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Influence of soil phosphorus status, texture, pH and metal content on the efficacy of amendments to pig slurry in reducing phosphorus losses

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Abstract

Cost-effective strategies for using chemically amended organic fertilizers need to be developed to minimize nutrient losses in surface and groundwater. Coupling specific soil physical and chemical characteristics with amendment type could increase their effectiveness. This study investigated how water-extractable phosphorus (P) was affected by chemical amendments added to pig slurry and how this effect varied with soil properties. A 3-month incubation study was conducted on 18 different mineral soils, stored at 10 °C and 75% humidity and treated with unamended and amended slurry which was incorporated at a rate equivalent to 19 kg total P (TP)/ha. The amendments examined were commercial-grade liquid alum, applied at a rate of 0.88:1 [Al:TP], and commercial-grade liquid poly-aluminium chloride (PAC), applied at a rate of 0.72:1 [Al:TP]. These amendments were previously identified by the authors as being effective in reducing incidental losses of P. The efficacy of the amendments varied with the soil test P, the degree of P saturation (DPS) and the Mehlich aluminium, iron and calcium, but not soil texture. Chemical amendments were most effective in soils with DPS over approximately 20%. Due to their high cost, the incorporation of amendments into existing management practices can only be justified as part of a holistic management plan where soils have high DPS.

Keywords: Pig slurry, P-sorbing amendments, water framework directive, degree of P saturation, soil test phosphorus

Highlights

- Chemical amendment to organic fertilizer needs to be matched with the chemistry of the soil.
- The interaction between chemical amendment of pig slurry and soil chemistry was examined.
- The efficacy of the amendments depended on the initial soil test P and degree of P saturation.
- PAC appears to be the most suitable amendment with which to amend pig slurry.

Introduction

The long-term build-up of soil phosphorus (P) may lead to P losses in surface and subsurface pathways (Zhou *et al.*, 2016). Incidental losses in surface pathways take place when a rainfall event takes place shortly after slurry application and before slurry infiltrates the soil. Chronic losses are a long-term loss of P from soil as a result of a build-up in soil test P (STP), caused by repeated applications of inorganic fertilizers and manure in excess of crop requirements (Buda *et al.*, 2009; Schulte *et al.*, 2010). Pig (*Sus scrofa*) farms typically have high levels of STP due to their high stocking rates and P surplus, which results in an increased potential of chronic P losses in Critical Source Areas (CSAs; Doody *et al.*, 2012), where sources of P coincide with hydrologically active zones which are connected to waterbodies. As pig slurry is commonly landspread (Nolan *et al.*, 2012), various mitigation methods, mainly governed by legislation (exclusion zones, timing and magnitude of application), are used. To avoid losses of P, management practices such as avoiding P surpluses and improving P use efficiency should always take precedence. However, when this is not possible, chemical amendment of pig slurry may be an effective way

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to reduce incidental P losses. Previous research has demonstrated that chemical amendment of pig slurry is an effective means of reducing incidental P losses (Smith *et al.*, 2001, 2004; Dou *et al.*, 2003; O' Flynn *et al.*, 2012a,b, 2013a). However, no study has considered the role of soil P status, texture, pH or metal content on the efficacy of chemical amendments in pig slurry to reduce P losses.

The efficacy of chemical amendment of pig slurry to reduce incidental surface and subsurface losses of P has been considered previously (Smith *et al.*, 2001, 2004; O' Flynn *et al.*, 2012a,b, 2013a,b). O' Flynn *et al.* (2012b) found that poly-aluminium chloride ($AlCl_3$; PAC), followed by ferric chloride ($FeCl_3$) and alum (8% Al_2O_3, $Al_2(SO_4)_3.nH_2O$), was most effective in reducing surface losses of total phosphorus (TP) from laboratory run-off boxes when subjected to rainfall events with an intensity of 10.3 ± 0.15 mm/h at times ranging from 48 to 96 h following slurry application. However, O' Flynn *et al.* (2013a) observed that the efficacies of the chemical amendments in reducing losses appeared to be related to soil properties.

Due to their high cost, chemical amendments of pig slurry should only be used in targeted areas (e.g. CSAs), where they are most effective, and as part of a holistic slurry management strategy that includes amendment in storage to abate ammonia and greenhouse gas emissions. Research has continued to be conducted to improve mitigation measures in CSAs (Doody *et al.*, 2012; Thompson *et al.*, 2012; Thomas *et al.*, 2016). It is also vital to match the chemical amendment with an appropriate soil within CSAs, as their effectiveness is likely to differ depending on inherent physical and chemical make-up of the soil.

Before work can be advanced on the use of chemically amended pig slurry to agricultural grasslands, it is critical that soil characteristics are considered when examining the potential of amendments to reduce chronic P losses. To date, such studies have mainly considered one soil property at a time. For example, Kalbasi & Karthikeyan (2004) examined the effect of chemically amending dairy cattle slurry with alum, $FeCl_3$ or lime on silty loam soils with three different STP levels (12, 66 and 94 mg/kg Bray-1 P, respectively) in an incubation experiment conducted over 24 months. They found that the effect of chemical amendment depended on treatment type, P application rate and background STP level and also recommended that more work was needed to investigate the effectiveness of amendments in soils varying in textural and chemical characteristics. Moore & Edwards (2007) found that following long-term (7 yr) land application of alum-amended poultry litter on a silt loam soil, run-off P and water-extractable phosphorus (WEP) in soil was reduced in plots receiving alum-treated poultry manure. In an incubation study, Shreve *et al.* (1996) added unamended poultry litter and poultry litter amended with either alum (100 or 200 g/kg), lime (25 or 50 g/kg) or $FeSO_4$ (100 or 200 g/kg) to soils with pH values between 4.0 and 8.0. They found that both unamended and amended slurry significantly increased WEP compared to unamended soils, that amendments to slurry significantly reduced WEP and that an apparent equilibrium in WEP was attained 98 d after treatment. Previous research (Regan *et al.*, 2010) has shown a significant relationship between STP [based on WEP, Morgan's P (P_m) and Mehlich P (M3P)] and run-off dissolved reactive phosphorus (DRP). Therefore, it is essential that soil texture and availability of P in soil are considered when proposing potential methods to mitigate losses of P.

The hypothesis of this study was that the efficacy of the chemical amendments to reduce WEP in different soils varies with soil properties such as texture, metal content and degree of P saturation. This would potentially allow a soil to be matched to a specific chemical amendment to prevent P losses from a CSA. To address this hypothesis, this paper examined how WEP was affected by chemical amendments added to pig slurry and how the effect varied with soil properties.

Materials and methods

Slurry collection and characterization

Pig slurry was taken from an integrated pig unit in Teagasc Research Centre, Moorepark, Fermoy, Co. Cork, Rep. of Ireland, in November 2012. The sampling point was a valve on an outflow pipe between two holding tanks. To ensure a representative sample, this valve was turned on and left to run for a few minutes before taking a sample. The slurry was stored at 10 °C in a 25-litre drum for 3 days prior to testing. It was thoroughly mixed immediately prior to testing. The TP was determined using persulfate digestion (APHA, 2005). Ammonium-N (NH_4^+-N) was determined by adding 50 mL of slurry to 1 L of 0.1 M HCl, shaking for 30 min at 200 rpm, filtering through 0.45 μm Whatman filter paper and analysing using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland) (APHA, 2005). Slurry pH was determined using a pH probe (WTW, Germany). Dry matter (DM) content was determined by drying at 105 °C for 24 h. The physical and chemical characteristics of the pig slurry used in this experiment and characteristic values of pig slurry from other farms in Ireland are presented in Table 1.

Pig slurry amendment

Amendments for this study were chosen based on effectiveness of P sequestration and feasibility criterion (cost and potential environmental impediments) determined by O' Flynn *et al.* (2012a,b). The amendment rates, which were applied on a stoichiometric basis, were as follows: (i) commercial-grade liquid alum (8% Al_2O_3) applied at a rate

Table 1 Characteristics of the pig slurry used in this experiment and of other farms in Ireland

TP	NH_4^+-N			
(mg/L)		pH	DM (%)	References
525 ± 27	2171 ± 30	7.3 ± 0.1	5.1 ± 0.3	The current study
800				S.I. 610 of 2010
1630			5.8	McCutcheon (1997)[a]

TP, total P; NH_4-N, ammonium-N. [a]Values converted to mg/L assuming densities of 1 kg/L.

of 0.88:1 [Al:TP] and (ii) commercial-grade liquid PAC (10% Al_2O_3) applied at a rate of 0.72:1 [Al:TP].

Soil collection and analysis

Samples of the plough layer (top 0.2 m), selected to represent a variety of STP and textural classes, were collected from 18 sites across Ireland (Table 2). The soils were air-dried, sieved (<2 mm) and thoroughly mixed. Soil samples (n = 3) were oven-dried at 40 °C for 72 h, crushed to pass a 2-mm sieve and analysed for P_m using Morgan's extracting solution (Morgan, 1941), and M3P using M3 extracting solution (Mehlich, 1984). Mehlich-3 Al and iron (Fe) (M3Al and M3Fe) were used to estimate degree of P saturation (DPS) in the soils (Maguire & Sims, 2002):

$$\mathrm{DPS}(\%) = \frac{\mathrm{M3P} \times 100}{\mathrm{M3Al} + \mathrm{M3Fe}} \quad (1)$$

where M3P, M3Al and M3Fe are the molar concentration of the Mehlich-3 extractable P, Al and Fe (mmol/kg), respectively. Mehlich-3 calcium (Ca), cobalt (Co), copper (Cu), potassium (K), magnesium (Mg), manganese (Mn) and zinc (Zn) were also analysed using M3 extracting solution (Mehlich, 1984). Soil WEP (100:1 deionized water: soil) was determined after McDowell & Sharpley (2001). Soil pH (n = 3) was determined using a pH probe (WTW, Germany) and a 2:1 ratio of deionized water-to-soil, and the soil organic matter (SOM) was determined using loss on ignition (B.S. 1377-3; British Standards Institution 1990). The particle size distribution was determined using a sieving and pipette method (B.S.1377-2; British Standards Institution 1990).

Incubation experiment

Four treatments were examined in quadruplicate (n = 4): (i) unamended soil, (ii) soil with unamended slurry (the study control), (iii) soil with alum-amended slurry and (iv) soil with PAC-amended slurry. One hundred gram samples of sieved (<2 mm), oven-dried soil were placed in 0.5-L Perspex containers (70 × 70 mm base). Slurry or amended slurry was added at a rate equivalent to 19 kg TP/ha and mixed thoroughly before enough deionized water required to achieve 80% water-filled pore space (WFPS) was added. Less deionized water was added to soils receiving unamended and amended slurry, to take account of the water present in slurry. The soil was then compacted to achieve a bulk density (ρ_b) of 1.2 g/cm^3. The containers were covered with Parafilm™, perforated to allow air to circulate and were stored in a controlled environment for 3 months at 10 °C and 75% humidity. During the study, containers were weighed intermittently and water was added to ensure that approximately 80% WFPS was maintained. After 3 months, soils were destructed, oven-dried at 40 °C for 72 h and crushed to pass a 2-mm sieve before being analysed for WEP, P_m, pH, M3P and M3Al, Ca, Fe, Co, Cu, K, Mg, Mn and Zn.

Statistical analysis

The data were analysed in SPSS 20 (IBM SPSS Statistics 20 Core System) using a general linear model. Mean values of WEP, P_m, M3P, pH, DPS, M3Al, Fe, Ca, Co, Cu, K, Mg, Mn and Zn were analysed in a multivariate Tukey analysis when unamended soil, soil plus slurry (the study control) and soil plus slurry treated with alum and PAC were applied. The fixed effects were soil type and slurry treatment, and the data met the normal distributional assumptions required. Probability values of $P > 0.05$ were deemed not to be significant.

Results

Water-extractable phosphorus

There was a significant interaction between soil and treatment, but not soil texture, for WEP ($P < 0.001$). The addition of unamended slurry to soil resulted in increased levels of WEP (Table 3). The addition of alum and PAC resulted in reductions of soil WEP. Within individual soils, there were no statistically significant differences between the levels of WEP in soil treated with either alum or PAC-amended slurry. Averaged across all soils, the levels of WEP (in decreasing order of WEP) were as follows: unamended slurry > unamended soil > PAC > alum. Both amendments resulted in significantly decreased ($P < 0.05$) soil WEP compared to unamended slurry. As the DPS increased in the soil above a threshold of approximately 20%, the WEP of the amended soil reduced for both treatments, and there was no significant difference between them (Figure 1).

Soil pH

There was a significant interaction between soil and treatment, but not soil texture, for pH ($P < 0.001$). Averaged

Table 2 Soil physical and chemical properties before commencement of the incubation experiment. Soils placed in ascending order of degree of phosphorus saturation (DPS)

Soil	Sand %	Silt %	Clay %	Texture	DPS[1] %	Soil pH	WEP[2] mg/kg	P_m[3] mg/L	P index[4]	M3P[5] mg/kg	M3Al[6] mg/kg	M3Ca[7] mg/kg	M3Co[8] mg/kg	M3Cu[9] mg/kg	M3Fe[10] mg/kg	M3K[11] mg/kg	M3Mg[12] mg/kg	M3Mn[13] mg/kg	M3Zn[14] mg/kg	Soil org matter, %
C	38.1	39.8	22.1	Loam	3.0	5.8	4.9	9.5	4	127	910	1304	0.5	2.2	129	77	122	163	9.8	8.7
G	57	31.5	11.5	Sandy loam	6.0	4.7	9.1	6.3	3	53	542	1224	0.1	2.9	229	72	135	140	6.3	8.9
D	68.2	20.6	11.1	Sandy loam	6.1	5.1	6.7	1.4	1	137	966	1383	0.5	2.5	138	64	282	162	10.6	9.3
I	27.3	50	22.8	Silt loam	7.1	6.6	11.8	7.5	3	124	744	955	0.1	0.2	270	325	167	50	3.9	10.4
A	26.8	48.4	24.8	Loam	7.5	5.4	2.2	8.3	4	69	749	1867	0.3	3.0	122	229	169	146	6.7	14.8
H	44.7	28.6	26.6	Clay loam	7.5	5.2	10.1	2.3	1	38	1003	1310	0.2	7.1	226	214	126	202	2.6	13.6
E	75.2	15.3	9.5	Loamy sand	11.3	4.7	7.8	6.9	3	50	676	2181	0.4	3.6	106	110	121	138	10.2	6.1
Q	43.6	34.9	21.4	Loam	11.3	4.9	30.4	22.5	4	119	540	1520	0.1	3.7	167	219	383	59	6.4	11.5
F	29	48	23	Loam	11.6	4.9	9.0	5.9	3	52	688	2181	0.4	3.6	108	428	174	141	10.6	12.0
L	50.3	29.6	20	Loam	11.6	5.7	16.0	12.1	4	78	515	1343	0.4	4.5	182	247	149	122	4.4	12.2
M	68.8	23.1	8.1	Sandy loam	11.8	5.1	17.2	13.9	4	91	519	2459	0.1	3.6	321	112	128	83	8.9	11.0
B	33.5	43.8	22.7	Loam	11.9	4.9	4.2	4.1	2	139	947	1332	0.6	2.1	135	56	123	190	11.1	10.6
K	40.7	43.4	15.9	Loam	12.3	5.7	13.7	10.1	4	75	808	1905	0.3	3.2	116	367	176	154	7.0	11.2
N	41.2	42	16.8	Loam	12.5	5.4	20.9	14.8	4	125	746	970	0.0	0.2	261	143	164	49	3.9	11.2
J	22.7	42.3	35.1	Clay loam	15.8	5.5	12.7	2.6	1	129	907	1347	0.5	2.8	127	77	87	159	10.9	17.5
P	36.2	39.6	24.2	Loam	16.7	4.8	27.5	23.5	4	196	702	1349	0.1	5.6	212	330	334	64	6.6	6.7
O	46.2	36.9	16.9	Loam	21.3	4.9	23.0	28.5	4	204	1042	2467	0.3	13.3	171	323	239	205	10.6	9.2
R	50.2	32.9	17	Loam	41.6	5.0	37.3	30.8	4	240	343	1884	0.0	12.7	329	354	269	25	25.9	8.3

[1]Degree of phosphorus saturation; [2]Water-extractable phosphorus; [3]Morgan's phosphorus; [4]Soil phosphorus ranges for grassland as per S.I. 610 of 2010; [5]Mehlich-3 phosphorus; [6]Mehlich-3 aluminium; [7]Mehlich-3 calcium; [8]Mehlich-3 cobalt; [9]Mehlich-3 copper; [10]Mehlich-3 iron; [11]Mehlich-3 potassium; [12]Mehlich-3 magnesium; [13]Mehlich-3 manganese; [14]Mehlich-3 zinc.

across all soils, the addition of unamended slurry led to significant ($P < 0.001$) increases in pH compared to unamended soil (Table 4). Soils treated with amended slurry were not significantly different to unamended slurry, but were significantly different ($P < 0.001$) to unamended soil. The average pH for alum and PAC treatments was 5.60 and 5.73, respectively. There was a strong correlation between soil pH and WEP, M3Al, M3Ca, M3P, DPS and P_m ($P < 0.001$).

Table 3 Soil water-extractable P (mg/kg), including standard deviation (in parenthesis), for each soil type and treatment after incubation

	Treatment			
Soil	Unamended soil	Soil plus slurry	Alum	PAC
H	15.3 (2.1)	18.5 (0.7)	10.9 (0.5)	12.0 (0.9)
E	9.1 (0.5)	10.6 (1.1)	6.0 (0.5)	7.3 (0.5)
F	6.0 (2.0)	11.8 (1.6)	9.2 (1.1)	11.8 (1.5)
G	12.4 (1.3)	18.8 (1.4)	15.7 (1.0)	14.8 (1.2)
A	2.6 (0.1)	3.8 (0.6)	2.3 (0.2)	3.2 (0.3)
K	12.9 (0.9)	19.7 (0.5)	14.0 (1.4)	15.4 (1.2)
M	24.9 (1.6)	24.6 (1.3)	20.5 (2.1)	22.5 (1.1)
B	4.7 (0.7)	7.4 (0.3)	4.0 (0.4)	5.7 (0.3)
L	16.9 (0.4)	21.0 (1.6)	13.2 (0.4)	15.0 (1.2)
C	6.8 (1.0)	8.6 (1.2)	5.2 (1.2)	6.7 (0.1)
I	11.4 (0.7)	26.3 (1.1)	15.4 (0.8)	15.8 (0.8)
D	9.1 (0.6)	15.6 (2.2)	8.1 (0.9)	10.7 (1.3)
N	23.5 (1.9)	27.9 (2.1)	19.5 (2.3)	20.7 (2.8)
J	22.4 (1.5)	27.3 (1.7)	18.7 (2.2)	24.1 (1.6)
Q	22.1 (1.5)	26.8 (1.3)	18.4 (0.6)	19.0 (2.7)
O	40.5 (1.4)	40.3 (2.9)	33.3 (2.4)	26.7 (1.2)
P	44.5 (1.9)	42.3 (1.4)	34.8 (1.3)	32.9 (4.4)
R	45.7 (3.1)	54.0 (2.1)	31.8 (0.4)	37.7 (5.3)

Morgan's phosphorus and Mehlich-3 phosphorus

Figure 2 shows the relationship between P_m and M3P for each treatment. There was a positive linear relationship between P_m and M3P for all treatments ($P < 0.001$), and a significant interaction between soil and treatment, but not texture, for the P_m and M3P of the soil ($P < 0.001$).

Extractable metal concentrations

There was a positive correlation between M3Al and WEP, M3Fe, M3P, DPS, pH and P_m ($P < 0.001$); between M3Fe and WEP, M3Al, M3P, DPS, M3Ca and P_m ($P < 0.001$); and between M3Ca and WEP, M3Fe, pH and P_m ($P < 0.001$). Averaged across all soils, the use of alum-amended slurry led to a significant ($P < 0.01$) increase in M3Al compared to PAC-amended slurry. Slurry treatments resulted in significant ($P < 0.05$) decreases in M3Fe compared to unamended soil, but addition of either amendment did not lead to significant differences compared to unamended slurry. There were also no observed differences between slurry treatments for M3Ca, Co, Cu, K, Mg, Mn and Zn, which indicated that the addition of amendments did not adversely affect the availability of these metals and nutrients to plants.

Discussion

The DPS is recognized as an accurate indicator of the potential of P loss from soils to the environment in surface run-off events (Bortolon *et al*., 2016). It has been estimated that above a critical DPS of approximately 25% P loss in run-off is more likely (Schoumans & Chardon, 2015). In the current study, it was noted that above a threshold of

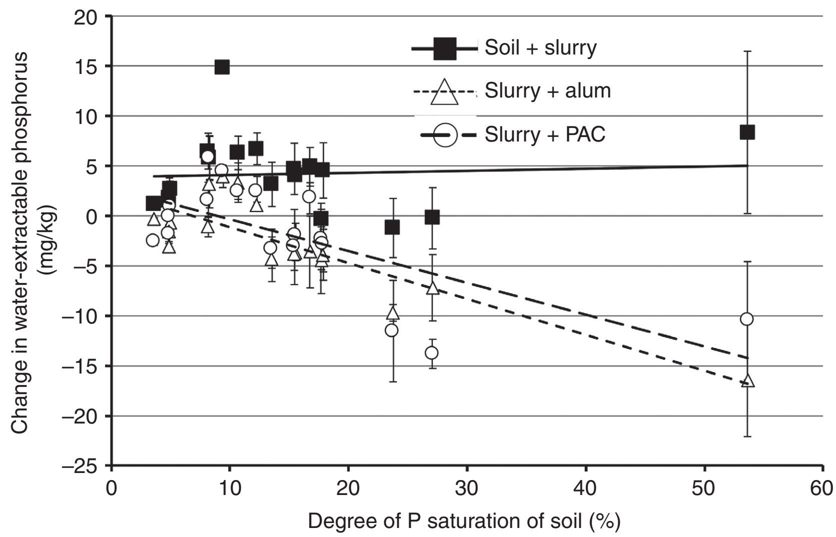

Figure 1 Relationship between degree of phosphorus saturation (DPS) (%) of the soils and the change in the water-extractable phosphorus (WEP) after 3 months of incubation. The plotted points are the means and 95% confidence intervals of each treatment.

Table 4 Soil pH for each soil type and treatment. Values in parenthesis represent changes in pH from the unamended soil

Soil	Treatment						
	Unamended soil	Soil plus slurry		Alum		PAC	
H	5.0[a]	5.7[b]	(+0.7)	5.8[b]	(+0.8)	5.7[b]	(+0.7)
E	5.2[a]	6.1[b]	(+0.9)	5.8[b]	(+0.6)	6.1[b]	(+0.9)
F	5.1[a]	6.0[b]	(+0.9)	6.0[b]	(+0.9)	6.2[c]	(+1.1)
G	4.8[a]	5.9[b]	(+1.1)	5.6[c]	(+0.8)	5.7[d]	(+0.9)
A	5.2[a]	5.0[a]	(−0.2)	5.0[a]	(−0.1)	5.0[a]	(−0.2)
K	5.1[a]	5.4[ab]	(+0.3)	6.0[b]	(+0.9)	5.3[ab]	(+0.2)
M	5.7[a]	5.0[a]	(−0.7)	45.0[a]	(−0.8)	4.9[a]	(−0.8)
B	4.9[a]	5.1[b]	(+0.2)	5.1[b]	(+0.2)	5.3[c]	(+0.4)
L	5.3[a]	5.8[b]	(+0.4)	5.8[b]	(+0.5)	5.8[b]	(+0.5)
C	6.4[a]	6.5[a]	(+0.0)	5.9[b]	(−0.5)	6.5[a]	(+0.0)
I	5.3[a]	5.5[ab]	(+0.2)	5.3[a]	(−0.0)	5.7[b]	(+0.4)
D	5.2[a]	6.4[b]	(+0.2)	5.8[ab]	(+0.6)	5.9[ab]	(+0.7)
N	5.3[a]	5.4[ab]	(+0.1)	5.6[ab]	(+0.3)	5.6[b]	(+0.3)
J	6.1[a]	5.6[ab]	(−0.5)	5.2[b]	(−0.9)	5.5[b]	(−0.7)
Q	5.0[a]	5.4[a]	(+0.3)	5.3[a]	(+0.3)	5.8[b]	(+0.7)
O	5.1[a]	5.6[b]	(+0.6)	5.5[c]	(+0.5)	5.6[c]	(+0.5)
P	5.3[a]	6.0[b]	(+0.8)	6.1[b]	(+0.8)	6.2[b]	(+0.9)
R	5.4[a]	6.4[b]	(+0.9)	6.1[b]	(+0.6)	6.4[b]	(+0.9)

[abcd]Means in a row, which do not share a superscript, were significantly different ($P < 0.05$).

approximately 20%, WEP increased upon application of slurry to the soil. The amendments performed differently across different soils and were most effective in soils with a high DPS. In these soils, there is a need to increase the capacity of the soil to store P. In soils with a low DPS, there is already an abundance of sites to attenuate P and apart from a potential reduction in incidental losses of nutrients and suspended sediment in run-off (O' Flynn *et al.*, 2012b), chemical amendments to manure appear to have limited long-term benefits. The DPS of the soils before incubation ranged from 3 to 42%. After incubation, there were small differences in the DPS of the unamended soil, which may have been due to releases of additional extractable Al and Fe during processing and incubation.

The P_m of the soils selected in the current study ranged from 1.4 mg/L (classified in Ireland as P index 1 soils (S.I. 610 of 2010), which are unlikely to release P in run-off events) to 31 mg/L (P index 4 soils, which are highly likely to release P and onto which P application in fertilizer is prohibited) (Table 2). Regan *et al.* (2010) estimated that losses of DRP in excess of 30 μg/L may occur in soils with a P_m above 10 mg/L. Concentrations of DRP in excess of 30 μg/L may lead to eutrophication. Similar to the DPS results, both chemical amendments were equally effective in reducing WEP and, based on the study of Regan *et al.* (2010), the loss of DRP in run-off. Below a P_m of 10 mg/L, both chemical amendments had negligible impact on WEP, whereas slurry had greatest impact, increasing WEP by up to 15 mg/kg compared to unamended soil (data not shown).

Previous work of the authors identified PAC and alum as effective amendments to pig slurry to reduce DRP in surface run-off (O' Flynn *et al.*, 2012a,b, 2013a) and leaching (O' Flynn *et al.*, 2013b) from grassed soil. However, due to the high cost of amendments, their incorporation into an existing holistic nutrient management regime can only be justified on a targeted basis, in particular soils with high hydrological transfer potential to surface water, that is CSAs. Phosphorus losses from such high-risk source areas have the potential to become exported along the transfer continuum within a catchment and may adversely affect surface and groundwater quality (Wall *et al.*, 2011). Once an area has been identified as a CSA, an assessment must be conducted based on each individual soil present to determine whether chemical amendment is an appropriate mitigation measure. For each soil, the most suitable amendment and addition rate must be established before proceeding. The current study advances the previous work by suggesting that the DPS of a soil is an important parameter to consider if chemically amending a

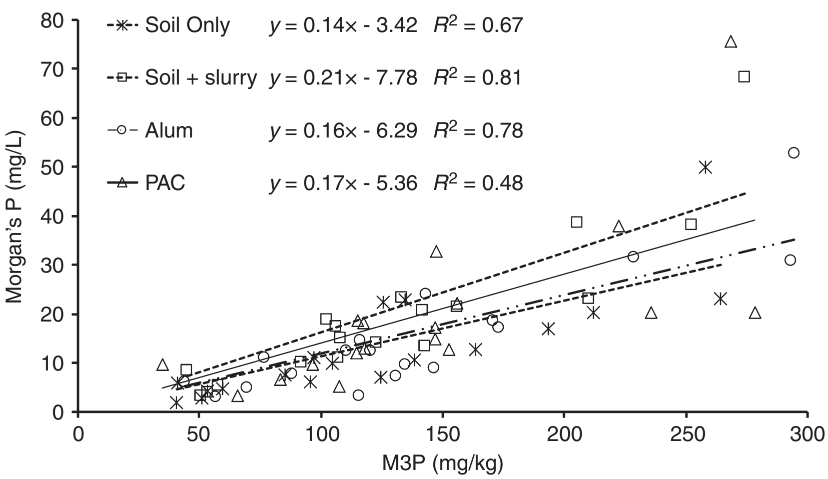

Figure 2 Morgan's P (mg/L) versus Mehlich-3 P (mg/kg) for each treatment.

wastewater prior to land application in a CSA. Losses from a CSA can therefore be protected during sensitive periods, especially with respect to episodic rainfall events within the 48-h period after application.

It must also be borne in mind that CSAs are temporally variable in size and shape, and delineation is a difficult task, but can form part of cost-effective programme of measures (Doody *et al*., 2012). At present, there is no provision in legislation to landspread any of these amendments in Europe and if chemical amendments were to be used, a regulatory framework would need to be introduced by the relevant bodies. Future research must take place at field and catchment scale under real-life conditions, which cannot be replicated at laboratory scale, and take account of such factors as flow dynamics, the presence of a water table and extreme weather conditions.

Conclusions

The addition of slurry increased soil WEP and pH across all soils examined in this study. The efficacy of amendments to slurry to reduce WEP depended on the initial soil STP and DPS, M3Al, M3Fe and M3Ca, which indicated the importance of identifying appropriate amendments for the diverse range of soil properties and their P status that may be present on a farm. The texture of the soil did not influence the efficacy of the amendments. Commercial-grade liquid poly-aluminium chloride and alum were both equally effective in reducing WEP, but were most effective in soils with a DPS > 20%. Due to their high cost, the incorporation of amendments into existing management practices could only be justified in a targeted manner in areas such as CSAs, which have a high risk of P loss. Chemical amendment of pig slurry is less attractive than avoiding excess P balances and improving P use efficiency. However, chemical amendment of pig slurry could be justified based on cost as part of a holistic management strategy, where amendment abates ammonia emissions during storage and losses in run-off when applied to land. Future research must examine at field and catchment scale over a range of soils, how amendments affect nutrient balances under real-life conditions which cannot be replicated in laboratory testing.

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