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Potential phosphorus leaching from sandy topsoils with different fertilizer histories before and after application of pig slurry

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Abstract

This study investigated the effects of historical long-term and recent single applications of pig slurry on phosphorus (P) leaching from intact columns of two sandy topsoils (Mellby and Böslid). The soils had similar physical properties, but different soil P status (ammonium lactate-extractable P; P-AL) and degree of P saturation (DPS-AL). Mellby had P-AL of 220–280 mg/kg and DPS-AL of 32–42%, which was higher than for Böslid (P-AL 140 mg/kg and DPS 21%). The study investigated the effects since 1983 of four treatments with different fertilizer histories, in summary high (HighSlurryMellby) and low (LowSlurryMellby) rates of pig slurry and mineral P (MinMellby) applications at Mellby and mineral P application at Böslid (MinBöslid). The columns were irrigated in the laboratory five times before and five times after a single application of pig slurry (22 kg P/ha). Concentrations of dissolved reactive P (DRP), dissolved organic P and total-P (TP) in leachate and loads were significantly higher ($P < 0.005$) from the treatments at Mellby than those at Böslid. TP concentrations followed the trend: HighSlurryMellby (0.57–0.59 mg/L) > MinMellby (0.41–0.49 mg/L) > LowSlurryMellby (0.31–0.36 mg/L) > MinBöslid (0.14–0.15 mg/L), both before and after the single slurry application. DRP concentrations in leachate were positively correlated with DPS-AL values in the topsoil ($R^2 = 0.95$, $P < 0.0001$) and increased with greater DPS-AL values after the single slurry application ($R^2 = 0.79$, $P < 0.0001$). Thus, DPS-AL can be an appropriate indicator of P leaching risk from sandy soils. Moreover, the build-up of soil P because of long-term repeated manure applications seems to be more important for potential P losses than a single manure application.

Keywords: Manure management, pig slurry, phosphorus leaching, intact topsoil columns, soil phosphorus status, degree of phosphorus saturation

Introduction

Managing animal manure is an indispensable part of sustainable nutrient management, which is essential for combating the environmental threat of accelerating eutrophication of water bodies (Smith *et al*., 1998; Maguire *et al*., 2009). Enhanced risk of nutrient loss from soils treated with animal manure has been demonstrated in many studies (Sharpley *et al*., 1999). This is of particular concern in regions with more intensive and specialized livestock production, where application of manure exceeding crop requirements often occurs for a long time and creates a soil P surplus (Bergström *et al*., 2005). In Sweden, farmers are not allowed to apply more than 110 kg P/ha with animal manure during a 5-yr period, that is, on average 22 kg P/ha/yr as a mean for the entire farm area to ensure good water quality (SBA, 2010).

Long-term repeated applications of manure contribute to high soil P status and saturation, which can increase the risk of P loss. Elevated soil P content correlates with leaching of dissolved reactive P (DRP) in tile drains (Heckrath *et al*., 1995) and in lysimeters (Hesketh & Brookes, 2000). Long-term manure P applications in large amounts exceeding crop uptake needs can also be a source of downward movement of P through the soil (Koopmans *et al*., 2007). High P concentrations in soil increase the risk of P loss to drainage water and groundwater when the P sorption capacity of soil approaches saturation (Schoumans & Groenendijk, 2000). For instance, Nelson *et al*. (2005) observed elevated P concentrations in soil and soil solution below the root zone in

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sandy soils where pig slurry had been applied at a rate at least of 35 kg excess P/ha/yr over 20 yr.

Recently applied P may also result in high P loss. Withers *et al.* (2003) review incidental P loss via surface and subsurface runoff from a large number of plot and field experiments when rainfall occurred directly after the spreading of fertilizers or excretion of manure on the soil surface. Many of the studies demonstrate very high P concentrations and significantly increased P loads in surface and subsurface runoff after fertilizer or manure application with peak concentrations and loads in the first runoff. However, such incidental P losses could be reduced by limiting the application rates of P and incorporating fertilizers or manure in soil soon after application.

The importance of site-specific soil properties for risk assessments of P loss has been demonstrated (Djodjic *et al.*, 2004). For instance, Glæsner *et al.* (2011) stress that soil texture and therefore active flow volume are of great importance in affecting P leaching in soil associated with manure application. For sandy soils, P input to soil and measurements of soil P content should be combined with measurements of other soil properties such as P sorption capacity (Liu *et al.*, 2012), and chemical conditions in the subsoil should also be considered (Ulén, 2006). The degree of P saturation (DPS), interpreted as the percentage of a soil's P adsorption capacity already occupied by P (van der Zee & van Riemsdijk, 1988), has been widely used to predict the potential of soil to adsorb and release P (Gburek *et al.*, 2005). Strong correlations between DPS and dissolved P in various types of solutions have been found from laboratory experiments (Beauchemin *et al.*, 1996; Hooda *et al.*, 2000), in surface runoff (Pote *et al.*, 1996; Tarkalson & Mikkelsen, 2004), and in leachate from lysimeters (Leinweber *et al.*, 1999). In Sweden, DPS is suggested to be determined based on the ammonium lactate extraction method (Egnér *et al.*, 1960) and is expressed in the ratio between extracted P-AL (for estimating plant-available P in soil) and aluminium and iron in the same extract (Al−AL + Fe−AL) on a molar basis (Ulén, 2006).

The overall objective of the present study was to investigate the effects of pig slurry application on P leaching from intact sandy topsoil columns under intensive rainfall conditions. Specific objectives were to (i) estimate the effects of long-term repeated applications of pig slurry at high rates on P leaching; (ii) evaluate the effect of a single dose of pig slurry on P leaching; and (iii) determine how this is affected by soil P content and DPS.

Materials and methods

Sites and soil column sampling

A total of 16 intact topsoil columns (0–0.2 m depth) were collected from four treatments in two experimental fields. The two sites, Mellby and Böslid, are 15 km apart in the coastal region of southwest Sweden where the soils consist mainly of sand deposits. This part of Sweden is subject to intensive agricultural production and high precipitation. The two sites have the same soil type (loamy sand) and similar soil texture, with 6–7% clay and a total carbon content of 2.4–3.1%. Soil texture and some physical properties of the topsoil are given in Table 1. Both soils are homogeneous without visible aggregates or cracks.

Table 1 Selected soil physical properties at the two experimental sites. Measurements were taken in 1988 for Mellby (Johnsson (1991)) and in 2003 for Böslid.

	Mellby		Böslid	
	0–0.2 m	0.2–1.0 m	0–0.2 m	0.2–1.0 m
Soil texture (%)				
Clay (< 0.002 mm)	5.9	1.7	7.0	1.0
Silt (0.002–0.0625 mm)	10.3	1.1	5.2	0
Sand (0.0625–2 mm)	83.7	97.2	87.8	99.0
Dry bulk density (kg/m^3)	1450	–	1340	–
Pore volume (%)	44.5	–	47.3	–
Water content at different matric tensions (%)				
0.05 m	40.7	–	42.4	–
0.50 m	36.3	–	38.2	–
1.50 m	29.7	–	24.8	–
5.00 m	24.5	–	21.0	–

The Mellby experimental field (56°29′N, 13°00′E) has 10 separate tile-drained plots treated with different application rates of manure in combination with and without catch crops since 1983. Overall, this field has high soil P and DPS status (Table 2) because the field received large amounts of manure for a long time before the field experiment started. A detailed description of this field is given by Liu *et al.* (2012). Four replicate intact soil columns were collected from each of the three treatments (without catch crops) at the Mellby site, supplied with either mineral fertilizer (MinMellby), a low rate of pig slurry (LowSlurryMellby), or a high rate of pig slurry (HighSlurryMellby). Phosphorus application rates since the experiment started in 1983 are shown in Table 3. The low rate of pig slurry represents the amount produced on a farm with the maximum permissible animal density in Sweden (1.4 large animal units per hectare). The high application rate is approximately twice the low rate. The application rate of P and N in the MinMellby treatment aimed to meet the requirements for crop growth in the region (on average 18 and 65 kg P/ha for spring cereals and potatoes, respectively). This meant that there were some additional applications of mineral P also in slurry treatments, especially for potatoes, which were grown about every sixth year. Other crops in the crop rotation were predominantly spring barley and oats. The removal of P with harvested biomass was about 19 and 15 kg P/ha for spring cereals and potatoes, respectively. The plots

Table 2 Selected chemical properties of the topsoil (0–30 cm) in plots from which the intact soil columns were taken. AL refers to extraction with ammonium lactate

Site	Treatment	pH (H_2O)	Total-C	WEP	P-HCl	P-AL	Fe-AL	Al-AL	Ca-AL	DPS-AL
			(%)	(mg/kg)						(%)
Mellby	LowSlurryMellby	6.2	2.6	4.6	690	220	240	490	1800	32
	HighSlurryMellby	6.6	3.1	6.0	730	280	200	480	2470	42
	MinMellby	6.4	2.4	4.1	680	240	170	530	2010	34
Böslid	MinBöslid	6.0	2.5	1.3	–	140	140	540	2870	21

DPS, degree of P saturation; WEP, water-extractable P.

Table 3 Experimental long-term repeated P applications to the plots from which the intact soil columns were taken

Site	Soil P & DPS status	Treatment	Experimental P application (kg/ha/yr)	Description
Start in 1983				
Mellby	High	LowSlurryMellby	30	On average 24 kg P/ha/yr with pig slurry and 6 kg with mineral P
		HighSlurryMellby	44	On average 41 kg P/ha/yr with pig slurry and 3 kg with mineral P
		MinMellby	22	Only mineral P applications
Start in 2003				
Böslid	Low	MinBöslid	18	Only mineral P applications

were mouldboard ploughed in autumn. The pig slurry and mineral P were applied and incorporated by harrowing before sowing in the spring of each year.

The Böslid experimental field (56°35′N, 12°56′E) was constructed with separately tile-drained experimental plots in 2002 (Aronsson *et al*., 2011). This field did not receive any manure for many years. It has a moderate level of soil P and DPS status in the context of southern Sweden (Table 2), but lower than the Mellby field, so these parameters are referred to as 'low' in this study. The plot in which the four intact soil columns were taken was treated with 18 kg/ha/yr mineral P during 2003–2009 (Table 3).

The intact topsoil columns were collected from both sites at the beginning of September 2009 when the crops had been harvested, but before ploughing. The four replicate soil columns taken per plot were distributed evenly along one of the diagonals of the plot 5–8 m from each other. A 20-cm-long PVC cylinder (inner diameter 18.8 cm) with a sharp steel cutting ring at the bottom end and a hard wooden board at the top was placed on the ground. The cylinder was pressed gently into the soil by the mechanical force of a tractor front-loader until the cylinder top was about 1 cm from the soil surface. The column was then manually excavated with care. The columns were stored in a cool room with a stable temperature of 4 °C until the laboratory leaching experiment started, 8 months later.

Rain simulator

For irrigation of the soil columns, two indoor mobile sprinkler systems of stainless steel were used (Figure 1). Each of these systems had places for 10 columns on a bench at a fixed height. The sprinkler heads (one for each column, 40 cm apart) could be raised to 105 cm above the bench, with sufficient spacing to avoid interference between the spreading areas of the sprinklers. Sliding doors of plexiglass were fitted in the frame of the system to prevent wind turbulence during irrigation. For irrigation, hydraulic atomizing fine spray nozzles with a drop diameter of 0.07–0.10 mm and a capacity of 7 L/h were used.

The tap water used for irrigation had the following composition: pH = 8.2, EC = 45 mS/m, 106 mg HCO_3/L, 35 mg Ca/L, 15 mg Mg/L, 20 mg Na/L, 40 mg SO_4/L, 40 mg Cl/L, 0.02 mg TP/L and 1.6 mg TN/L. The water passed through a filter before entering the irrigation system where pressure can be adjusted to between 0 and 600 kPa. The desired irrigation intensity (mm/h) was achieved by adjustment of the working time for the sprinklers using a datalogger. In the logger program that could be set for each sprinkler, the working interval of the sprinklers was specified as the number of seconds on and off. As both water pressure and the height of the sprinklers above the soil surface affected the spreading area and amount of water applied on

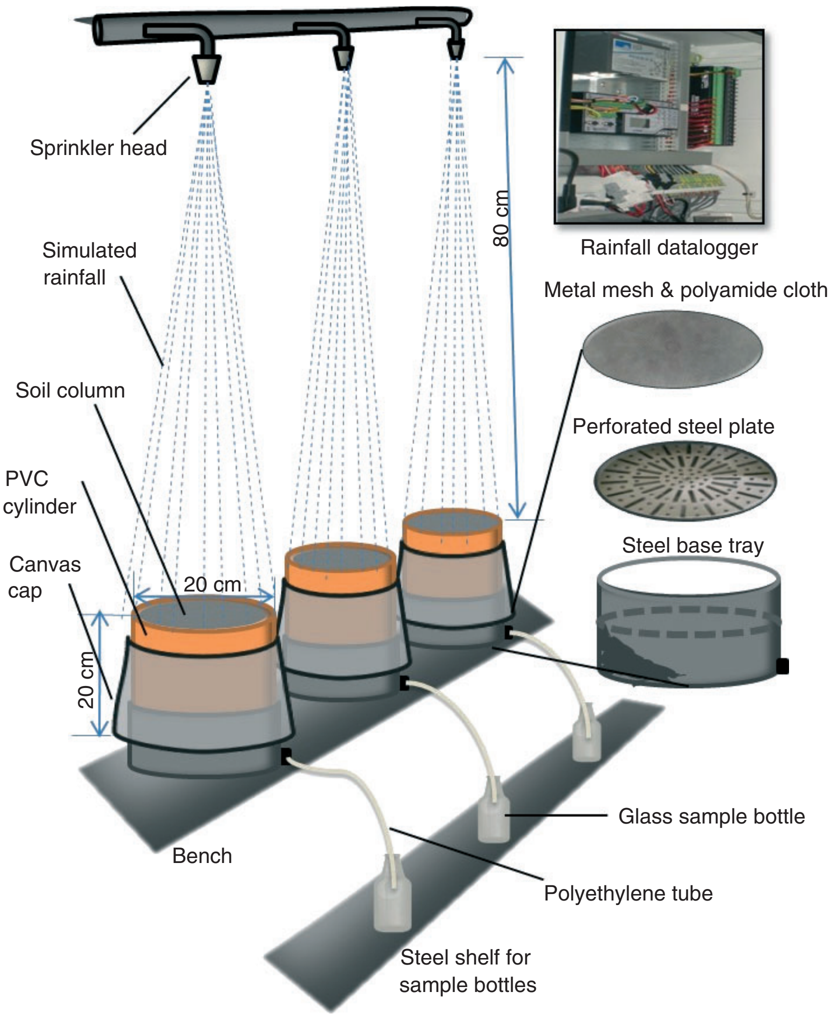

Figure 1 Rain simulator and the equipment for leaching studies with soil columns.

the soil columns, the system was calibrated before the start. The design permitted excess water that was not applied to the columns to drain away on a sloping groove.

The sprinklers were lifted to the highest position with a vertical distance of 80 cm to the soil surface. Each soil column, the bottom of which was prepared by carefully cutting off excess soil with a knife and removing loose particles with a vacuum cleaner, was fitted with a polyamide cloth filter (50 μm) and placed on a supporting stainless steel base tray with narrow openings and a removable metal mesh. This system allowed free drainage of water but prevented loss of large particles (>50 μm) with the drainage water. Flow of water on the outside of the column to the base tray was prevented by use of tight canvas caps that covered the gap between column and base. The drainage water from each column was led through a polyethylene tube to a glass bottle on a shelf under the column bench where samples were collected manually.

Leaching experiment

Intensive rainfall was simulated with a rotation of 16 s of rain under a pressure of 50 kPa and 47 s of no rain which gave a rain intensity of 9 mm/h. Before the leaching experiment started, the soil columns were irrigated for 2–3 h until leachate began to drain out, which was assumed to indicate that the soil was close to water saturation. A total of 10 leachate samples were collected from each column after each 1-h simulated rainfall event, five before and five after slurry application. Two rainfall events were simulated on 1 day, with an interval of 6–16 h between two events. This time interval was enough for most of the applied water to drain and be collected just before the next rainfall simulation.

Liquid pig slurry, with a dry matter content of 7.30%, and a total-C content of 31.2% and a total-P (TP) content of 1.71% in dry matter, was applied to each soil column at a rate of 22 kg P/ha after the columns were drained naturally for 60 h. The slurry was collected from a farm with a fattening pig unit and stored under cover. Before slurry application, the upper 1-cm soil layer was removed and mixed with the slurry before being returned to the soil surface. The columns were then stored at 4 °C for 2 weeks before the second rainfall simulation sequence to allow the soil and manure to interact.

Analysis of soil and water samples

A soil sample, taken at plough depth when preparing the bottom of each column, was dried, ground and sieved for chemical analysis. Soil samples were extracted with the ammonium lactate method, that is, ammonium lactate (0.1 M) and acetic acid (0.4 M) at pH 3.75 and a soil/solution ratio of 1:20 (Egnér *et al*., 1960). The extracts were analysed with inductively coupled plasma (ICP) spectrometry for P-AL, Fe-AL, Al-AL and Ca-AL. The DPS-AL value (%) was calculated as the ratio between P-AL and Fe-AL + Al-AL, expressed on a molar basis (Ulén, 2006). Water-extractable P (WEP) was extracted with distilled water at a soil/water ratio of 1:3. Hydrochloric acid P (P-HCl) was extracted in 2 M HCl (KLS, 1965). The concentrations of WEP and P-HCl were analysed after centrifuging and filtering (0.2 μm) the extracts according to colorimetric method of the International Standard Organization (ISO, 2003), and values were converted to mg/kg soil.

Leachate was collected and weighed in individual glass bottles for each column after each simulated rainfall event. It was sampled for analysis of TP, total dissolved P (TDP) and DRP. These analyses were carried out according to the colorimetric methods of the International Standard Organization (ISO, 2003). Total-P concentrations were determined on unfiltered samples and TDP on filtered samples (0.2 μm), both analysed after oxidation with sulphuric acid (H_2SO_4) and potassium persulphate ($K_2S_2O_8$) as oxidizing reagents. The concentrations of DRP were determined on filtered samples without oxidation. Particulate P (PP) concentration was defined as the difference between TP and TDP concentrations and dissolved organic P (DOP) as the difference between TDP and DRP.

Statistical analysis

The SAS program (version 9.2) was used for statistical analysis. The repeated measurements of leachate amount, concentrations of various P forms and P leaching losses were analysed with the Mixed Model (Littell *et al*., 2006). The General Linear Model (GLM) was used to analyse the regression of DPS and DRP. A significance level of $\alpha = 0.05$ was used throughout this study. The P concentrations in the leachate and leaching losses from one replicate of the LowSlurryMellby treatment were excluded from the analysis because the polyamide cloth used for this column split and failed to capture large particles during the experiment.

Results

Leachate amounts

In total, an average of 36 mm leachate was collected from each soil column during the five events before slurry application and 38 mm during the five events after slurry application (Table 4), which represented ca. 80% of the total water input. The total amount of leachate during the 10 events accounted for ca. 25% of mean annual drainage under field conditions (280 mm) as measured during 1989–2003 (Liu *et al*., 2012).

Leachate amounts were quite similar for the different treatments and different events, with small variations between replicates, although somewhat more leachate (0.4 mm per event) was always collected from the Mellby soil than from the Böslid soil (difference not significant). This difference could be due to lower water retention capacity at Mellby (Table 1). Owing to the possibly incomplete water-saturated soil conditions before the first irrigation, the leachate amount from this event was significantly lower than from the

Table 4 Mean values of leachate amounts and leaching loads of different forms of P for the five leaching events before (B) and after (A) slurry application to the soil columns ($n = 4$ except $n = 3$ for the LowSlurryMellby treatment)

		Leachate	DRP	PP	DOP	TP
Treatment	Slurry	(mm)	(kg/ha)			
LowSlurryMellby	B	7.06 ab	0.0158 b	0.0027 a	0.0030 a	0.0212 b
	A	7.78 c	0.0260 c	0.0034 a	0.0019 a	0.0275 bc
HighSlurryMellby	B	7.24 abc	0.0295 c	0.0033 a	0.0075 b	0.0401 de
	A	7.60 bc	0.0376 d	0.0038 a	0.0039 a	0.0440 e
MinMellby	B	7.35 abc	0.0223 bc	0.0037 a	0.0039 a	0.0299 bcd
	A	7.57 bc	0.0274 c	0.0074 b	0.0021 a	0.0370 cde
MinBöslid	B	6.85 a	0.0060 a	0.0021 a	0.0016 a	0.0097 a
	A	7.13 ab	0.0077 a	0.0021 a	0.0013 a	0.0111 a

Small letters indicate significant differences within each table column ($\alpha = 0.05$).

following four events in all treatments for both Mellby and Böslid soils ($P < 0.0001$), although the difference was only 10%.

Mean P concentrations and loads

Overall, the slurry application history at the two sites in terms of different application rates of slurry since 1983 and large loads of manure even before that on the Mellby plots and no slurry application on the Böslid plot had a great impact on P leaching and P concentrations. This is shown in Figure 2 and Table 4 as the mean of leaching events before and after the single slurry application. DRP was the dominant form of P in the leachate and constituted 61–94% of TP. The concentrations and loads of P were significantly higher (DRP $P < 0.0001$; DOP $P < 0.005$; TP $P < 0.0001$) from all Mellby columns with high soil P and DPS status (HighSlurryMellby, LowSlurryMellby, and MinMellby) than from Böslid columns with lower soil P content and DPS value (MinBöslid). The concentration of TP in leachate from the soil columns ranged from 0.14 to 0.57 mg/L before the single slurry application in the laboratory and from 0.15 to 0.59 mg/L after the slurry application. The concentrations followed the same trend both before and after the single slurry application: HighSlurryMellby > MinMellby > LowSlurryMellby > MinBöslid (Figure 2). Significant differences were found between the treatments HighSlurryMellby, LowSlurryMellby and MinBöslid. The trend was also the same for the cumulative TP load from the 10 leaching events.

The concentrations of DRP and DOP decreased in the first one or two leaching events after the soil columns were applied with a single dose of pig slurry and stored at 4 °C for 2 weeks in the laboratory and then gradually increased and levelled out until the end of the experiment (Figure 3). The concentration of PP reached a peak at the first event after the single slurry application and decreased afterwards except in the HighSlurryMellby treatment (Figure 3). Overall comparison of the five leaching events after with those before the single slurry application showed that the concentration of DRP in leachate increased by 20–50% ($P = 0.02$), while DOP concentration decreased by 20–50% ($P = 0.03$). The PP concentration increased significantly from 13 to 21% of TP in the MinMellby treatment ($P = 0.04$), but not in any other treatment. The TP concentration had a tendency to increase after the single slurry application, but the increase was not significant in any treatment (Table 4).

DRP concentrations in leachate and DPS-AL in topsoil

The concentrations of DRP and TP in leachate and loads from different treatments followed the same order as percentage DPS-AL in the topsoil, that is, HighSlurryMellby (DPS-AL: 42%) > MinMellby (DPS-AL: 34%) > LowSlurryMellby (DPS-AL: 32%) > MinBöslid (DPS-AL: 21%). The DRP concentrations in the leachate were correlated significantly with the DPS-AL values in the topsoil, both before and after slurry application in the laboratory (Figure 4). Mean DRP concentrations in leachate increased significantly with increasing DPS-AL values in the topsoil ($R^2 = 0.95$, $P < 0.0001$). Furthermore, the increase in DRP concentration after a single slurry application was greater with higher DPS-AL values ($R^2 = 0.79$, $P < 0.0001$).

Discussion

Effect of long-term repeated slurry application

In the Mellby soil, TP leaching was greater from the treatment with the high application rates of slurry than where

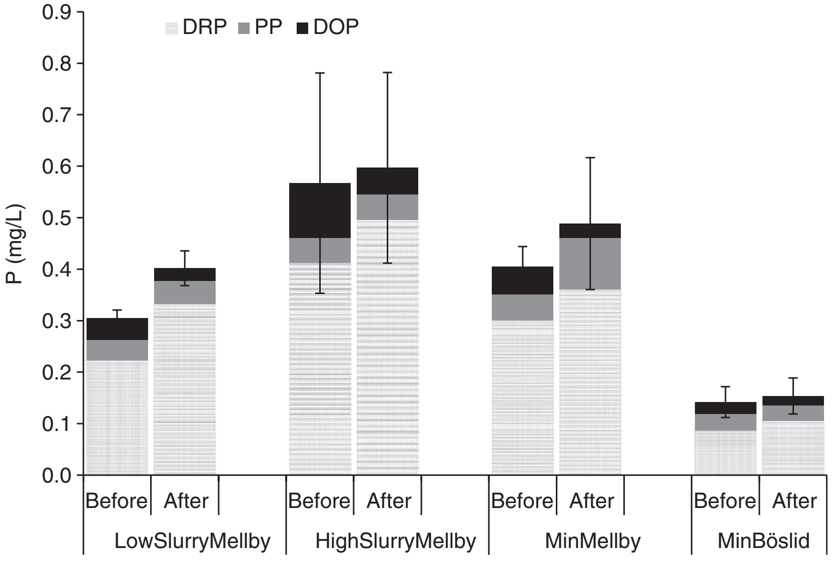

Figure 2 Mean concentrations of P in leachate before and after slurry application. Bars represent standard deviation of TP ($n = 4$ except $n = 3$ for the LowSlurryMellby treatment).

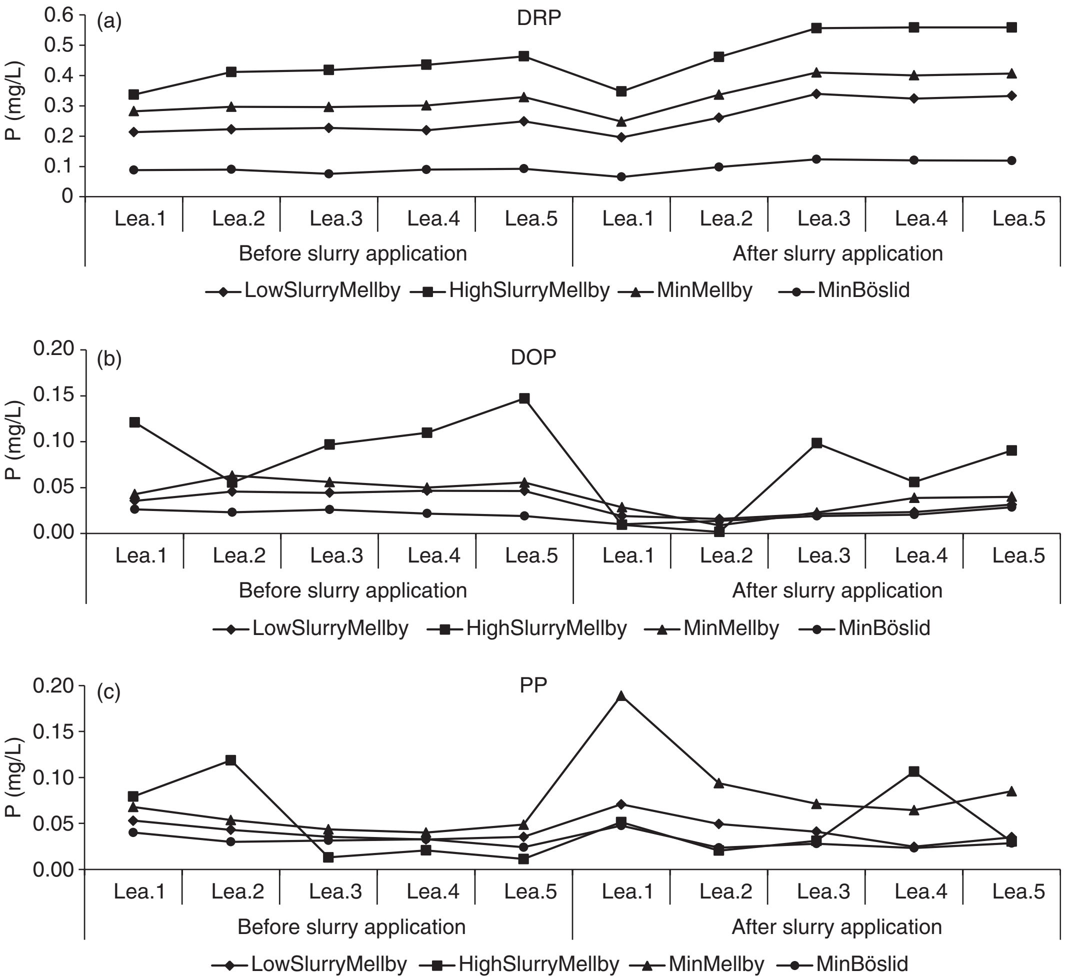

Figure 3 Mean concentrations of various forms of P in each effluent sample for different treatments before and after slurry application to the soil columns (n = 4 except n = 3 for the LowSlurryMellby treatment). (a) DRP; (b) DOP; (c) PP. Note: different scales were used for Y-axis.

low rates of slurry or mineral P had been used since 1983, although only the difference between HighSlurryMellby and LowSlurryMellby was significant. This was due mainly to build-up of the P pool in the soil, leading to higher P status and degree of P saturation when the large rates of slurry exceeding crop uptake was applied for a long term (Table 2). The lack of significant difference between the slurry treatments and mineral P treatment at Mellby was somewhat surprising because slurry P was applied at a rate of 40–200% higher than mineral P. The fact that great variation existed between replicates and too few replicates were used was probably the main reason for this. In the long term, manure is regarded to have equivalent value to mineral fertilizers in supplying P for crops (Smith & van Dijk, 1987) and building up soil P status (Smith *et al*., 1998). Other studies, with considerably larger application rates than in this study, have shown that addition of organic acids and other organic materials in manure can increase the availability of P in soils by decreasing adsorption of P and increasing solubilization of P compounds (Bolan *et al*., 1994; Eghball *et al*., 1996). This may even increase the P leaching potential compared with mineral P fertilizers (Tarkalson & Leytem, 2009).

Land use history before the Mellby field experiment started in 1983 also had an important role in influencing current P leaching. Similar amounts of mineral P were applied to MinMellby and MinBöslid during recent years. Also, the Mellby and Böslid soils had very similar textures and therefore similar flow paths were expected, which resulted in similar amounts of leachate. Despite this, TP leaching from the Mellby soil was over threefold greater than leaching from the Böslid soil. This can be attributed to the large amount of applied manure to the Mellby site before 1983, which resulted in much higher soil P-AL and DPS-AL values than the Böslid site without manure input. However, the effects of manure application on P turnover and leaching are complex. It is difficult to determine whether repeated applications of organic matter and/or other components in manure or large P surplus, or both, control P leaching. DRP was the dominant form of P in the leachate. This can be explained by the high proportion of inorganic forms of P (up to 60–90%)

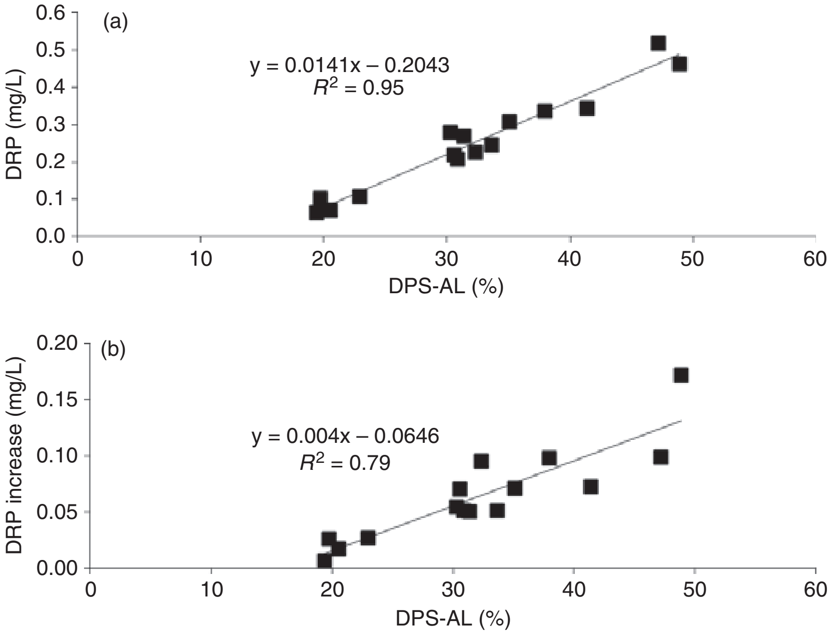

Figure 4 Regression lines between DPS-AL in the topsoil and (a) mean concentration of DRP in leachate before slurry application to the soil columns, and (b) increase in DRP concentration after slurry application (n = 15).

in pig slurry (Mullins *et al*., 2005) and the high mineralization rate of the other organic forms (Killorn, 1993).

Effect of a single application of slurry

Leaching of DRP slightly increased in all treatments (P = 0.02) after a single slurry application and 2 weeks of storage at 4 °C, but the difference in TP leaching compared with that before slurry application was not significant because of decreased DOP leaching. Concentrations of both DRP and DOP decreased at the first event after the single slurry application. This was probably due to a decrease in dissolved P concentration in the soil solution in a new equilibrium with the soil matrix at a low temperature. Chapman *et al*. (1997) observed that the concentrations of DRP in the soil solution of a sandy soil decreased by 50% and DOP by 95% after storage for 8 days at 4 °C.

One reason why a single application did not increase TP could be that the application rate of 22 kg/ha was not high enough to promote concentrations of TP in the leachate to a significant extent. Another possible reason is that the pig slurry was incorporated and incubated for 2 weeks before rain simulations, which may have allowed efficient adsorption of P. Although surface-applied slurry P has higher mobility than solid manure and mineral fertilizers (Tarkalson & Leytem, 2009), other studies have shown that slurry incorporation/injection can reduce P mobility in soil and TP losses in runoff by up to 80–90% (Uusi-Kämppä & Heinonen-Tanski, 2008). Glæsner *et al*. (2011) found a 20%, 60% and 50% reduction in P leaching from topsoil of loamy sand, sandy loam and loam, respectively, after injection of dairy slurry to a depth of 8 cm. They attribute the reduction to physical retention of PP and DOP and chemical retention of DRP. The lowest effect of injection on the loamy sand in that study was probably because that soil had fewer preferential flow paths than the structured soils. A relatively homogenous water flow through the topsoil, which enables efficient chemical retention of DRP without incorporation, would be expected from the loamy sands in this study. An irrigation experiment with dye on the Mellby soil showed that 94% of the cross-sectional area at 20 cm depth participated in the transport of water (Bergström & Shirmohammadi, 1999). However, preferential flow paths may occur to some extent even for soils such as the Mellby soil in the field circumstance (Liu *et al*., 2012). Water repellency caused by high organic matter content was one explanation for the preferential flow behaviour in the Mellby soil (Larsson *et al*., 1999). Therefore, incorporation of applied P probably decreased the risk of P leaching to some extent also for these soils.

After the single slurry application, the treatment ranking in terms of TP concentrations and losses was the same as before (Table 4). This suggests that the long-term repeated P application, including that before the experiment started in 1983, affected TP leaching more than a recent single P application. In a study on five Swedish soils, A. Svanbäck *et al*. (unpublished observations) found increasing leaching of TP and DRP from three soils after a single application of dairy manure to intact topsoil columns and concluded that the increase was soil type specific and affected by historical P applications.

DPS-AL as an indicator of P leaching

DPS-AL was an appropriate indicator of potential DRP leaching in this study, with strong correlation with both DRP concentration in the leachate and the increase in DRP concentration after the single slurry application. Potential of DRP leaching from soil increases with greater degrees of P saturation. Moreover, with the same amount of applied P, P leaching increased more from the soil with higher DPS-AL values (Figure 4b), presumably because the sorption sites in the soil became occupied by phosphate ions (Heckrath *et al*., 1995; Börling *et al*., 2004). This indicates that the soil with high DPS-AL values was more vulnerable to increased P loss after additional application of manure and applications on such soils should be avoided.

Similar studies elsewhere have identified critical DPS values, for example 25% in the Netherlands (van der Zee *et al*., 1990) and 30% in Belgium (De Smet *et al*., 1996), for predicting an increase in P loss from soils with similar texture to those in the present study. A DPS of 25% as identified by the researchers in the Netherlands corresponds to a dissolved P concentration of 0.1 mg/L in the soil solution at the mean highest water level (Breeuwsma & Silva, 1992), which was approximately the lowest mean concentration of P in leachate (0.087 mg/L) from the soil with a DPS-AL value of 21% in this study. There is need also to identify such critical values for the better assessment of P losses and management of P in Swedish soils. However, we did not find a critical value in the present study where the relationship between DRP concentrations in leachate and soil DPS-AL values was linear. The linear relationship is probably because only a narrow total range of DPS-AL was used in this study. This was reported by Koopmans *et al*. (2002) who also concluded that under such a condition, a critical value is difficult to detect. More studies are needed to determine an appropriate value based on DPS-AL for predicting critical P losses associated with long-term manure applications.

Applicability of results

There are always questions about the applicability of results from laboratory studies to field circumstances. In this study, the risk of P leaching from topsoil after a single application of P might have been underestimated because the slurry was mixed into the soil and the columns were stored for 2 weeks before irrigation. This resulted probably in efficient adsorption of P. Moreover, the tap water used for irrigation had higher amounts of basic cations and electrical conductivity, which might have resulted in less transport of applied P than if natural rain water had been used. Irrigation with water of high ionic strength causes increased retention of DRP and decreased DRP transport (Jensen *et al*., 1998; Schärer *et al*., 2006). However, our results indicate that the risk of P leaching increases, especially from soil with high DPS-AL values, even with moderate single slurry applications. The risk of P leaching may become even greater if incidental P leaching occurs, that is, if rainfall occurs immediately after slurry application (Withers *et al*., 2003) or if slurry is applied on the soil surface without subsequent incorporation as discussed above.

On the other hand, the irrigation and soil water regimes represented very wet conditions with about 45 mm of rain during 3 days. However, rainfall events of this magnitude (> 15 mm/day) occur a few times per year in the region where the columns were collected. Slurry was applied 60 h after the last rainfall, which meant that the soil was wet, but represented conditions when a farmer might perform manure applications, for example during autumn or spring. Drain flow mainly occurs during October-April under field conditions.

The most important problem with this type of study is that an appropriate risk assessment of P leaching for real conditions must include subsoil properties, which can have a considerable impact. Several studies have shown the importance of water flow paths, especially through the subsoil for the risk of P leaching, which may overshadow soil chemical properties (Pote *et al*., 1999; Djodjic *et al*., 2004). In this study, we overestimated probably the risk of P leaching, because the subsoil that contained 97–99% sand and considerable amounts of Fe and Al oxides and had low DPS-AL values (8–11%) may have acted as a filter to reduce P leaching. In a field study by Liu *et al*. (2012), TP leaching as measured in drainage water from Mellby and collected at 0.9-m depth was 5–9 times less than leaching from the topsoil columns in this study. The importance of the subsoil to sandy soils in the retention of P and therefore reduction in P leaching is also suggested by results from lysimeters (Shepherd & Withers, 1999, 2001). However, the subsoil may be saturated with P to a critical point as if large amounts of slurry applications continue and this in turn may increase the risk of P loss to nearby water bodies.

Conclusion

This study on two sandy soils under laboratory conditions shows that a single application of pig slurry (22 kg P/ha) only increased slightly DRP leaching from the topsoil. A more important parameter relevant to P leaching was the long-term history of manure or mineral P application, which resulted in different degrees of soil P saturation. The DPS-AL values correlated highly with those from P leaching both before and after a single application of pig slurry, which suggests that DPS-AL is a suitable indicator of the risk of P leaching from Swedish sandy topsoils. It also suggests that the soils with high DPS-AL values have high potential P loss and are more vulnerable to P loss after additional P applications. To assess the risk of P leaching losses in the field, the chemical and physical properties of the subsoil must also be considered. This study confirms that great attention should be paid to sites with a long history of repeated manure applications when identifying hotspots and designing mitigation strategies to reduce P leaching.

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