm $P_{sorb} = KbP_e/(1 + KP_e)$, where P_{ads} = amount of P sorbed per unit mass of soil, and P_e = P concentration in solution at equilibrium. The soil Q/I parameters K = P affinity constant, b = P sorption maximum, PBC_m = Kb = maximum P buffering capacity, were determined from fitted equations (Holford and Mattingly, 1976). Desorption data were fitted to the Freundlich equation $P_{des} = k - aP_e^{1/n}$ where P_{des} = amount of P desorbed per unit mass of soil, P_e = P concentration in solution at equilibrium. In the equation k and n are constants and a = desorption rate coefficient.

RESULTS AND DISCUSSION

Soil total nitrogen (TN) was significantly lower in pig treatments compared to cattle treatments (Table 1). In the Long Term Slurry Experiment slurry has been applied by volume and nutrient composition of the slurry determined retrospectively to assess nutrient inputs. As slurry composition varies, parity bewteen manure types was not expected although in general the differences have been relatively small in N and P.

There has been some evolution in N and P inputs over the life of the experiment in line with variations in manure composition. This is illustrated in Fig. 1 giving total P balance for the high input treatments since 1970. For most of the duration of the experiment, P inputs have been higher in treatments receiving pig manure (Figure 1, Table 1) than those receiving cattle manure, although a broad trend towards equalisation has been apparent over the span of the experiment. N inputs have in general been lower in pig compared to cattle manure treatments over the lifetime of the experiment (P. Christie, pers. comm.). Total organic carbon levels in treatment soils are significantly higher in cattle than pig plots due to the much higher dry matter and therefore organic matter content of the cattle manures used in the experiment. The bulk of the excess organic matter in cattle manure plots is mineralised leaving relatively small differences in soil TOC content by the following spring of any given year as illustrated for February 2001 in Table 1. As might be expected, differences are more substantial and reflect the high input of organic matter in cattle manure (about four-fold compared to pig) in mid season - May 2001 in Table 1. These differences will become pertinent to observations of P behaviour in the respective plots made later in the discussion.

Table 1. Soil nitrogen, organic matter and phosphorus content in high input animal slurry plots with or without manure addition in the previous year.

Plot treatments	TOC (Feb 2001) %	TOC (May 2001) %	N %	P_{ols} mg L^{-1}	P_{ox} mg kg^{-1}	DPS %	P_w mg kg^{-1}
Cattle manure, manured previous year	5.57	6.73	0.526	89.7	1.57	38.8	17.58
Cattle manure, manure withdrawn	5.26	6.05	0.490	73.0	1.36	31.4	12.64
Pig manure, manured previous year	5.14	5.44	0.476	208.3	2.49	58.8	20.28
Pig manure, manure withdrawn	4.78	5.08	0.450	145.0	2.46	47.4	16.64
Significance:							
Manure type -	***	***	***	***	***	***	ns
Manured vs unmanured -	**	**	**	*	ns	**	*

Soil agronomic P parameters illustrate the differences in P balance between pig and cattle manure treatments (Table 1), with pig values for P_{Ols}, for instance, being much higher than for equivalent cattle values. Previous work has demonstrated

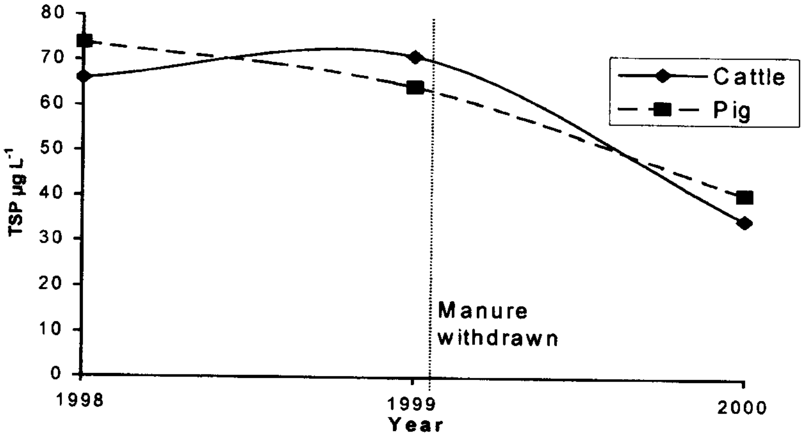

Figure 2. Average annual total soluble P at 35cm in suction cup collectors.

that Olsen P, oxalate-extractable P and degree of P saturation (DPS) accurately reflect total P concentrations of soil in the respective treatments, and therefore soil agronomic P reserves (Anderson and Wu, 2001). There is some disagreement between these agronomic values, however, and estimates of the soil matrix's ability to sorb and retain (inorganic) P. Thus, so-called environmentally sensitive measures of soil P (P_w, PSI), as well as sorption and desorption parameters derived from P isotherms, as well as P concentrations in soil micropore water (Table 2), suggest that the differences between pig- and cattle-manured plots in the experiment are in fact much smaller in relation to risk of P loss to the environment, than would be indicated from agronomic P contents. This may be explained by the large differences in the organic matter inputs from the respective manure types, as mentioned previously.

Organic matter is known to occlude P binding sites in soil and therefore to increase P desorptivity and risk of P loss. The lower P_{ols} content of cattle-manured plots is therefore deceptive, as the risk of loss of inorganic P is as high as in the much higher-P pig plots, and is very likely affected by the high organic matter inputs to the cattle manure plots compared to pig plots. Disposal of cattle manure, particularly high dry matter content manure, may therefore pose environmental risks where stocking rates are high and the available land area for disposal is small.

The soils in this experiment are managed in a three-cut silage system. It should therefore be possible to reduce the P reserves in the soil quite rapidly by continuous cropping in the absence of manurial inputs. Withdrawal of manure for one year had the effect of reducing the P_{ols} levels in treatment soils significantly (Table 2), by 18.6% and by 30.4% in the cattle manure and pig manure plots respectively. Previous work on these plots has indicated that loss of P to micropore soil water is very small at or below Olsen P contents in cattle soils of

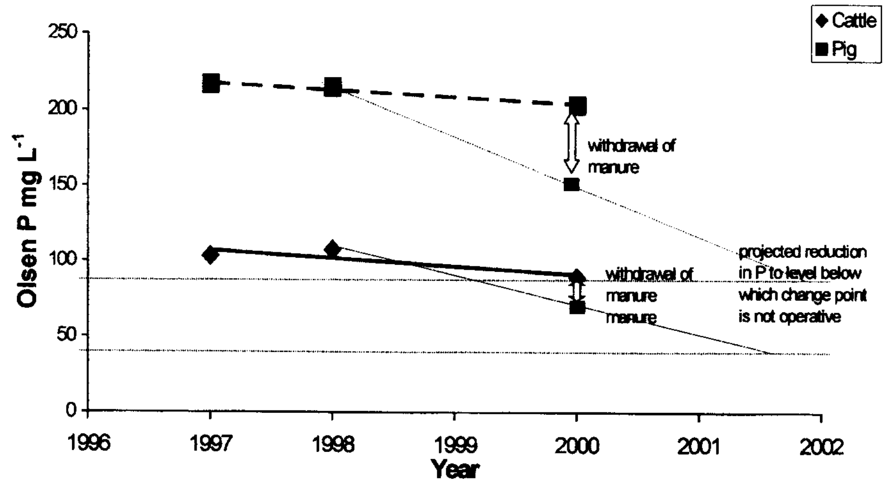

Figure 3. Variation in Olsen P in soil surface with time.

35 mg L^{-1}, and at Olsen P levels in pig soils of 73 mg L^{-1} (Anderson and Xia, 2001). These correspond to change points in the respective plots as exemplified by Heckrath et al. (1995).

A plot of P_{ols} over three years in the experimental plots (Fig. 3) illustrates the potential decline in soil P levels below these critical thresholds within two years of cessation of manuring in both treatments. This is corroborated by the decline in TSP in soil micropore water during the experiment (Table 2). Percentage declines in TSP were 37% for pig plots and 51% for cattle plots in the first year (Table 2). It should be noted that the decline is greater in the pig treatment soils than in the cattle treatment soils and is proportional to the P loading in the respective soils. As P loading declines with continued off-take, the rate of P removal will also reduce.

The form of the P present in soil water was examined after manure withdrawal from experimental plots. Prior to the experiment in 1999, the percentage of organic P in collected soil water was approximately 34 % and 27 % for cattle and pig treatments (Table 3; see also Anderson & Xia, 2001). This increased to 72 % and 67 % respectively after withdrawal of manure (Table 3). High manure loadings have previously been correlated with a high percentage of inorganic P in the soluble P pool of soil micropores (Anderson and Xia, 2001). This seems a reverse of logic but is probably a result of substantial P mobilisation and, more importantly, exchange, in the inorganic form during intense microbial activity.

Withdrawal of manure application, not surprisingly, appears to reverse this process. It might be expected that the observed changes in the composition of soil micropore water would be reflected in standard water-soluble P measurements, despite the difference in scale. To test this, extracts for water-soluble P (P_w)

determination were additionally acidified and autoclaved to determine total soluble P content. Differences between the P thus determined and P_w were taken as a measure of the soluble organic P fraction (Table 3). Organic P is also given as a percentage of total P in Table 3. There is a significant increase in the organic fraction as a result of manure withdrawal but this only amounts to about a third of the total P pool extracted in water. However, the direction of the change lends support to the hypothesis that soils heavily manured with organic matter tend to release P in the inorganic form preferentially as a result of microbial activity.

Table 2. Soil P sorption/desorption parameters and P content of soil micropore water in relation to manure application.

Plot treatments	b	Kb	EPC_0 mg L^{-1}	PSI mg kg^{-1}	TSP_{soil} water µg L^{-1}	DPS %
Cattle manure, manured previous year	545	93.5	1.32	353	[71.1]*	38.8
Cattle manure, manure withdrawn	553	172.6	1.00	436	35.1	31.4
Pig manure, manured previous year	802	50.7	5.54	312	[64.4]*	58.8
Pig manure, manure withdrawn	832	122.3	3.14	359	40.7	47.4
Significance:						
Manure type -	ns	ns	ns	*	ns	***
Manured vs unmanured -	ns	*	ns	*	**	**

- Year totals previous to withdrawal of manure from experimental plots (Fig. 2)

The overall effect of these changes for P loss from the soil system are unclear. It has been postulated that organic P can move more readily through the soil matrix than inorganic P, and where organic P is generated in soils, the risk of loss to drainage therefore increases (Eghball et al., 1996). On the other hand, organic matter *per se* has been postulated to increase P loss through occlusion of P binding sites. Both hypotheses could apply in the present situation. An apparent increase in the organic P fraction of soil micropore water and a reduction in organic matter applied to the soil surface have, however, clearly generated a net reduction in TSP in micropore water (Table 2). The risk of P loss would, overall, appear to be reduced. Soil macropores play a significant role in allowing solubilised P to move through the soil profile (Jensen et al., 2002). In cracking clay soils such as those in the present experiment, preferential movement may be a significant process and become entrenched where the soil matrix lies undisturbed for long periods. The macropores may become lined with organic matter from the manure applications and solublized P may therefore effectively bypass the strongly adsorbing clay mineral matrix. Even if manure applications are suspended it may take ploughing or the passage of considerable time periods to regenerate lost P immobilising capacity. The changes observed here are postulated to arise almost entirely from the reduction in P inputs from cessation of manuring and from withdrawal of P by cropping of the silage sward.

Table 3. The organic fraction of soil micropore water and the effect of rewetting upon solubilisation of inorganic P from air-dried soils

Plot treatments	P_w mg kg $^{-1}$	Organic P in P_w mg kg $^{-1}$	Organic P % P_w	% organic P in micropore water, 1999	% organic P in micropore water, 2000
Cattle manure, manured previous year	52.9	18.9	26.3	34.4	-
Cattle manure, manure withdrawn	24.4	14.2	37.7	-	71.9
Pig manure, manured previous year	54.6	11.1	16.9	27.0	-
Pig manure, manure withdrawn	20.7	9.57	32.2	-	67.1
Significance:					
Manure type -	ns		ns	ns	ns
Manured vs unmanured -	***		**	-	-

To ensure better long-term protection from P loss, the best strategy would appear to be a combination of reduced organic matter and P input combined with ploughing. Ploughing re-integrates the very high levels of P which accumulate in the top few cm of soil and will disrupt organically saturated macropores which contribute to P loss (Georhing et al., 2001).

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