

# Effects of pig and dairy slurry application on N and P leaching from crop rotations with spring cereals and forage leys

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**Abstract** Two crop rotations dominated by spring cereals and grass/clover leys on a clay soil were studied over 2 years with respect to nitrogen (N) and phosphorus (P) leaching associated with pig or dairy slurry application in April, June and October. Leaching losses of total N (TN), total P (TP), nitrate-N and dissolved reactive P (DRP) were determined in separately tile-drained field plots (four replicates). Mean annual DRP leaching after October application of dairy slurry ( $17 \text{ kg P ha}^{-1}$ ) to growing grass/clover was  $0.37 \text{ kg ha}^{-1}$ . It was significantly higher than after October application of pig slurry ( $13 \text{ kg ha}^{-1}$ ) following spring cereals ( $0.16 \text{ kg ha}^{-1}$ ) and than in the

unfertilised control ( $0.07 \text{ kg P ha}^{-1}$ ). The proportion of DRP in TP in drainage water from the grass/clover crop rotation (35 %) was higher than from the spring cereal rotation (25 %) and the control (14 %). The grass/clover rotation proved to be very robust with respect to N leaching, with mean TN leaching of  $10.5 \text{ kg ha}^{-1} \text{ year}^{-1}$  compared with  $19.2 \text{ kg ha}^{-1} \text{ year}^{-1}$  from the cereal crop rotation. Pig slurry application after cereals in October resulted in TN leaching of  $25.7 \text{ kg ha}^{-1}$  compared with  $7.0 \text{ kg ha}^{-1} \text{ year}^{-1}$  after application to grass/clover in October and  $19.1 \text{ kg ha}^{-1} \text{ year}^{-1}$  after application to spring cereals in April. In conclusion, these results show that crop rotations dominated by forage leys need special attention with respect to DRP leaching and that slurry application should be avoided during wet conditions or combined with methods to increase adsorption of P to soil particles.

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## Introduction

In regions with high animal stocking densities, manure plays a major role for nitrogen (N) and phosphorus (P) losses (Carpenter et al. 1998). Long-term manure application increases the amounts of N and P in the

soil, which can increase the risk of losses (Dilz et al. 1990; Hesketh and Brookes 2000; Börling et al. 2004). For P, this risk is correlated with the degree of P saturation of the soil (Heckrath et al. 1995; Hooda et al. 2000), which determines the capacity for additional P sorption. Although studies of topsoils have shown that the risk associated with the long-term build-up of soil P is larger than the risk associated with single slurry applications (Liu et al. 2012a; Ulén et al. 2013), several field studies have reported that the timing of manure application is highly important for reducing P losses. Spring application of manure is generally preferable to autumn application with respect to fertiliser effect and also to the risk of N and P losses (Jackson and Smith 1997; Beckwith et al. 1998). However, autumn application is often necessary for practical reasons, e.g. to minimise the need for manure storage on the farm and or to utilise the available time.

Soil tillage and crop growth during autumn strongly affect the availability of N for leaching. Soil tillage increases N mineralisation, which can make a considerable contribution to N leaching if crop uptake is low (Møller Hansen and Djurhuus 1997; Stenberg et al. 1999), while intensive crop growth during autumn reduces leaching (Neumann et al. 2011). Soil tillage can disturb established soil pore systems and thus reduce the risk of P leaching from soils with macropores (Ulén et al. 2010), but it is also known to increase the risk of surface losses of P (Lundekvam and Skøien 1998). Leaching studies including the subsoil have shown that the sorption and transport characteristics of P in the subsoil greatly affect leaching (Liu et al. 2012a; Andersson et al. 2013). This implies that e.g. low P sorption capacity of the subsoil and/or fast transport pathways, which prevent P retention by the soil matrix (Bergström and Shirmohammadi 1999; Glæsner et al. 2011), can increase the risk of losses associated with a single application of manure. For soils with macropore flow pathways, incorporation of manure can decrease the P losses considerably due to increased contact with the soil matrix (Djodjic et al. 2002; Glæsner et al. 2011; Liu et al. 2012b). Immediate incorporation is also very important for reducing ammonia losses from the manure (Sommer and Hutchings 2001).

Unlike for N, surface runoff is often presumed to be the dominant pathway for P losses. However, leaching may be of equal or even higher importance under certain

circumstances, where factors such as rainfall distribution and intensity, topography and soil infiltration capacity will be important for the partitioning of rainfall between surface runoff and infiltration. For instance, considerable amounts of P leaching have been observed from well-structured clay soils, where P is lost through macropore flow pathways (Djodjic et al. 1999) and in tile drains, which provide a short-cut for P losses to surface waters (Sims et al. 1998). Laboratory soil nutrient analyses and lysimeter studies can provide reasonable insights into potential N and P losses from selected points of a field. However, field leaching studies include all soil profile properties integrated over a representative area. They enable testing of agricultural management practices that affect the processes involved in N and P mobilisation and transport, and are thus a unique way to obtain information about actual losses in water draining from agricultural soils. This production system study investigated N and P leaching losses from a clay soil in a field leaching experiment situated in an area with intensive livestock production. Two crop rotations, dominated by spring cereals and grass/clover leys and representing pig and dairy production, respectively, were studied over a two-year period. The main objective was to identify possible risks of N and P leaching losses in these two types of systems and to identify ways to improve management practices for reducing these risks. The focus was on practices related to the timing and to the technique used for applying manure in the crop rotations.

## Materials and methods

### Field site

The field study was conducted on a clay soil at Lilla Böslid experimental farm in the coastal region of south-west Sweden (56°35'N, 12°56'E). This is an area with intensive livestock production and relatively high precipitation (803 mm year<sup>-1</sup>, Halmstad 1961–1990). The experimental site was established in 2008 by construction of 10 m × 16 m field plots, separately tile-drained at 0.9 m depth. This approximately corresponds to the groundwater level during the period September–April, which is the main drainage period for the site. The tile drains were installed at 7 m spacing (two tile drains per plot). All plots were equipped for continuous measurements of

**Table 1** Mean values of selected soil physical and chemical properties, with SD in brackets

Soil properties	Soil depth		
	0–0.3 m	0.3–0.6 m	0.6–0.9 m
Physical properties			
Soil texture (%)			
Clay (<0.002 mm)	29 (1.6)	37 (2.6)	40 (2.9)
Silt (0.002–0.0625 mm)	43 (2.6)	42 (3.6)	45 (4.6)
Sand (0.0625–2 mm)	28 (3.5)	22 (5.4)	15 (6.4)
Sat hydr conductivity (cm h <sup>-1</sup> )	1–350	2–2,000	2–2,000
Chemical properties			
Total C (%)	2.2 (0.2)	0.7 (0.2)	0.3 (0.1)
P-AL (mg kg <sup>-1</sup> )	49 (8.9)	23 (8.8)	114 (24)
P-HCl (mg kg <sup>-1</sup> )	54 (6.3)	36 (6.0)	57 (5.3)
K-AL (mg kg <sup>-1</sup> )	133 (34)	128 (22)	163 (22)
Fe-AL (mg kg <sup>-1</sup> )	270 (20)		
Al-AL (mg kg <sup>-1</sup> )	210 (30)		
DPS-AL (%)	16.9 (4.2)		
PSI	3.0 (0.1)		

Saturated hydraulic conductivity was estimated according to Karlsson and Håkansson (1983)

**Table 2** Experimental treatments (four replicates)

Treatment	Fertiliser	Ploughing
Control		
C Spring barley/oats	Mineral N, no P	November
Crop rotation with pig slurry		
P1 Spring barley/oats	Pig slurry and mineral N in April, incorporated by harrowing	November
P2 Spring barley/oats	Mineral N before sowing, pig slurry in April on soil surface	November
P3 Spring barley/oats	Mineral N and P in spring, pig slurry on surface in October (for crop in P4 next year)	November
P4 Spring barley/oats	Mineral N in spring, no slurry	November
Dairy crop rotation		
D1 Spring barley/oats + under-sowing	Dairy slurry and mineral N in April, incorporated by harrowing	–
D2 Ley	Mineral N 3 times, dairy slurry in October on surface	–
D3 Ley	Mineral N 3 times, dairy slurry in June	November

Spring barley was grown in 2010 and oats in 2011. Slurry was applied on 6 and 31 October and the soil was ploughed on 18 and 23 November in 2010 and 2011, respectively

drainage flow and flow-proportional water sampling. The plots were separated by plastic sheeting installed vertically down to 1–1.5 m to prevent lateral flows of water between the plots. The field is flat and the rainfall intensity very rarely exceeds the infiltration capacity of the soil. No surface runoff was observed during the experimental period.

The soil at the site is a clay loam, with pH (H<sub>2</sub>O) 6.5 and 29 % clay content in the topsoil (0–0.3 m). Detailed

soil physical and chemical characteristics are shown in Table 1, where the texture analyses were based on samples at 18 locations, evenly distributed over the field. Values for soil P, K and C content were measured in each plot before the experiment started. The ammonium lactate-extractable (AL) amounts of P and K roughly represent plant-available pools in the soil (Egnér et al. 1960), while P extracted with hydrochloric acid (HCl) also covers more tightly bound P (KLS 1965).

The AL-extractable Fe and Al amounts and P sorption index (PSI) for the topsoil were based on 16 samples taken within a study by Liu et al. (2012b) in the same field. Degree of P saturation (DPS) in the soil was calculated as ratio between P-AL and Fe-AL + Al-AL, expressed on a molar basis (Ulén 2006). PSI was analysed and calculated according to Börling et al. (2001).

### Crop rotations and manure treatments

The two crop rotations, representing dairy and pig production respectively, and a control treatment (without P addition and with mineral N fertilisation) were established during 2009–2010 on 32 plots. Triticale (*X Triticosecale* Wittmark) was sown in all plots in 2009, with an under-sown grass/clover ley consisting of 15 % clover (*Trifolium pratense* L., *Trifolium repens* L.) and 85 % grass (*Phleum pratense* L., *Festuca pratensis* L., *Lolium perenne* L.) in 8 plots. All plots were fertilised with 90 kg N and 12 kg P ha<sup>-1</sup> as mineral fertiliser, which resulted in average dry matter yield of 7,260 kg grain ha<sup>-1</sup>. The experimental management practices, i.e. crops, manure treatments and tillage, were implemented in spring 2010 (Table 2), when the experiment started. The treatment effects on crop yield and leaching of N and P were investigated from 2010 until 2012, i.e. two full growing and two drainage seasons.

The manure treatments included different components; two types of slurry (dairy or pig), different times of application (April, June or October) and incorporation or not. Some of these components were combined and could not be evaluated separately. The aim of the experiment was to study two production systems which represented common animal stocking rates and crop rotations for the region, in order to identify risks associated with the practices applied in such systems and to make suggestions for possible improvements. More detailed studies on the effect of incorporation on potential P leaching after pig slurry application to this soil, and also to a sandy soil, were made within the same research project. Those studies, which were conducted on topsoil lysimeters collected in autumn 2009 before the start of the field experiment, were reported by Liu et al. (2012b).

The pig crop rotation (P1–P4) was represented by spring cereals in both years, spring barley (*Hordeum vulgare* L.) in 2010 and oats (*Avena sativa* L.) in 2011,

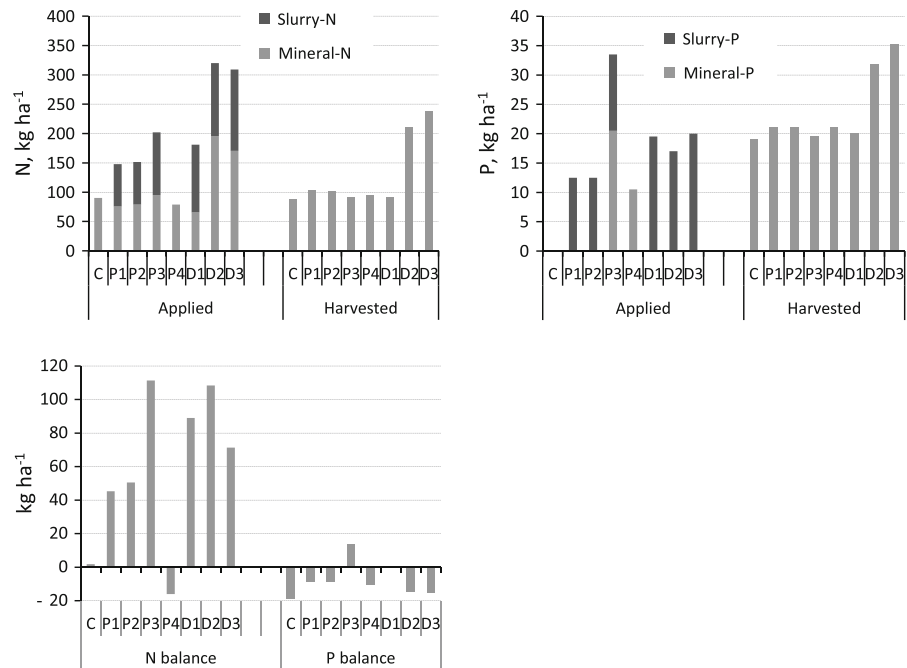
with ploughing in November (Table 2). Pig slurry was applied in spring or in autumn in both study years except in treatment P4, where the slurry was applied in P3 in the previous October (Table 2). For the dairy crop rotation (D1–D3), the ley was under-sown with a grass clover mixture (see above) in spring and harvested three times during June–September for silage production. This type of crop rotation experiment (Olesen et al. 2000) enabled the different manure treatments to be evaluated each year with related preceding treatments (Table 2). There was one exception, P4 in 2010, where no slurry was applied in autumn 2009. Thus mineral P was applied in spring to P4 in this first year. The controls were on the same plots in both years.

The amount of slurry P applied (25–40 t ha<sup>-1</sup>) was designed to supply about 20 kg P ha<sup>-1</sup> year<sup>-1</sup>, which is a general recommendation for Swedish conditions. In Sweden, national legislation limits the amount of P added with manure to 22 kg P ha<sup>-1</sup> year<sup>-1</sup> as an average value over a 5-year period. In practice, assumptions had to be made on the P content of the slurry, since analytical data were not available at the time of application. As a result, an average of 19 kg P ha<sup>-1</sup> year<sup>-1</sup> was applied with the dairy slurry, but only 13 kg P ha<sup>-1</sup> year<sup>-1</sup> with the pig slurry, due to a lower P content than expected. The pig slurry had an average total P (TP) content of 0.36 kg t<sup>-1</sup> and a total N (TN) content 2.5 kg t<sup>-1</sup> (76 % as NH<sub>4</sub>-N). The corresponding values for the dairy slurry were 0.49 TP kg t<sup>-1</sup> and 1.8 kg TN t<sup>-1</sup> (60 % as NH<sub>4</sub>-N). Additional N, K and P (P3 in both years, P4 in 1 year) was supplied in the form of mineral fertiliser. The mineral fertiliser N rate was calculated from the expected amount of plant-available N in slurry, which in turn was dependent on ammonia volatilisation after spreading and leaching/denitrification losses over winter. Estimates of the nutrient value in the slurry were based on figures used in a Swedish advisory programme. For example, 70–90 % of ammonia-N was assumed to be plant-available after spring application and 25 % after application in autumn. The total amounts of N and P applied are presented in Fig. 1.

### Sampling and analysis of drainage water and crops

Flow-proportional water samples (15 mL per occasion) were taken using a peristaltic pump after every

**Fig. 1** Mean amounts of N and P applied annually and removed with the harvested crop during the two study years (*above*) and differences between inputs and outputs (*below*). Applied amounts include mineral fertilisers and total N and total P in slurry. The different treatments are described in Table 2. In P3, the mineral P was applied in spring and the slurry in autumn. In P4, mineral P was only applied in spring during the first year, while autumn application in P3 in that year was dedicated for the crop in P4 during the second year



0.2 mm discharge. The samples were collected in individual polyethylene bottles for each plot, which were emptied every 2 weeks during drainage periods for analyses of TN, nitrate N (NN), TP and dissolved reactive P (DRP). To determine TN concentration, a combustion catalytic oxidation method was used where all N was converted to nitrous oxide before analysis (Shimadzu TOC-VCPH +TNM-1) according to the relevant European standard (SS-EN 12260-1). The concentration of nitrate N (NN), including nitrite N, was analysed by flow injection analysis (Tecator AB, Höganäs, Sweden) according to the colorimetric Cd reduction method (APHA 1985). The TP concentration was determined on unfiltered samples according to methods issued by the International Standard Organization (ISO 15681-12003), where all P is oxidised with  $K_2S_2O_8$  to  $PO_4-P$ , which is analysed photometrically. The concentration of DRP in the drainage water was determined on filtered samples (0.2  $\mu$ m) using the same method, but without oxidation.

The daily leaching loads of N and P were calculated by multiplying the concentrations in each sample during the 2-week period prior to the sampling date by the daily amount of drainage. The values were accumulated to monthly leaching loads and then divided by monthly

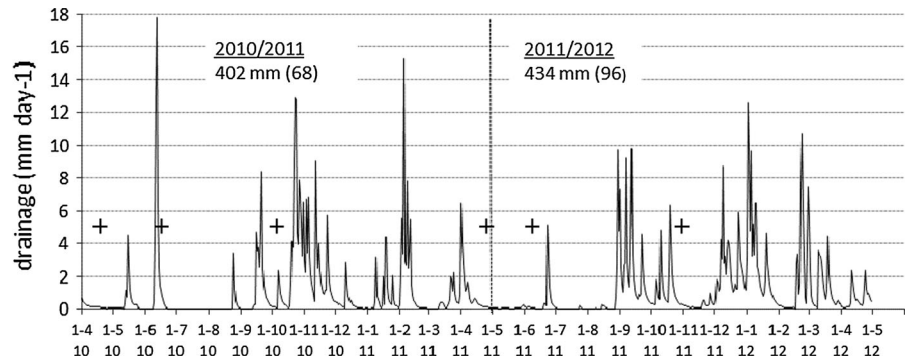
drainage amounts to give mean monthly concentrations. Yearly values were summed for the period 1 May to 30 April.

All crops were harvested in three strips per plot, resulting in three samples which were dried at 50 °C and weighed. The N content in the crop samples was analysed by combustion on an elemental analyser (Leco CNS-2000, Leco Corp., St Joseph, MI, USA; Kirsten and Hesselius 1983), while the P content was analysed by an ion-coupled plasma (ICP, Perkin Elmer, Wellesley, America) method after digestion with  $H_2SO_4$ .

#### Statistical analysis

The Mixed Model (Littell et al. 2006) in SAS (Version 9.2) was used to compare treatment effects on drainage amounts, P and N concentrations and transport in each year, the two-year cumulative drainage amounts and P and N transport, as well as DRP/TP and NN/TN ratios. The effects of block and plot were assumed to be random. Values of  $LSD_{0.05}$  (least significant difference at  $\alpha = 0.05$ ) were calculated when the main effect was significant. Differences of least square means (LSmeans) were calculated to compare pairs of treatments. A “contrast” statement

**Fig. 2** Mean daily drainage ( $\text{mm day}^{-1}$ ), with P application occasions marked in the diagram. Yearly sums for the period 1 May–30 April are presented, with SD in brackets



was used to compare the pig and dairy rotation systems. The residuals of the data followed a normal distribution, which was tested before conducting analysis on treatment effects. A significance level of  $\alpha = 0.05$  was used throughout the study unless otherwise stated.

## Results

### Crop yields and balance between fertiliser input and yield

Mean grain yield of spring barley in 2010 and of oats in 2011 amounted to 6,200 and 5,000  $\text{kg ha}^{-1}$  of dry matter, respectively. The grass/clover ley yielded 11.2–11.5  $\text{t ha}^{-1}$  as a sum of yields for the three cuts. There were no significant differences between the treatments as regards yield.

A simple field balance between the amount of N (mineral fertiliser and slurry) applied and the amount removed with the harvested crops indicated an average surplus of N in both crop rotations, of 48  $\text{kg N ha}^{-1} \text{ year}^{-1}$  for the pig slurry rotation and 90  $\text{kg ha}^{-1} \text{ year}^{-1}$  for the dairy slurry rotation (Fig. 1). Note that this balance did not include other flows such as leaching, ammonia losses from the applied slurry, N fixation by clover and atmospheric N deposition. In the control, where no slurry was applied, the N surplus was on average 2  $\text{kg ha}^{-1} \text{ year}^{-1}$ , while the P balance equalled the P removal in the harvested crops, on average  $-19 \text{ kg ha}^{-1}$ . The pig, and especially the dairy crop rotation, had P deficits of on average  $-3$  and  $-11 \text{ kg P ha}^{-1} \text{ year}^{-1}$ , respectively. It was only in P3, where slurry was applied in autumn for P4, that a substantial surplus of P was observed on a yearly basis.

### Drainage amounts and leaching before the start of the experiment

After construction of the experimental site in 2008, measurements of drainage and water sampling started in early summer 2009, i.e. 1 year before the start of the present experiment. The mean concentration of TN and TP during the first drainage season, after harvest of the triticale on all plots, was 5.7 and 0.05  $\text{mg L}^{-1}$ , respectively. Mean annual drainage amount for the period May 2009 to April 2010 was 235 mm, and which was considerably lower than during the two following experimental years (Fig. 2). Precipitation this year, 821 mm, was close to the long-term average. There were variations between individual plots in terms of both drainage amounts and nutrient concentrations, but there was no correlation between the P and N concentrations and drainage amounts, which might otherwise have indicated dilution with groundwater.

### Average drainage and leaching losses

Drainage during the experimental period (May 2010–April 2012) occurred mainly during the period September–April, but some drainage events were also observed during summer 2010 and 2011 (Fig. 2). During both years, precipitation exceeded the long-term average value for the region, by 200 and 400 mm respectively. The time distribution of precipitation differed somewhat from the long-term average value, with 40 % of the precipitation during the period May to August compared to 30 %. Drainage amounts constituted 36–40 % of the precipitation on a yearly basis. As shown in Fig. 2, there were no major drainage events immediately after slurry application,

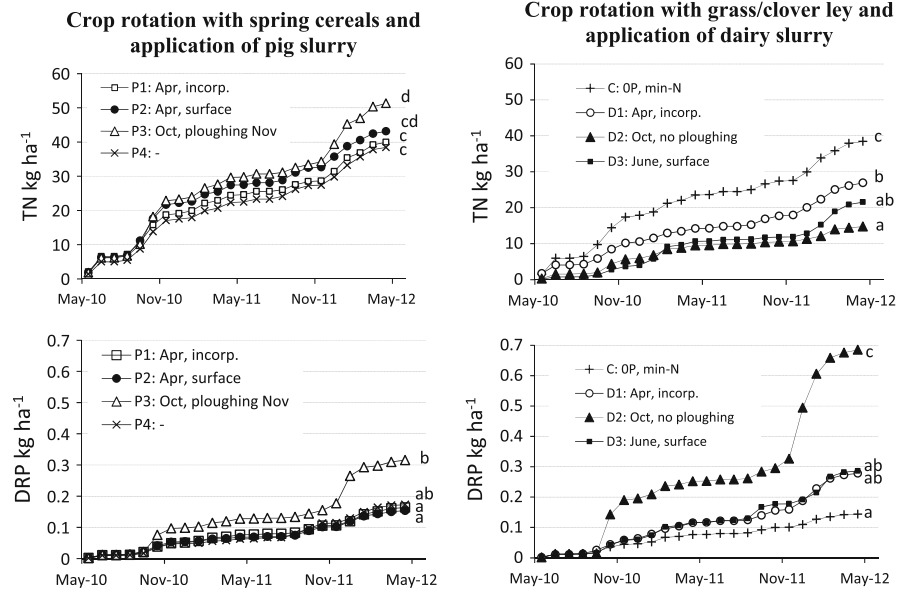


**Table 3** Yearly drainage amounts, mean annual concentrations of N and P in drainage water and yearly leaching losses, including *p* values and LSD values

	Drainage (mm)	Concentration (mg L <sup>-1</sup> )				Leaching (kg ha <sup>-1</sup> )			
		DRP	TP	NN	TN	DRP	TP	NN	TN
<b>2010/2011</b>									
C	415ab	0.019a	0.106a	5.1b	5.7b	0.077a	0.424ab	21.1c	23.5c
P1	416ab	0.018a	0.087a	5.3bc	5.9b	0.076a	0.358a	22.2cd	24.4cd
P2	400ab	0.017a	0.088a	6.3bc	6.9bc	0.068a	0.336a	24.9cd	27.4cd
P3	408ab	0.031a	0.124a	6.7c	7.5c	0.128a	0.529ab	26.5d	29.6d
P4	371ab	0.017a	0.079a	5.6bc	6.1bc	0.063a	0.294a	20.4c	22.3c
D1	419ab	0.027a	0.086a	3.0a	3.4a	0.116a	0.369a	12.5b	14.2b
D2	381a	0.089b	0.206b	1.9a	2.6a	0.297b	0.677b	6.5a	8.8a
D3	455b	0.026a	0.093a	1.8a	2.4a	0.117a	0.422ab	8.3ab	10.7a
<i>p</i> value	0.39	<.0001	0.008	<.0001	<.0001	<.0001	0.139	<.0001	<.0001
LSD0.05	NS	0.016	0.061	1.4	1.5	0.076	NS	5.1	5.2
<b>2011/2012</b>									
C	412a	0.017a	0.193a	3.1c	3.6c	0.067a	0.670a	13.1b	14.9b
P1	415a	0.021ab	0.155a	3.5c	3.8c	0.087a	0.640a	14.4bc	15.5bc
P2	431a	0.020a	0.112a	3.4c	3.6c	0.086a	0.486a	14.7bc	15.7bc
P3	390a	0.048b	0.152a	5.0d	5.6d	0.188a	0.567a	19.1c	21.7c
P4	459a	0.025ab	0.143a	3.2c	3.5c	0.110a	0.661a	14.7bc	16.1bc
D1	497a	0.032ab	0.131a	2.2b	2.5b	0.163a	0.650a	11.2b	12.7b
D2	442a	0.101c	0.186a	0.8a	1.2a	0.433b	0.812a	3.4a	5.2a
D3	423a	0.036ab	0.139a	2.1b	2.5b	0.169a	0.636a	8.9a	10.9ab
<i>p</i> value	0.9	<.0001	0.726	<.0001	<.0001	0.0002	0.8643	0.002	0.01
LSD0.05	NS	0.027	NS	0.68	0.75	0.12	NS	5.8	6.6

Significant differences between treatments (*p* < 0.05) are indicated by different letters

**Fig. 3** Accumulated leaching of TN and DRP during May 2010 to April 2012. Treatments P1–P4 and C were cropped with spring cereals and ploughed in November. In D1, a grass/clover ley was under-sown in spring cereal and followed by forage ley in D2 and D3. D3 was ploughed in November. Significant differences (*p* < 0.001) are indicated by different letters



which took place at the end of April, in June or in October. With two exceptions (D2 and D3 during the first year), there were no significant variations in yearly amounts of drainage between the different treatments (Table 3). The losses of both N and P mainly occurred in generally unfrozen conditions during November–December 2010 and November 2011–January 2012 (Fig. 3).

Nitrate-N constituted on average 88–90 % of the TN in drainage water in the control treatment and in the pig crop rotation, while the NN/TN ratio was significantly lower, 79 %, for the dairy crop rotation ( $p < 0.0001$ ). For P, DRP constituted a significantly higher proportion of TP ( $p = 0.0023$ ) in the dairy crop rotation (35 %) than in the pig crop rotation (25 %) or in the control (14 %).

Mean N leaching from the dairy crop rotation, where a ley was grown during autumn (until November in D3) in all years, was  $10.5 \text{ kg TN ha}^{-1}$ . It was significantly ( $p < 0.0001$ ) higher,  $19.2 \text{ kg ha}^{-1}$ , in the pig crop rotation, with spring cereals and ploughing in November. This was despite the considerable N surplus in the dairy crop rotation (Fig. 1). In contrast, mean leaching of P was higher from the dairy crop rotation ( $0.58 \text{ kg TP ha}^{-1}$ ) than from the pig crop rotation ( $0.48 \text{ kg TP ha}^{-1}$ ), a difference which was significant ( $p < 0.0001$ ) for DRP. This was despite larger P removal with the harvested crops and larger deficit in the P balance in the dairy rotation. Including all treatments, there were no correlations between annual balances of N and P (fertilisers–harvests) and mean annual concentrations or annual leaching losses. Thus, N and P balances were not indicators of leaching losses.

#### Nitrogen leaching associated with different treatments

Crop growth as grass/clover during autumn was obviously an important factor controlling N leaching in the dairy crop rotation. The accumulated N leaching losses from treatments D1, D2 and D3 over the 2 years of the study were all significantly lower than from the other treatments (Fig. 3). Monthly TN concentrations in plots cropped with cereals (pig rotation) were higher during the whole year, as illustrated in Fig. 4. Application of dairy slurry in October to D2 plots did not result in increased N leaching over winter. Moreover, incorporation of

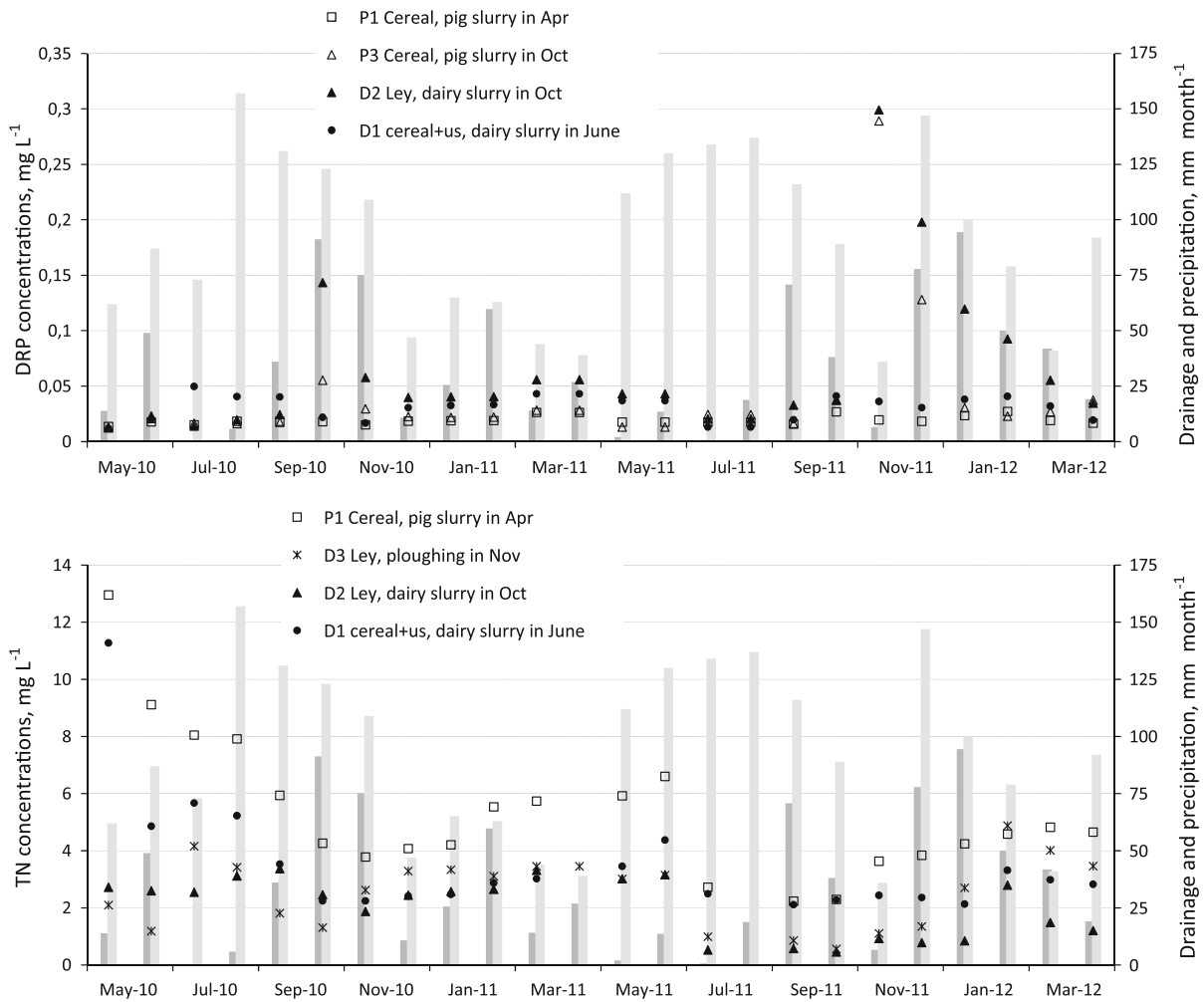
the ley in November (D3) did not result in significantly increased N leaching over winter during 2010/2011, while there was some indication of greater leaching than in D2 during 2011/2012 (Fig. 3). This was related to higher TN concentrations during winter-spring 2011/2012 (Fig. 4). Pig slurry application in October to cereal stubble resulted in the largest N leaching losses, especially during the second year, when NN and TN concentrations in drainage water in P3 were significantly higher than in all other treatments ( $p < 0.0001$ ) (Table 3). The TN concentration remained high over the whole winter in that year (Fig. 4).

#### Phosphorus leaching associated with different treatments

As was the case for N, application of mineral fertiliser or slurry in spring (incorporated or not) did not increase TP losses compared with the control. The timing of P application rather than incorporation seemed to be the most important factor for P leaching, with application in October (P3 and D2) resulting in increased DRP losses in both rotations (Fig. 3). In P3 in the pig crop rotation, the accumulated DRP leaching losses were significantly higher than from C, P1 and P2 (Fig. 3). The P3 treatment was also supplied with mineral P in spring and thus received in total  $34 \text{ kg P ha}^{-1}$ , which might be one reason for the increased leaching. However, in D2, where no P was applied other than with the slurry and where there was grass/clover growing over winter, the DRP losses were significantly higher than from all other treatments. In this treatment the accumulated DRP leaching over 2 years amounted to  $0.69 \text{ kg ha}^{-1}$ , compared with  $0.14 \text{ kg ha}^{-1}$  in the unfertilised control and  $0.32 \text{ kg ha}^{-1}$  in P3 (which in addition to autumn application received the largest amount of fertiliser P of all the treatments). The corresponding accumulated TP leaching did not differ significantly between treatments, with values of 1.4 and  $1.1 \text{ kg ha}^{-1}$  in D2 and C, respectively.

Thus, it was mainly DRP transport which was affected by application of slurry in autumn. On examining the concentration dynamics of DRP in drainage water, two treatments (P3 and D2) had very distinct peaks in DRP concentrations during late autumn/winter after application of slurry in October (Fig. 4). However in D1, where dairy slurry was applied in June, the DRP concentrations in drainage





**Fig. 4** Mean monthly concentrations ( $\text{mg L}^{-1}$ ) of DRP (*above*) and TN (*below*) in drainage water for some of the treatments (*us* under-sown), and mean monthly precipitation and drainage amounts ( $\text{mm month}^{-1}$ )

water increased in July 2010 due to intensive rain and drain flows (Fig. 2).

**Discussion**

Soils with a high risk of P losses are often characterised by high P input over time, and consequently much attention has been devoted to management strategies for reducing P input and the build-up of soil P pools (Sharpley et al. 2001). However, the results of the present study show that it is also very important to include the transport pathways through the soil for appropriate leaching risk assessment, and that the risks

are not only restricted to build-up of soil P. The soil at the field site proved to have a potentially high risk of losses of both particle-bound and dissolved P, despite the negative P balance ( $-3$  to  $-11 \text{ kg ha}^{-1} \text{ year}^{-1}$ ), the moderate P content in the topsoil and the low degree of P saturation (17 %). The P leaching was considerable ( $0.3$ – $0.8 \text{ kg ha}^{-1} \text{ year}^{-1}$ ) for Swedish conditions and was substantially larger than found in earlier field leaching studies on a nearby loamy sand ( $0.13 \text{ kg ha}^{-1}$ ) with long-term high input of P (Liu et al. 2012a). Some of this might be explained by the higher P content of the subsoil (0.6–0.9 m depth; Table 1), which might also explain why plant P uptake was not negatively affected in the control treatment.

However, P concentrations in drainage water during the year before the start of the experiment were low overall, and the relative differences between treatments were presumably not affected by this.

This soil obviously has efficient transport pathways, as indicated by the rapid increases in P concentrations and as found in the lysimeter study by Liu et al. (2012b). For soils like this, the timing and P application technique can greatly affect the risk of DRP transport, as our results show. Application of pig or dairy slurry to the soil surface in October (on average  $13 \text{ kg P ha}^{-1} \text{ year}^{-1}$  in P3 and  $17 \text{ kg P ha}^{-1} \text{ year}^{-1}$  in D2) was identified as the main risk factor in DRP losses. This was despite the fact that there were no major flow events directly after slurry application. Leaching increased 2.3-fold in P3 (application after cereal) and fivefold in D2 (application on ley), compared with the control. In a laboratory study of irrigated topsoil columns collected from the same experimental field, incorporation of the slurry immediately after application was found to reduce the risk of DRP leaching by 50 %, but did not eliminate it (Liu et al. 2012b). The findings in the present study, with 2 years without major flow events after slurry application in spring, indicate that incorporation of slurry in spring is not always important for reducing P losses. Moreover, incorporation did not increase the measured N uptake by the crop, although it has been proven to be very important for reducing gaseous losses of N, and thereby increasing N efficiency, by facilitating binding ammonium to soil particles (Sommer and Hutchings 2001).

Having a grass/clover crop growing on the soil during autumn reduced N leaching by 45 % compared with after cereals, and the proportion of NN in drainage water also decreased, probably due to efficient crop uptake of N. The grass/clover ley in D2 effectively buffered against N leaching after slurry application in October, confirming findings in other studies on manure application to grass or grass/clover crops (Torstensson and Aronsson 2000; Neumann et al. 2011). In P3, where there was no crop cover during autumn, N leaching increased significantly after slurry application, which was identified as the main risk factor for N leaching. Crop uptake of N in the slurry, but also retention in the soil matrix, favourable conditions for denitrification (Munch and Velthof 2007) and losses through ammonia volatilisation may explain low N leaching losses from the

grass/clover ley. Application to a growing crop can increase the ammonia losses by 50 % compared with incorporation before sowing a crop, according to a review by Sommer and Hutchings (2001), but this effect is strongly dependent on e.g. application method, weather conditions and crop species. Several other factors such as pH (Vandré and Clemens 1997) ammonia content, dry matter content and particle size distribution of the slurry also affect the risk of ammonia losses after application (Sommer et al. 2006). This might also have contributed to differences between the two slurries used in the rotations, an aspect which was not examined here. In addition, P availability and mobilisation might be affected in different ways when using different types of slurry.

This study showed that P leaching losses were small in relation to crop uptake of P and that they were dependent on crop uptake during autumn to a much lower extent than N leaching. It appears that a combination of soil chemical and physical characteristics and transport pathways is the most important factor controlling P leaching. In contrast to N, DRP losses were larger from the grass/clover crops than from the cereals with no crop in autumn, including the unfertilised control. The average P applications (mineral fertiliser and slurry) were equal for the two rotations ( $18.3 \text{ kg P ha}^{-1} \text{ year}^{-1}$ ), while the deficit was larger for the grass/clover rotation than the cereal rotation ( $-11 \text{ kg}$  compared with  $-3 \text{ P ha year}^{-1}$ ). The results indicate a clear difference in the effect on N and P leaching of these two crop types and raise questions about whether conversion to grassland or growth of cover crops can be regarded as a general measure to prevent P losses (e.g. Schoumans et al. 2014). For some soils, e.g. in flat areas where crop cover to reduce soil erosion is not needed, use of a cover crop seems questionable. Substantial P leaching losses from permanent grassland that were no lower than those from arable cropping have also been reported by Meissner et al. (1995) and Turtola and Jaakkola (1995). These losses are suggested to be due to stabilisation of macropores (Culley et al. 1983; Van Es et al. 2004). In studies by Toor et al. (2003, 2005), P losses from grassland were dominated by unreactive organic P, but it was also shown that this can be rapidly converted to DRP through enzyme activity in the water. In this study, the grass/clover ley in D3 was ploughed down during the third autumn. Slurry was applied in October during the second autumn (D2)

which was the first autumn with the ley as the main crop. Thus, it seems somewhat unreasonable to expect extensive development and stabilisation of macropores as in permanent grassland. In fact, application of slurry to the grass/clover ley in autumn resulted in larger DRP losses than application to stubble that was ploughed down 5–6 weeks later. However, different types and somewhat different amounts of slurry were applied, which confounded the comparisons.

Other contributions to the increased DRP leaching losses from leys could be P release and leaching from slurry components or plant material, especially after freezing-thawing events during autumn–winter (Liu et al. 2013; Riddle and Bergström 2013). Another explanation might be increased P transport in cracks, created by drier conditions caused by longer growing season and larger water consumption by the ley. However, total drainage amounts were not smaller from the plots with ley compared with cereals (Table 3), although this could be expected. Lewan (1993) found that drainage start was delayed with a few days, when examining undersown grass crops in comparison with bare soil in the same region. This could not be shown here, but there were differences in drainage distribution over the year between the two systems. When comparing three-month periods, plots grown with ley had, on average, 23 mm less drainage during the period July to September, but 40 mm larger drainage during January to March. For the periods October to December and April to June, there were no differences. It is possible that dryer conditions during summer might have contributed to build-up of cracks which facilitated water transport during wintertime. It seems reliable that part of the explanation for the greater transport of DRP from the grass/clover plots lies in rhizosphere processes. The activity of the rhizosphere microflora and plant roots (e.g. plant uptake, pH change and root exudates) can greatly affect P release and mobility in soils (Hinsinger 2001). These rhizosphere processes are affected by plant species and plant nutritional status, as well as soil conditions. For example, Jones (1998) found that root release of organic acids in the rhizosphere varied between plant species, with e.g. a legume crop (*Lupinus*) showing considerable release of citrate, which plays an important role for P availability.

Although leys are very robust with respect to N leaching, an increased risk of N leaching in ley

rotations when the crop is incorporated into the soil is often reported. Ploughing under leys in general results in intensive net mineralisation of N and accumulation of mineral N in the soil (Francis et al. 1992; Lindén and Wallgren 1993; Wallgren and Lindén 1994). When done in summer or early autumn in particular, this results in a high risk of N leaching (Djuurhus and Olsen 1997; Neumann et al. 2011). The risk of P leaching may also be increased due to rapid release of DRP from ley material after incorporation (Ulén et al. 2005) and increased transport of particle-bound P (Schelde et al. 2006). Incorporation of ley in spring can considerably reduce the risk of N leaching, although there may be an increase in N leaching during the following autumn/winter due to delayed N release from plant material (Torstensson 1998; Thorup-Kristensen and Dresbøll 2010). There were some indications of increased N leaching after incorporation of the ley in autumn 2011 in the present study, but annual values of N or P leaching were no higher than from the ley growing over winter. Torstensson (1998) and Wallgren and Lindén (1994) also reported that incorporation in November does not substantially increase N leaching, but results in a good fertiliser effect on the following crop.

## Conclusions

For this soil with apparently fast transport pathways, the timing of slurry application was the main management issue. Slurry application, even at moderate rates, close to the drainage season in autumn resulted in increased losses of DRP, NN and TN. The risk of P losses was not primarily related to commonly used indicators, such as soil P status or degree of P saturation.

For N, October application only constituted a risk of increased leaching when there was no efficient crop cover during autumn, while grass/clover ley proved to be very robust to N leaching. However, it was shown that crop rotations with grass/clover crops need special attention with respect to P leaching, since the DRP/TP ratio in drainage water from grass/clover ley was significantly higher than from cereals and since DRP losses increased substantially after slurry application in October to growing grass/clover. The results indicate that slurry application in wet conditions should be avoided or combined with methods for

increased adsorption of P to soil particles on this type of soil.

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