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Phosphorus leaching from liquid digested sewage sludge applied to sandy soils

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SUMMARY

The aim of the experiment was to determine the importance of liquid digested sewage sludge ('sewage sludge') as a source of phosphorus leaching from sandy soils in the UK. The sewage sludge was applied to uncropped loamy sand and sandy loam monolith lysimeters (1·2 m deep) annually for 3 years. The application rate was sufficient to supply approximately 60 kg P/ha annually. An application equivalent to four times this amount was also applied to two other loamy sand lysimeters to test the effects of excessive amounts. Total P (TP), total dissolved P (TDP) and molybdate-reactive P (MRP) concentrations were measured in the drainage water and were compared with leaching from untreated control soils.

After two sewage sludge applications, Olsen's extractable P content of the topsoil had increased: a P surplus of *c*. 100 kg/ha was required to raise the topsoil concentration by 5 mg/kg. Sewage sludge applications at the lower rate did not increase P concentrations in the drainage. Phosphorus concentrations were generally small and were, as an average of both soil types and nil and lower rate sludge applications, 12, 20 and 34 µg/l for MRP, TDP and TP respectively. Phosphorus leaching losses from the higher rate (excessively large sewage sludge applications) were more variable but not significantly ($P > 0{\cdot}05$) different from the other treatments. Average concentrations were 9, 23 and 50 µg/l for MRP, TDP and TP respectively. Leaching from sludge biosolid applications at operational rates to sandy soils moderately well supplied with P is not a major P loss pathway.

INTRODUCTION

The increased incidence of eutrophication of UK surface waters has been attributed to increased phosphorus (P) loads (Moss 1996). Although nitrogen (N) and carbon inputs are also associated with eutrophication, P is often considered the most appropriate limiting element (Sharpley & Menzel 1987). Therefore, reducing loads of P to water is important for the control of eutrophication.

Point sources of phosphorus, such as discharge from sewage treatment works, are relatively easily controlled (EU Urban Wastewaters Directive: Anon. 1991). However, diffuse agricultural P sources are more difficult to identify and control. Phosphorus, as phosphate, is essential for plant growth, and applications to soils that are deficient are economically justified. The major pathway for P loss from soil are movement of particulate P by soil erosion and movement of dissolved P by surface or subsurface run-off. Until recently, leaching of soil P has not been considered an important loss pathway for UK soils because of the affinity with which phosphorus is retained by soil colloids. However, where soils become only partly saturated with phosphorus due to excess fertilization with farm wastes, then significant leaching of orthophosphate may occur (Breeuwsma & Silva 1992; Heckrath *et al.* 1995; Eghball *et al.* 1996). Sommers *et al.* (1979) similarly found increased soluble P concentrations at depth after regular applications of municipal wastewater on a sandy soil, but not a clay soil.

Dissolved organic P can also form a major part of the total P present in soil solutions (Hannapel *et al.* 1964; Shand *et al.* 1994). Chardon *et al.* (1997) postulated that this might be more mobile than inorganic orthophosphate and could be an important source for P movement; their experiments confirmed this. As long ago as 1934, Spencer & Stewart reported greater leaching from organic P sources because of the soil's inability to fix these compounds; they need to be mineralized to orthophosphate before fixation can occur.

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Sewage sludge is an important source of P (and N) for agriculture in the UK. Furthermore, because of changes in sludge processing requirements (Urban Wastewater Directive: Anon. 1991) and the removal of the option for sea dispersion, the amount of sludge available for agriculture is increasing (Anon. 1995). The aim of this work was therefore to test whether regular applications of sewage sludge pose any risk to P leaching through a sandy soil under UK conditions.

MATERIALS AND METHODS

Site and lysimeter details

Gleadthorpe Research Centre is in central England and comprises sandy soils developed over the Sherwood Sandstone, which is a major UK groundwater aquifer. The average annual rainfall of 625 mm is distributed evenly through the year. The experiment used 12 monolith lysimeters which had been installed 3 years previously, and had been cropped uniformly over that time.

Eight lysimeters contained undisturbed cores of a loamy medium sand overlying medium sand to depth (Cuckney series: Ragg *et al.* 1984). These soil cores were taken from an adjacent field site at the Research Centre. Four other monoliths contained a sandy loam soil taken from IACR Rothamsted (Cottenham soil series: Hodge *et al.* 1984).

The lysimeter cores were taken by the method described by Belford (1979). The base of the lysimeter (of the same material as the lysimeter sleeves) contained 10 cm gravel and a drainage port which allowed the drainage water to be collected into plastic bottles. The soil cores were 0·8 m diameter (in sleeves of glass fibre reinforced polyester, coated with epoxy resin on the inner surface), and were 1·2 m deep (including the gravel fill), spaced around central inspection hatches, which allowed collection and replacement of the drainage bottles.

Treatments and statistical design

Liquid digested sewage sludge from a nearby sewage treatment works (Stoke Bardolph, near Nottingham) was used. Treatments were based on target total P loadings from sewage sludge to each soil type. The number of available lysimeters meant that there was an unequal number of replicates:

1. loamy sand soil, no sludge (3 replicates);
2. loamy sand soil, sewage sludge at a rate equivalent to *c.* 6 kg P/ha annually (3 replicates);
3. loamy sand soil, sewage sludge at a rate equivalent to *c.* 240 kg P/ha annually (2 replicates);
4. sandy loam soil, no sewage sludge (2 replicates);
5. sandy loam soil, sewage sludge at a rate equivalent to *c.* 60 kg P/ha annually (2 replicates).

The lower application rate could be considered as 'Good Agricultural Practice' and would supply sufficient phosphate for the following 3–4 arable crops (Anon. 1985). The higher rate was included to test the effects of excessive P application. Sewage sludge was applied to the same lysimeters each year for 3 years (Table 1). Treatments were allocated at random, apart from the constraint of soil type: all four sandy loam monoliths were positioned around one inspection hatch.

The experiment was analysed statistically as a completely randomized design, analysing each soil type separately. For P leaching losses, year and treatment were both included as factors.

Application of sewage sludge to the lysimeters

Sewage sludge, approximately 150 litres, was collected in 25 litre plastic containers each year. It was stored below 4 °C while subsamples were analysed for total P content, so that application rates to achieve the target P loadings could be calculated.

Before application to the lysimeters, all containers were emptied into a holding tank and agitated to ensure the sludge was of uniform composition for all lysimeters. Then, to simulate sludge injection, topsoil to a depth of 20 cm was removed from the lysimeter (and placed on a polythene sheet), the sewage sludge was applied and the topsoil replaced. Three subsamples of sludge were taken for a detailed phosphorus analysis.

The lysimeters were kept bare throughout the experiment. The soils were cultivated thoroughly to their full topsoil depth (30 cm) each year before the next application of sewage sludge.

Sampling and chemical analysis

After cultivation each September, but before each sewage sludge application, topsoil samples (0–30 cm, 8 cores per lysimeter) were taken for analysis for Olsen-extractable P, total P, total N and pH. Soils were air-dried and ground to pass a 2 mm sieve. Analytical techniques are detailed in Anon. (1986).

Leachates were generally collected fortnightly for analysis. Frequency was increased in wet winter periods and was decreased during the dry summer months. Subsamples of leachate (200 cm^3) were transported to a central laboratory for analysis within 48 h of collection. During this time they were stored below 4 °C. Leachates were analysed for molybdate reactive phosphorus (MRP), total dissolved phosphorus (TDP) and total phosphorus (TP). MRP was determined colorimetrically at 880 nm after filtration through a 0·45 μm filter. TDP and TP were initially

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Table 1. *Details of liquid digested sewage sludge analyses (mean of three subsamples, expressed on a fresh basis) and nutrient loadings for each autumn and the total. 't60' and 't240' refer to the annual target application rates of 60 and 240 kg P/ha*

	1994/95			1995/96			1996/97				
		Applied			Applied			Applied		Total applied	
	Conc. g/l	t60 kg/ha	t240	Conc. g/l	t60 kg/ha	t240	Conc. g/l	t60 kg/ha	t240	t60 kg/ha	t240
Total solids	23·3	—	—	30·3	—	—	13·8	—	—	—	—
Total N	1·6	186	742	1·7	243	936	1·3	182	702	610	2380
Ammonium N	0·43	50	199	0·78	108	418	0·86	121	466	279	1083
Total P	0·48	55	222	0·56	78	301	0·40	57	219	190	741
P, HCl Sol	0·36	42	169	0·47	66	253	0·17	29	113	137	535
P, $NaHCO_3$ Sol	0·18	21	84	0·17	24	93	0·16	22	84	62	241
P, NaOH Sol	0·08	10	39	0·12	17	64	0·13	18	71	45	174
P, H_2O Sol	0·10	12	48	0·05	7	25	0·11	15	60	34	133
Application date		19.9.94			12.10.95			12.9.96			
Application rate (m^3/ha)	—	116	464	—	140	540	—	140	540	396	1544
Total solids (t/ha)	—	2·7	10·8	—	4·2	16·3	—	1·9	7·5	8·9	34·6

Table 2. *Topsoil analysis (0–20 cm) sampled in September at the start of the experiment and after two liquid digested sewage sludge applications. 't60' and 't240' refer to the annual target application rates of 60 and 240 kg P/ha. Ext P is Olsen's extractable P*

	September 1994				September 1996				Change			
Sludge rate	Ext P mg/kg	Total N %	Total P mg/kg	pH	Ext P mg/kg	Total N %	Total P mg/kg	pH	Ext P mg/kg	Total N %	Total P mg/kg	pH
Loamy sand soil												
nil (3 reps)	32	0·07	535	6·3	32	0·07	466	6·5	0	0·00	−69	0·2
t60 (3 reps)	31	0·07	527	6·5	37	0·07	485	6·2	6	0·00	−42	−0·3
t240 (2 reps)	31	0·07	563	6·5	55	0·09	617	5·8	24	0·02	55	−0·7
S.E. (5 D.F.) 3 rep	—	—	—	—	1·9	0·004	10·9	0·11	1·2	0·008	20·4	0·06
S.E. (5 D.F.) 2 rep	—	—	—	—	2·4	0·014	13·3	0·13	1·5	0·01	25·0	0·07
P	—	—	—	—	0·002	0·031	0·001	0·02	0·001	0·28	0·03	0·001
Sandy loam soil												
nil	27	0·11	852	7·2	31	0·09	741	7·2	4	−0·03	−111	0·1
t60	30	0·11	900	7·2	40	0·11	823	7·2	10	−0·01	−77	0·0
S.E. (2 D.F.)	—	—	—	—	2·2	0·005	38·8	0·11	1·6	0·005	25·3	0·08
P	—	—	—	—	0·1	0·1	0·27	0·77	0·12	0·11	0·44	0·70

determined by inductively coupled plasma–optical emission spectrometry (ICP–OES), either after filtration through a 0·45 μm filter, no digestion (TDP), or after digestion with aqua regia, no filtration (TP). However, ICP–OES was found to be insufficiently sensitive (in agreement with Rowland & Haygarth 1997). To decrease our analytical limit of detection from 50 to 10 μg/l, TDP and TP were measured colorimetrically at 880 nm after digestion with persulphate on 0·45 μm filtered (TDP) or unfiltered (TP) solutions. These changes were made during the first year of the experiment. Therefore, for the few early solutions that were reported with P concentrations of < 50 μg /l, it was assumed that the P concentration was 25 μg/l when calculating P fluxes.

Sewage sludge samples were analysed on a fresh basis. Total N was determined by the Kjeldahl method, and NH_4-N colorimetrically after dilution with water and filtration (Anon. 1986). Total P was determined on dried (100 °C for 16 h), milled (1 mm sieve) samples digested with aqua regia and analysed by ICP–OES.

The sewage sludge was also chemically fractionated by shaking separate samples for 16 h with the appropriate reagent, filtering and analysing for MRP colorimetrically: water, Olsen's reagent, 0·1 M NaOH

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Table 3. *Drainage collected from the lysimeters each autumn/winter. 't60' and 't240' refer to the annual target application rates of 60 and 240 kg P/ha*

Sludge rate	Drainage (mm) 1994/95	1995/96	1996/97	Mean
Loamy sand soil				
nil (3 reps)	297	171	223	230
t60 (3 reps)	317	191	248	252
t240 (2 reps)	343	208	241	264
S.E. (15 D.F.)				
min rep	—	12·1	—	7·0
max rep	—	9·9	—	5·7
Mean	316	188	237	247
Sandy loam soil				
nil	296	176	244	238
t60	305	210	276	264
S.E. (6 D.F.)	—	13·4	—	7·7
Mean	301	193	260	251

or 1 M HCl. The extractant to sample ratio was 20, based on a fresh sludge sample (but a dried, milled sample for the HCl extraction).

RESULTS

Sludge composition and loadings

Sewage sludge was variable between years in solids, N and P contents even though the sludge was collected from the same works each time (Table 1). The N:P ratio was reasonably consistent, however, with a mean value of 3·2 (range 3·1–3·4). The ammonium-N content varied from 27–66% of the total N (mean 46%).

Over the three applications, we achieved close to our target applications of 180 and 720 kg P/ha. The fractionation of the sludges again showed some variation between years (Table 1). On average, 72% of total P was HCl-extractable, 33% was bicarbonate-extractable, 23% was sodium hydroxide-extractable and 18% was water soluble. These values are in good agreement with data from other UK sewage sludges (Withers 1998).

Soil analyses

Within soil types, all lysimeters showed similar chemical analyses at the start of the experiment (Table 2). All topsoils were moderately well supplied with Olsen-extractable P, as defined by UK fertilizer

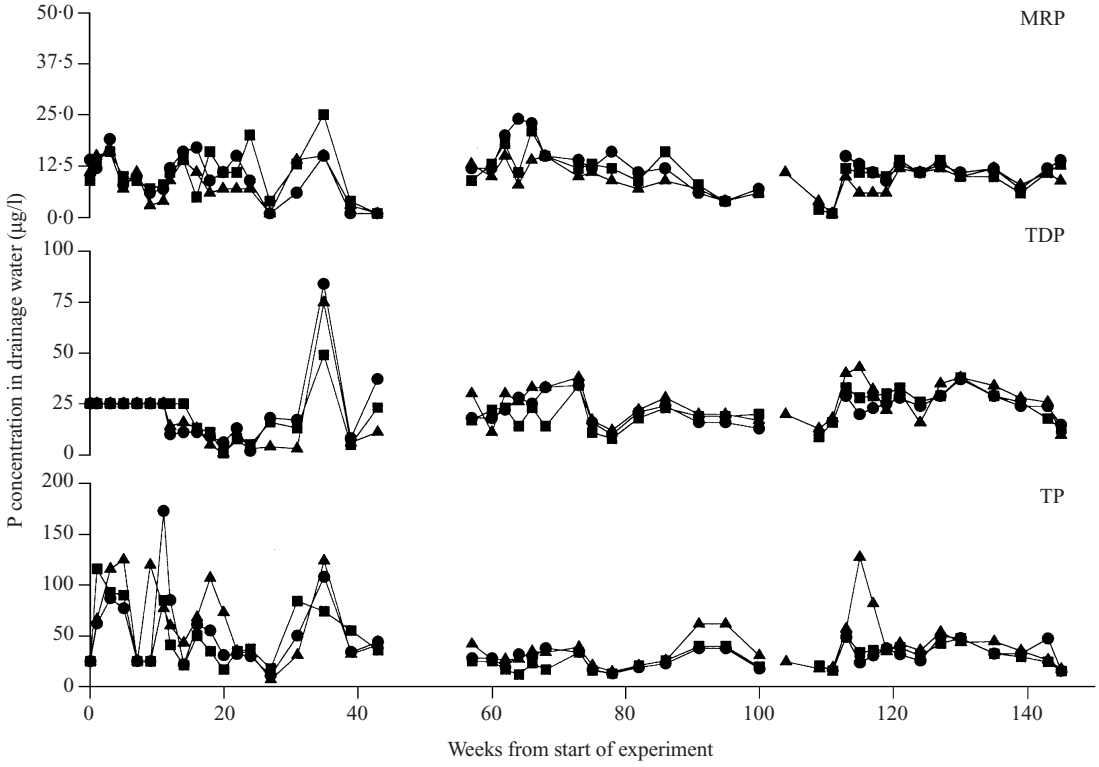


Fig. 1. Phosphorus concentrations in the drainage collected from the loamy sand soil over the three winters of the experiment: molybdate reactive P (MRP), total dissolved P (TDP) and total P (TP). No sludge: ●; sludge equivalent to approximately 60 kg P/ha/year: ■; sludge equivalent to approximately 240 kg P/ha/year: ▲.

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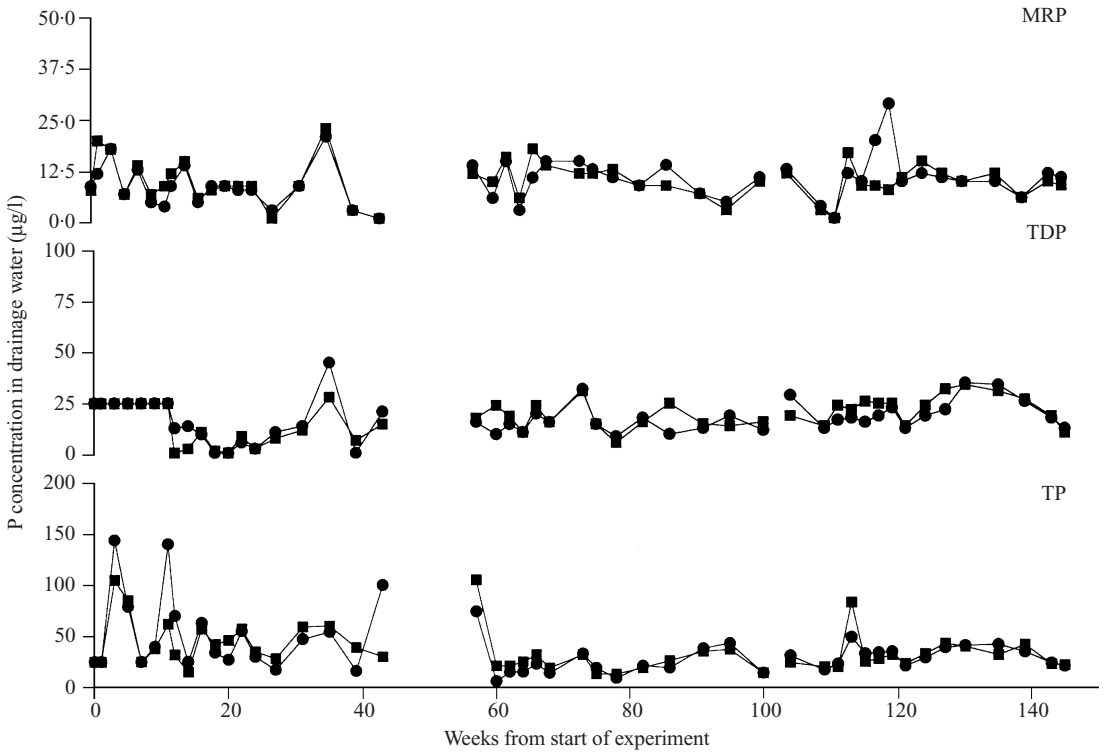


Fig. 2. Phosphorus concentrations in the drainage collected from the sandy loam soil over the three winters of the experiment: molybdate reactive P (MRP), total dissolved P (TDP) and total P (TP). No sludge: ●; sludge equivalent to approximately 60 kg P/ha/year: ■.

recommendations (Anon. 1994). The heavier textured sandy loam contained more total N and total P, as would be expected, and the pH was also higher.

After two sludge applications in the absence of a growing crop, statistically significant increases in total N and total and Olsen-extractable P were observed on the loamy sand soil (Table 2). These differences appeared mainly to be attributable to the higher annual sewage sludge loading, with only small differences between the control and lower rate sludge. Similar trends in N and P were observed between the control and lower rate sludge on the sandy loam soil. However, no effects were significant at $P = 0{\cdot}05$, presumably because the higher sewage sludge loading was not applied to this soil type.

A clear decrease in pH was observed on the poorly buffered loamy sand soil. This may have been due to the acidification resulting from nitrification of the applied ammonium or the mineralization of sulphur (Withers & Smith 1997). This was not noted, however, on the heavier textured, better buffered, sandy loam soil.

Drainage

In the first year there was, on average, 312 mm drainage from the lysimeters between the start of the experiment and mid-July when the lysimeters stopped draining. The second year was drier with, on average, 190 mm drainage from the lysimeters between the end of October and mid-July. The third and final winter was wetter than the second year (average drainage *c.* 250 mm). As a mean of the 3 years, there was an effect of sewage sludge rate on drainage from the loamy sand (Table 3), significant at $P = 0{\cdot}005$, this was due to the large volumes of liquid that were applied. The effect was not significant ($P = 0{\cdot}06$) on the sandy loam.

Phosphorus leaching

Throughout the first winter, P concentrations in the leachate were small. TDP and TP concentrations were almost always at or below our initial analytical limit of detection using ICP–OES. Phosphorus concentrations in the second year and third years were again small and generally below 50 µg/l (Figs 1 and 2).

Averaged over all treatments and all years, there was *c.* 100 g TP/ha loss from the loamy sand soil, of which 53% was as TDP and 29% MRP (Table 4). Similar partitioning was observed in P leached from the sandy loam soil: 90 g TP/ha, of which 49% was as TDP and 30% as MRP.

Differences in leaching losses were small between

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Table 4. *Phosphorus leaching losses for each drainage season: molybdate reactive P (MRP), total dissolved P (TDP) and total P (TP). 't60' and 't240' refer to the annual target application rates of 60 and 240 kg P/ha*

	MRP loss (g/ha)				TDP loss (g/ha)				TP loss (g/ha)			
Sludge rate	1994/95	1995/96	1996/97	Mean	1994/95	1995/96	1996/97	Mean	1994/95	1995/96	1996/97	Mean
Loamy sand soil												
nil (3 reps)	33·3	27·9	28·4	29·9	50·0	42·9	51·7	48·2	143·6	47·3	74·6	88·5
t60 (3 reps)	36·6	26·3	29·1	30·7	56·1	39·3	64·5	53·3	128·1	41·9	85·4	85·1
t240 (2 reps)	29·6	23·0	20·5	24·4	52·1	55·1	69·3	58·8	225·5	67·0	134·8	142·4
S.E. (15 D.F.)												
min rep	—	3·49	—	2·01	—	5·20	—	3·00	—	32·98	—	19·04
max rep	—	2·85	—	1·64	—	4·25	—	2·45	—	26·93	—	15·55
Mean	33·6	26·1	26·7	28·8	52·8	44·6	60·9	52·8	158·3	50·2	93·7	100·7
Sandy loam soil												
nil	28·2	18·6	31·5	26·1	45·5	31·8	44·4	40·5	137·0	35·3	82·1	84·8
t60	31·8	24·4	29·4	28·6	40·3	42·6	59·9	47·6	130·1	50·2	107·5	95·9
S.E. (6 D.F.)	—	3·04	—	1·75	—	4·97	—	2·87	—	13·14	—	7·59
Mean	30·0	21·5	30·5	27·3	42·9	37·2	52·1	44·1	133·6	42·8	94·8	90·4

Table 5. *Flow-weighted average concentrations of phosphorus in the drainage water: 't60' and 't240' refer to the annual target application rates of 60 and 240 kg P/ha*

	MRP concentration (µg/l)				TDP concentration (µg/l)				TP concentration (µg/l)			
Sludge rate	1994/95	1995/96	1996/97	Mean	1994/95	1995/96	1996/97	Mean	1994/95	1995/96	1996/97	Mean
Loamy sand soil												
nil (3 reps)	11·2	16·1	12·7	13·3	16·8	25·0	23·1	21·7	48·5	27·6	33·3	36·5
t60 (3 reps)	11·5	13·9	11·6	12·4	17·7	20·8	26·1	21·5	40·4	22·1	34·4	32·3
t240 (2 reps)	8·7	11·2	8·5	9·4	15·3	26·1	28·6	23·3	63·9	31·4	54·3	49·9
S.E. (15 D.F.)												
min rep	—	1·45	—	0·84	—	1·93	—	1·11	—	9·51	—	5·49
max rep	—	1·19	—	0·68	—	1·58	—	0·91	—	7·77	—	4·48
Mean	10·7	14·1	11·3	12·0	16·8	23·7	25·6	22·0	49·3	26·5	39·0	38·2
Sandy loam soil												
nil	9·5	10·6	12·9	11·0	15·3	18·1	18·2	17·2	46·5	20·1	33·7	33·4
t60	10·4	11·7	10·8	10·9	13·1	20·3	21·6	18·4	42·4	24·1	39·5	35·3
S.E. (6 D.F.)	—	1·25	—	0·72	—	1·20	—	0·69	—	—	—	—
Mean	10·0	11·1	11·8	11·0	14·3	19·2	19·9	17·8	44·4	22·1	36·6	34·4

untreated soils and those that had received the lower-rate sewage sludge on both soil types (Table 4). There were no significant treatment effects on losses of MRP, TDP or TP from the sandy loam. On the loamy sand, the analysis of variance also included the higher rate sewage sludge. Even including this higher rate, there was no significant effect on MRP loss (in fact, control values appeared larger than from sludge treated soils). However, there was a small, but significant, effect of sewage sludge on TDP loss, with losses following the expected order of control < low rate sewage sludge < high rate sewage sludge. The apparently much larger losses of TP from the high rate sludge (Table 4) were not statistically significant ($P = 0{\cdot}07$).

It was possible that some of the differences in P loss were due to differences in drainage volume from the treatments, rather than from the P applied in the sewage sludge. Determining flow-weighted average concentrations of MRP, TDP or TP (Table 5) tested this. As an average of 3 years, MRP, TDP and TP concentrations leaching from the sandy loam were not affected by application of sewage sludge at a target loading of 60 kg P/ha/year. On the loamy sand, average MRP concentration was decreased ($P = 0{\cdot}008$) by sludge applications, due to the dilution effect of the additional drainage. There were no treatment effects on TDP concentration suggesting that increased losses in terms of g/ha were caused by the additional drainage arising from the sewage sludge applications. TP concentrations appeared much larger at the highest sewage sludge rate but were not significant ($P = 0{\cdot}07$).

DISCUSSION

Sludge composition and loadings

Organic wastes are heterogeneous materials, and differences in the nutrient composition of the sludges each year was to be expected. It does, however, illustrate the difficulty in nutrient planning when using average nutrient content data in the absence of a chemical analysis. Anon. (1994) suggests an average sludge P content of 0·064 % for sewage sludge at 4 % dry matter. This compares with our average of 0·048 % at *c.* 2 % dry matter.

The N : P ratio of the sewage sludge, however, was in good agreement with the 'typical' value of 3 : 1 provided by Anon. (1994). This means that if sewage sludge was applied at the rate of 250 kg N/ha recommended in the UK Code of Good Agricultural Practice (Anon. 1998), this would provide *c.* 80 kg P/ha. Our single application treatment was well within this guideline. However, even at this rate the sewage sludge would have supplied more than enough phosphate for an arable crop: 6 t/ha barley (straw removed) would take off *c.* 25 kg P/ha and 80 t/ha potato tubers would remove *c.* 35 kg P/ha (Anon. 1985). Clearly, the quadruple sewage sludge application rate was not sensible for N or P loading: the purpose of its inclusion was to measure P leaching under extreme conditions.

In the absence of crops in this lysimeter study, all P applied contributed to the soil pool (rather than some removed in the crop). The experiment therefore represented a quicker accumulation of soil P than would occur in a cropped system and was therefore a good test of the leaching risk from liquid digested sewage sludge. Withers (1998) also showed that liquid digested sewage sludge contains larger amounts of water-extractable P than other sludge types in the UK and, therefore, presents the greatest P leaching risk.

The P fractionation was an attempt to characterize the sludge and assess its likely environmental impact by using different strength extractants (modified from Hedley *et al.* 1962); it was not, however, a sequential extraction.

Soil analyses

Olsen-extractable P contents at the start of the experiment ranged from 27–32 mg/kg showing that the soils were well supplied with phosphorus (Table 2). The recommended fertilizer policy for soils of this P status would be to apply sufficient to balance crop removal (Anon. 1994). This would avoid unnecessary P build-up with minimum risk to crop yields. Since we did not crop the soils so that all applied P contributed to the soil pool, it is not surprising that we measured increases in Olsen-extractable P after two sewage sludge applications. A P surplus of *c.* 200 kg P/ha is required to raise the Olsen-extractable P status by *c.* 10 mg/kg, the exact amount depending on soil texture (Anon. 1985; Shepherd & Withers 1999). Therefore, the increases of 6 and 24 mg/kg from the two rates of sewage (133 and 523 kg P/ha over 2 years for the two application rates) are in good agreement with this. Applications at the higher sewage sludge rate produced measurable changes in total soil P also.

Phosphorus leaching

The liquid applied each year with the sewage sludge increased drainage and would, if practised over a sufficiently large area, increase aquifer recharge. This would be of benefit if the extra drainage was not contaminated with additional N or P. We did not measure N leaching, but would anticipate large losses in this experiment in the absence of a crop to utilize the applied ammonium-N.

Levels of P in the drainage from the untreated control soils were generally small and close to our analytical limits of detection. This confirms the findings of Shepherd & Withers (1999) that, for soils of this P status, downward movement of P is not a major loss pathway. Furthermore, we were unable to detect a significant increase in leaching from the lower

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rate applications of sewage sludge although they did increase topsoil P content. The Olsen-extractable P status was well below the 60 mg/kg threshold suggested by Heckrath *et al*. (1995) as the threshold for significant P loss. Total losses, and the average concentration, over the 3 years show conclusively that the single application rate of sewage sludge had no effect on P leaching. Similar results with sewage sludge were reported by Lindo *et al*. (1993), albeit on heavier textured soils. Sommers *et al*. (1979) found little P movement from the topsoil of a clay soil but measured significant leaching on a sandy soil that had received large amounts of municipal wastewater (1700 kg P/ha), well in excess of that applied in our experiment. Whereas others have implicated movement of additional organically bound P from manures as a mechanism for increased P leaching (Hannapel *et al*. 1964; Shand *et al*. 1994; Chardon *et al*. 1997), we measured no significant increases in TP from the single rate sewage sludge applications. This could be because liquid digested sewage sludge contains relatively little organic P (Withers 1998).

Data at the higher sewage sludge rate were more variable and although we were limited in replication because of the lysimeter installation, there was an indication of increased TDP and TP losses. This would support the suggestion of some organic P movement since MRP losses did not increase (and average MRP concentrations declined due to the dilution effect). However, the application rate that we tested was an extreme one and outside the UK Code of Good Agricultural Practice (Anon. 1998), particularly in the absence of any crop P uptake.

CONCLUSION

Regular sewage sludge applications in the absence of growing crops represented a situation of accelerated P inputs. However, despite the increase in soil P status we were unable to measure increased P leaching losses at application rates within the current UK Code of Practice. Phosphorus concentrations in the drainage, in general, were small suggesting that downward movement of P from sewage sludge is not a major loss pathway in sandy soils moderately well supplied with phosphorus. However, it should be stressed that this experiment measured losses on structureless soils with little chance of preferential pathways whereby P could leach before being fixed.

On soils with adequate P supplies it is important to adopt a fertilizer strategy that will not increase the P status and thereby increase leaching risk (and surface run-off). Balancing P inputs with crop P offtakes through the rotation will minimize this risk.

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