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Influence of soil phosphorus and manure on phosphorus leaching in Swedish topsoils

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Abstract

In Sweden, subsurface transport of phosphorus (P) from agricultural soils represents the primary pathway of concern for surface water quality. However, there are mixed findings linking P in leachate with soil P and limited understanding of the interactive effects of applied P sources and soil test P on P leaching potential. Identifying soils that are susceptible to P leaching when manure is applied is critical to management strategies that reduce P loadings to water bodies. Intact soil columns (20 cm deep) from five long-term fertilization trials across Sweden were used in leaching experiments with simulated rainfall to explore the interactive effects of dairy cow (*Bos taurus* L.) manure application, soil test P and cropping system. Strong relationships were observed between ammonium-lactate extractable P in soil and dissolved reactive P (DRP) concentrations in leachate, although regression slopes varied across soils. For three soils, application of manure (equal to 21-30 kg P ha^{-1}) to the soil columns significantly increased DRP leaching losses. The increase in DRP concentration was correlated to soil test P, but with wide variations between the three soils. For two soils leachate P concentrations after manure addition were independent of soil P status. Despite variable trends in P leaching across the different soils, P concentrations in leachate were always moderate from soils at fertilization rates equivalent to P removal with harvest. Results clearly stress the importance of long-term P balance to limit P leaching losses from Swedish agricultural soils.

Key words Phosphorus leaching · Ammonium lactate-extractable soil P · Rainfall simulation · Long-term fertility experiments · Manure management

Introduction

Eutrophication of the Baltic Sea has increased algal blooms and anoxic conditions, prompting an international accord to curb loadings of nutrients, particularly phosphorus (P) (HELCOM 2007). Agriculture is the main source of Sweden’s P contribution to the Baltic Sea (SEPA 2008), accounting for roughly 50% of the total anthropogenic load. Since agriculture in Sweden and Finland is mostly located on flat landscapes where soils are drained (open ditches and subsurface tile drains), subsurface transport of P represents the primary pathway of concern for downstream surface water quality (Turtola and Jaakkola 1995; Ulén 1995). As leaching serves to connect P at the soil surface with subsurface drains, understanding the factors controlling P leaching through agricultural soils is key in assessing practices and strategies aimed at mitigating diffuse P loads from Swedish agriculture (Ulén et al. 2007).

An extensive body of work has documented P leaching through soils, emphasizing the soil-specific nature of P leaching potential and the varying influence of management variables on P leaching processes (e.g. Djodjic et al. 2004; Kleinman et al. 2009; Kang et al. 2011). Phosphorus leaching from soils varies widely, from almost undetectable levels to several mg per litre of drainage water from arable and grassland soils (Brookes et al. 1997; Sims et al. 1998). Bypass or preferential flow via soil macropores represents one of the major transport mechanisms of P leaching through well-structured soils (Jensen et al. 1998; Stamm et al. 1998; Simard et al. 2000). As a result, cropping systems or practices that preserve soil structure and promote the maintenance of macropores (e.g. no-till and perennial forage systems) are particularly susceptible to P leaching losses (Sims et al. 1998; Chardon and van Faassen 1999). Phosphorus leaching was once seen as a phenomenon restricted to coarse-textured soils but has now been widely documented in finer textured soils with extensive macropore networks (Djodjic et al. 1999; van Es et al. 2004).

Research to date has yielded mixed findings on the relationship between soil test P and P leaching potential. A study by Heckrath et al. (1995), summarizing findings from shallow tile drains established in the Broadbalk (UK) cropping systems trials, identified a clear threshold in Olsen-P of surface soils above which the potential for leaching significantly increased. The ‘change point’ analysis performed by Heckrath et al. (1995) sparked an array of studies investigating critical thresholds of soil P above which P solubility and/or mobility increased significantly. For instance, McDowell and Sharpley (2001) and Maguire and Sims (2002) reported significant change points in the relationships between 0.01 M $CaCl_2$ extractable P and P sorption saturation of surface soils, respectively, and P concentration in leachate from column leaching experiments. In Sweden, Börling et al. (2004) reported strong relationships between ammonium lactate (AL) extractable P, the dominant agronomic soil P test for Scandinavia, and 0.01 M $CaCl_2$ extractable P, which is considered an indicator of potentially leachable soil P. In another Swedish study, Ulén et al. (2011) found AL-extractable P to be a reliable P risk index for soil profiles with high clay content in a catchment with overall balanced soil P level. However, in an intact soil column leaching study in which a range of Swedish soils was assessed, no relationship between AL-extractable P and leachate P was detected (Djodjic et al. 2004).

Application of manure to soils can temporarily elevate P concentrations in leachate from these soils, primarily as a result of transfer of manure P to infiltrating water. ‘Rapid incidental transfers’ (Preedy et al. 2001) of manure P to leachate are well documented (Geohring et al. 2001; Kleinman et al. 2005; 2009), with the greatest contributions of manure to leachate P typically occurring in the first leaching events after application (Chardon et al. 2007). In general, soluble P in the applied manure serves as the major source of P in leachate. Indeed, Kang et al. (2011) found that the water-extractable P concentration in manures and mineral fertilizers applied to soil columns was correlated with loads of dissolved reactive P (DRP) in leachate. However, little is known about the interactive effects of applied manures and fertilizers and antecedent soil properties and soil P status.

Given the lack of information on the relationship between soil P leaching and soil test P measured as AL-extractable P in Swedish soils, and the limited insight into the interactive effects of soil test P and applied P sources on P leaching potential, this study sought to examine the role of soil test P and applied P sources on P leaching from dominant types of agricultural soils in Sweden. Focus was on the topsoil which usually has higher concentration of P than deeper soil-layers, and P leaching from the topsoil was considered as potential P leaching which may reach deeper soil layers and drainage tiles. Specific aims of the study were to investigate: i) relationships between AL-extractable P and P leaching; ii) changes in P leaching from soils with varying AL-extractable P following manure application; and, iii) effects of cropping system properties on P leaching.

Materials and Methods

Site background and Soil description

The Swedish long-term fertility experiments (LTFEs), initiated between 1957 and 1969, consist of 12 field trials located across Sweden, representing dominant soils and cropping systems in the country. More details on these experiments can be found in

Carlgren and Mattsson (2001) and Kirchmann et al. (1999; 2005). Soil columns were collected from five of these 12 soils: Fjärdingslöv sandy loam (*Oxyaquic. Hapludoll*); Ekebo loam (*Oxyaquic Hapludoll*); Bjertorp silty clay loam (not classified); Klostergården silty clay loam (*Oxyaquic Haplocryoll*); and Högåsa loamy sand (*Humic Dystrocryept*). The experimental design of the LTFEs is similar for all soils, with application rates of P varying in relation to P removed by harvested products on duplicate field plots (6.25 m x 20 m) (Table 1). The different P application rates have, over time, resulted in substantially different soil P concentrations across treatments within soils (Table 2), also demonstrated by Ehde (2012). Field plots with the 'low P' treatment receive no mineral P applications, while P removed by harvested products is replaced in the 'medium P' treatment. The 'high' and 'very high P' application rates (Table 1) were intended to achieve slow and rapid increase, respectively, in soil P status. Recent intensive soil monitoring of LTFEs has demonstrated that the AL-extractable P values are only elevated for about 2-4 months after mineral P application and thereafter decline to approximately its original level. In the P replacement treatment any permanent increase in AL-extractable P is minor (Djodjic and Mattsson 2013).

The crop rotation period is four or six years and includes cereals (barley (*Hordeum vulgare* L.), winter wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.)), oilseed rape (*Brassica napus* L.), and, at Ekebo and Fjärdingslöv, sugarbeet (*Beta vulgaris* L.). Crop rotations are typical for the regions where the experiments are situated. Two cropping systems are represented for each soil. In the manured cropping system (MCS), a perennial forage crop is included, harvest residues are removed and dairy manure (30 ton ha^{-1}) is applied every sixth year, except on soils in southern Sweden (Ekebo loam and Fjärdingslöv sandy loam) where manure (20 ton ha^{-1}) is applied every fourth year. On average, 9 kg P ha^{-1} yr^{-1} have been applied as manure. The previous manure and P fertilizer application to this cropping system was made at least six months prior to soil column collection. When manure is applied, the rates of mineral fertilizer P are adjusted for the amounts of P applied in the manure. In the unmanured cropping system (UMCS) the harvest residues are incorporated into the soil. The experimental fields have been conventionally ploughed on a regular basis. Normal tillage depth for conventional ploughing is 23 cm and the depth of the tile drains is about 90 cm.

The carbon (C) content prior to soil column collection (2005-2007) was on average 2.0% of air-dry topsoil in MCS and 1.8% in UMCS at the study sites (Börjesson 2012). Other important soil properties are shown in Table 3. Except for Fjärdingslöv, all soils are acidic in reaction.

Soil and Soil Column Collection

Topsoil samples (0-20 cm depth) were taken in autumn 2007 from all plots at the five sites, within the normal sampling routine for Swedish LTFEs (Börjesson 2012). At least 10 subsamples were randomly obtained from each plot and pooled into one composite sample.

Intact soil columns were collected from the four P level treatments in both MCS and UMCS at the five sites. In each field plot, four soil columns were taken at least 1.5 m from any edge of the field plot, from an area of approximately 2.25 m^2 (160 columns in total). The collection took place after harvest but before any tillage treatment in autumn. Soil columns from Fjärdingslöv sandy loam and Ekebo loam were collected in September 2007 and from Bjertorp silty clay loam in October 2008.

These soil columns were extracted by gently pressing polyvinyl chloride pipes (20 cm in diameter and 20 cm long) into the soil using soil anchors and a hydraulic pump system (Jarvis et al. 2008). A sharp steel cutting ring was placed at the lower end of the pipes to facilitate insertion of the pipes into the soil. The Klostergården silty clay loam and Högåsa loamy sand soil columns were collected in September 2009. In those cases, the plastic pipes were gently pressed into the soil by a tractor with a front loader (Liu et al. 2012a). The columns were extracted and sealed using lids and plastic bags.

Soil columns were then stored at 2 ºC for approximately six months until they were prepared for the leaching experiment. Column preparation involved removing excess soil at the bottom along soil aggregate surfaces with a knife and vacuuming loose particles. A nylon fabric with a mesh size of 50 µm was then placed at the bottom of each column. Finally, the columns were placed on a base so that free drainage could occur during the leaching experiment and leachate water was collected in glass bottles.

Leaching experiment

Experiment 1

The leaching experiment was carried out in an indoor rainfall simulator (approximately 20 ºC) before and after application of manure to the columns, in order to assess the contribution of soil P and applied manure P to leachate. The rainfall simulation was performed in rounds with 16 soil columns. In each round, all the soil columns came from the same soil and cropping system, but had different P levels. Simulated rainfall consisted of two parts de-ionized water and one part tap water, to better resemble the chemical composition of natural rain water. The electrical conductivity of this simulated rainfall was 15 mS m^{-1} and the chlorine (Cl) concentration 13 mg L^{-1}. Irrigation was applied from air-atomizing spray nozzles located 1.2 m above the centre of each soil column (Larsbo et al. 2009). The rainfall intensity was 10 mm h^{-1} (standard deviation 2.6 mm h^{-1}) and the simulated rainfall was applied in three events lasting 2.5 h each, at 2-day intervals (76 mm in total) (Figure 1). The amount of applied water is more than would be expected under natural field conditions in Sweden, but was necessary to produce a sufficient volume of leachate for chemical analyses. After each 2.5 h rainfall simulation, the leachate was collected and stored at 6 ^{o}C prior to analysis.

Experiment 2

Following an initial period of leaching with three simulated rainfall events for all soil columns, fresh dairy cow (*Bos taurus* L.) manure collected on two occasions was applied to soil columns from the manured cropping system (Figure 1) at a rate corresponding to 30 tonnes ha^{-1}. As a result of differences in manure composition between collection occasions, the Fjärdingslöv sandy loam, Ekebo loam, and Bjertorp silty clay loam columns received 30 kg P ha^{-1} and the Klostergården silty clay loam and Högåsa loamy sand columns received 21 kg P ha^{-1}. When the manure was applied, 1 cm of soil was removed from the top of the soil column, the manure was distributed over the surface (to within approx. 2 cm from the edge), and the soil was then replaced on top of the soil column. After manure application, approximately 1.3 mm of water was added on two occasions with the rainfall simulator (Figure 1), to let some of the P in the manure move downwards in the column and equilibrate with the soil. A second period of leaching with three rainfall events was then carried out with soil columns from MCS (Figure 1).

Analysis of water and soil samples

The concentration of total P (TP) was measured on unfiltered leachate samples after acid digestion with potassium persulphate in sulphuric acid, and dissolved reactive P (DRP) was measured in leachate after filtration (Schleicher & Schüll GmbH, Dassel, Germany, membrane filter with pore diameter 0.2 μm). Both analyses were made colorimetrically according to the method issued by the International Standards Organization (ISO, 2003).

Soil samples were extracted with the AL method according to Egnér et al. (1960). Phosphorus determination on the extracts was conducted by inductively coupled plasma atomic emission spectroscopy (ICP-AES, OPTIMA 3000DV; Perkin Elmer, Waltham, USA) according to Swedish standards (1993). The AL extraction method is common in the Baltic region. Recent comparisons of the AL method with the Olsen-P and Mechlich-3 methods using a set of 99 topsoil samples from seven sites showed generally strong correlations with both Olsen-P and Mehlich-3 (Eriksson et al. 2013). However, for acidic Swedish clay soils the AL method extracted 3.6 times more P than Olsen-P and 1.7 times more than Mehlich-3.

Calculations and statistical analysis

Statistical analyses were performed using SAS software, version 9.2 (SAS Institute 2008). A mixed model approach was used for both experiments, following the example of Littell et al. (2006). The mixed model included both cropping system and soil as fixed categorical factors and AL-extractable P as covariate. Measurements made in different soil columns within each plot were included as nested factors and the different rainfall simulations were included as repeated factor with the correlation structure compound symmetry. The Kenward-Roger method was used to determine degrees of freedom and fixed effects standard error. Assumptions of normality were checked by residual plots. Statistical results were considered significant at $\alpha = 0.05$. Pairwise comparisons of means were adjusted using the Tukey-Kramer multiple comparisons test. Using the mixed model, we also estimated and compared the slopes of the regression of P leaching to the covariate AL-extractable P in the soil. Since the rainfall simulations were performed in a consistent way, we did not account for the fact that rainfall simulations were made in blocks with soil columns from the same soil and cropping system.

For experiment 1, the dependent variables DRP and TP were transformed with the natural logarithm (ln) because residuals were then closer to a normal distribution and homoscedastic. Data on AL-extractable P were also ln-transformed to linearize the relationship between AL-extractable P and the dependent variables. The dependent variables leachate volume and percentage of DRP in TP were not ln-transformed because residual plots were satisfactory without transformation. Cropping system, soil and the interaction between cropping system and soil were set as fixed effects. The ln-transformed values of AL-extractable P (ln-AL-P) were included as a covariate, including the interaction between cropping system and ln-AL-P, the interaction between soil and ln-AL-P, and the interaction between soil, cropping system and ln-AL-P. The random effects in the model were as described above. The magnitude of the response in P leaching to elevated AL-extractable P level, also referred to as the ‘extraction coefficient’ (Sharpley et al. 2002), was quantified by calculating the slope of the regression line for each soil.

For experiment 2, with recent manure application, the increase in DRP and TP leaching was calculated by subtracting the average concentration in leachate from three rainfall simulations before manure application from the average concentration in leachate from three rainfall simulations after manure application. We did not find any time trend in concentrations between the three consecutive rain simulations and, hence, the mean values of these were used in calculations. The increases in TP and DRP were used as dependent variables and the residual plots were satisfactory without ln transformation. The random effects in the model were due to the nested factors ‘soil column’ within the same soil and P level. Consequently, the interaction between soil and P level was a random effect, while soil, AL-extractable P and the interaction between soil and AL-extractable P were fixed effects. The effect of application rate could not be separated from the effect of soil, and was not accounted for in the analysis. The effect of application rate is therefore part of the effect of soil in this model.

The percentage of DRP in TP in leachate water from experiment 2 was included in a mixed model as a dependent variable and the residual plots were satisfactory without ln transformation of the dependent variable. The fixed effects were: ln-AL-P, soil and the interaction between ln-AL-P and soil. The random effects in the model were due to the nested factors ‘soil column’ within the same soil and P level, and ‘rainfall simulation’ within the same ‘soil column’.

Results and Discussion

Experiment 1 – before recent manure application

Leachate Volumes

No differences in leachate volume were found between the cropping systems in experiment 1 (Table 4), indicating that the variability in amount of applied water between simulation rounds was minor. Therefore, significant differences in leachate volumes between the different soils ($p<0.04$) probably reflect the varying hydraulic properties of the soils. Ekebo loam leached least water, while Högåsa loamy sand, which was the coarsest soil, was one of the two soils that leached the most (Table 5).

Another factor possibly explaining varying leachate volumes could be the initial moisture conditions at the start of the experiment. All soil columns were collected in September-October, which often is a time with moist soil conditions in Sweden, and none of the soils were particularly dry. Soil columns were then stored approximately six months at 2 °C prior to rain simulations. Initial soil moisture was not measured, and was likely different between soil columns from different soils. Slightly smaller leachate volumes in the first rainfall simulation compared with the second and third were recorded for three of the soils (Ekebo loam, Högåsa loamy sand and Klostergården silty clay loam), most likely due to lower initial soil water content. However, total leachate volumes for individual soils were quite stable.

During three rainfall simulations, 76 mm of water was applied to the soil columns and based on values of porosity in Table 3, this represents 83-109% of the pore volume in the soil columns. However, the entire pore volume is usually not equally active in water and solute transport (Flury et al. 1994; Gerke 2006) and the effective pore volume is much smaller than the total pore volume in most soils. Some reported values of effective pore volume for Swedish soils vary between 0.1-0.9 (Bergström et al. 2011; Ghafoor et al. 2013). The effect of this is that water applied on top of a soil column is likely to reach the bottom before one entire pore volume has passed. Only one soil in the present study was a weakly structured sand soil, while the other soils contained 14-48% clay and in such soils preferential solute transport has been shown to occur (Koestel et al. 2012). Both intensive rain and high water content in the soil, which are conditions that were valid in the present study, are factors which enhance macropore flow (Jarvis, 2007). Leachate water collected and measured in this study was therefore a mix of water applied as simulated rainfall and water present in the soil pores at the start of the experiment. However, bypass of binding sites by preferential flow, breakthrough curves or other physical effects from the soil structure were not evaluated in the present study.

Ponding was observed in a few soil columns directly after rainfall simulation, but generally the water infiltration was satisfactory. No systematic trends in ponding were observed by soil or cropping system and therefore the ponding was not likely to have had a large effect on the overall results in this experiment.

Soil P status and leachate P concentrations

Phosphorus concentration in leachate from the soil columns in the first three rainfall simulations increased with increasing AL-extractable P in the soil (Figure 2). Corresponding slopes for all soils were significantly different from zero for both DRP and TP as dependent variable (Table 5). The concentrations in the leachate from the rainfall simulations were relatively low for the LTFE plots with long-term fertilization rates equivalent to P removal with harvested products. The mean TP concentration in the leachate was 0.12 mg L^{-1}, compared with nine-fold higher concentrations from plots representing P application rates of replacement of P +15 or +20 kg P ha^{-1} yr^{-1}. The relationship between AL-extractable P and P leachate concentrations varied across soils from different sites, with a significant interaction between soil and AL-extractable P (Table 4) and significantly different slopes between most soils (Table 5). However, in the first rainfall simulation we cannot rule out that difference in P leaching between soils was affected by different initial soil moisture. The results confirm the controlling role of soil P, measured as AL-extractable P, on P leaching from surface soils and are in agreement with Börling et al. (2004), who observed significant relationships between AL-extractable P and $CaCl_2$-extractable P (a surrogate for leachate P) for surface soils (0-20 cm) from the same LTFEs.

Phosphorus-concentrations were relatively stable in rain simulations 2-3, although less than the theoretical pore volume had leached through. In a study similar to the present, Liu et al. (2012b) found constant P concentration in leachate from clay loam topsoil columns even after eight rainfall simulations, representing approximately two pore volumes. The present experiments represented conditions with a high groundwater level near water saturation in order to reproduce conditions with a high risk of P leaching from the actual topsoil. Rubaek et al. (2010) were also able to demonstrate relationships between P leaching and topsoil Olsen-P under conditions favouring preferential flow. They used suction-controlled lysimeters in order to simulate unsaturated conditions through topsoil (20 cm) columns. The results obtained in the present study for topsoil contrast with those reported from deeper soil cores (1 m) from the Swedish LTFEs, for which no relationships were observed between AL-extractable P and P leaching (Djodjic et al. 2004). This suggests that AL-extractable P is an important explanatory variable for P leaching from surface soils, but that subsoil properties and water transport pathways can have a modifying effect on P leaching in deeper soil layers.

Proportion of DRP in TP in leachate

The percentage of DRP in TP in leachate was significantly different at different soil concentrations of AL-extractable P (Table 4) and the percentage increased with increasing soil AL-extractable P (Figure 3). This is in agreement with Rubaek et al. (2010), who observed that the greater the concentration of Olsen-P in the soil, the greater the percentage of DRP in TP in leachate water. It is also in agreement with Ahlgren et al. (2013), who used magnetic resonance spectroscopy to investigate P forms in three of the Swedish LTFEs studied here. They found that the amount of orthophosphate increased with increasing AL-extractable P, but that the amount of phosphate monoesters was rather stable. As a result, the proportion of orthophosphate in the soil increased with increasing soil P status. The interaction between AL-extractable P and cropping system was not considered significant ($p=0.052$).

Cropping system, AL-extractable soil P and P concentration in leachate

Phosphorus removal with harvested products in the five LTFEs studied here has been less than the permitted maximum application rate of 22 kg P ha^{-1} yr^{-1} set by Swedish animal density regulations. On average, more P has been removed by harvested products in MCS (18 kg ha^{-1} yr^{-1}) than in UMCS (12 kg ha^{-1} yr^{-1}), and consequently application rates of P have been higher in MCS (Börjesson 2012). However, at the time of this study, AL-extractable P was generally lower in the MCS plots on Bjertorp silty clay loam and Klostergården silty clay loam (Table 2). In the three loamy soils with minor clay content (Ekebo, Fjärdingslöv, and Högåsa), historical P fertilization at higher rates has generally led to a greater AL-extractable P in MCS than in UMCS. The relative difference in applied P between MCS and UMCS was highest in plots with low P level which received no mineral P (UMCS) or only manure (MCS).

Significant differences in both DRP and TP leaching from topsoil columns were observed between the two cropping systems (Table 4), but these differences were not consistent and were only significant for two of the soils. For Fjärdingslöv sandy loam, the mean DRP and TP concentrations in the leachate were higher from UMCS than from MCS (Table 5), despite UMCS having a generally lower soil P status (Table 2). In contrast, for Klostergården silty clay loam, the mean TP concentration in the leachate was higher from MCS than from UMCS (Table 5) although this soil represented one of two with generally lower AL-extractable P in MCS compared with UMCS (Table 2).

A high content of organic matter is suggested to be a factor which could indirectly increase the P sorption capacity by inhibition of Al (aluminium) oxide crystallization (Borggaard et al. 1990). Positive correlations between organic C and P sorption were also reported in an earlier study which included the five soils used in the present study (Börling et al. 2001). However, this could not be demonstrated in the present study, where the relative differences in soil organic C between MCS and UMCS were small, with an average range of only 6% for Klostergården and 15% for the other soils. In addition, the general level of organic C content in the soil was rather low (1.2 - 2.2%).

The three-way interaction between AL-extractable P, soil and cropping system was significant ($p=0.03$) when TP concentration in leachate was the dependent variable (Table 4). This means that there were differences in slopes between cropping systems when looking at the soils separately, with a steeper slope in the UMCS for Fjärdingslöv sandy loam, Högåsa loamy sand, and Klostergården silty clay loam. Bjertorp silty clay loam had no differences in slopes between cropping systems, while Ekebo loam had a steeper slope in the MCS. However, differences in slopes were small. In conclusion, long-term moderate manure application in the LTFEs, which increased crop yield, did not seem to have had any overall effect on the P concentration in leachate, and hence on potential P leaching.

Experiment 2 - P leachate concentration after recent manure application

Soil P status and P concentration in leachate

Columns from Bjertorp silty clay loam, Fjärdingslöv sandy loam and Ekebo loam received 8 kg P ha^{-1} more than the maximum application rate (22 kg P ha^{-1} yr^{-1}) set by Swedish animal density regulations. In Bjertorp silty clay loam and Fjärdingslöv sandy loam, this application increased the mean concentration of DRP and TP in leachate and the increase was correlated to AL-extractable P (Figure 4). In Klostergården silty clay loam, which had received a P application very close to the maximum rate (21 kg P ha^{-1} yr^{-1}), the DRP and TP concentration in leachate also increased, but only the increase in DRP concentration was correlated to AL-extractable P (Table 7). However, significant differences in slopes and least squares means were found across soils after recent manure application (Table 7). In Ekebo loam and Högåsa loamy sand there were no increase in DRP after manure application (Table 7) and neither showed any significant correlation to AL-extractable P (Table 7). In experiment 1, for Högåsa loamy sand and Ekebo loam the DRP concentration in leachate was higher before recent manure application at the high AL-extractable P level than after manure application at the medium P level, which was also the case for Klostergården silty clay loam. Consequently, the long-term build-up of soil P was more important for leachate P concentration than recent manure application to these soils. Similarly, Hahn et al. (2012) found that manure application did not override the effect of soil P status on the P concentration in runoff water. Likewise, Liu et al. (2012a) found that the build-up of soil P with long-term manure application was more important for potential P leachate losses than a single manure application to loamy sand.

Temperature was approximately 20 ºC while soil columns were placed in the rainfall simulator and some mineralization of organic P may have taken place which could have changed P concentration in soil solution over time. However, He et al. (2004) found that when dairy manure was mixed with soil at a rate of 28 mg dairy manure P kg^{-1} dry soil and incubated at 25 ºC, the water extractable inorganic P remained stable over time. In our experiment the application rate was <10 mg dairy manure P kg^{-1} dry soil (calculated with dry bulk densities from Kirchmann et al. 1999; 2005), although, we did not mix the manure with the soil.

Proportion of DRP in the leachate

The percentage of DRP in TP (Fig. 3) was 49% on average across all soils after manure application, with Bjertorp silty clay loam having the highest percentage of DRP in TP and Ekebo loam the lowest (Table 7). Both soil and AL-extractable P had a significant effect on the percentage of DRP in TP after manure application (Table 6). The percentage of DRP in TP increased as AL-extractable P increased (Fig. 3) and slopes were not significantly different between soils (Table 6). Total P concentration in the manure was 0.69 and 1.0 g kg^{-1} and reported literature values of the proportion of inorganic P in Dairy cow manure are e.g. 54% (Pagliari and Laboski, 2012) and 63% (Barnett, 1994). However, of the P present in the leachate water, we cannot differentiate between the P that came from the manure and the P that came from the soil and pore water solution present in the soil. Transport pathways differ between soils due to differences in shape and size of the pores, and this affects how fast manure P is transported through the soil. Manure applications may also affect P adsorption properties in soils (Bolan et al., 1994), and consequently affect the source of P that is found in leachate.

Other P leaching indices for leachate P concentrations

No totally consistent comparisons can be made with P saturation indices such as P sorption maximum, P buffering capacity and degree of P saturation (Table 3), since these parameters were only measured in UMCS and in experiment 2 we applied manure to soil columns from MCS. However, it is interesting to note that Högåsa loamy sand and Ekebo loam, i.e. the two soils with rather constant P concentration in the leachate after manure addition, irrespective of soil P status, had the lowest degree of P saturation. Fjärdingslöv sandy loam had the second highest degree of P saturation as well as second highest DRP concentration in leachate. On the other hand, Bjertorp silty clay loam had the highest concentration of DRP in leachate but not very high degree of P saturation.

Manure application may increase soil P solubilization and decrease P adsorption due to increased amounts of organic acids (Bolan et al., 1994). This is a possible mechanism in the three soils in the present study where DRP leaching increased as AL-extractable P increased after recent manure application. In contrast, Guppy et al. (2005) suggested that increased leaching of DRP after manure application might be the result of P from the actual manure. This is in agreement with the findings for Högåsa loamy sand and Ekebo loam in the present study, which had more or less the same P leaching after recent application irrespective of soil P status.

Several other factors such as clay content or pH could not solely explain the different results between the five soils in the present experiment. Overall, the results show the complexity of P leaching from the soil. Furthermore, the presence of biopores and cracks in the soil columns was not evaluated in this study, but is likely to have an effect on P leaching losses after P application (Djodjic et al. 1999; Glaesner et al. 2011). Interactive effects between applied P sources of different types and soil test P on P leaching potential need to be further investigated in order to identify soils that are especially susceptible to P leaching and to avoid unnecessarily high P loadings to water bodies.

Conclusions

This study showed that soils that receive moderate and infrequent applications of manure in a cropping system which includes leys may not leach more P than an unmanured cropping system with cereals. However, soils behave differently regarding P leaching after recent manure application around current maximum permitted rates set by Swedish animal density regulations. In some soils, there was an increase in Dissolved Reactive P (DRP) concentration after dairy cow manure application and this increase was significantly correlated to soil test P. In other soils, there was no corresponding increase in P leaching after recent manure application. Identification of soils that are especially susceptible to P leaching when manure is applied is important in efforts to reduce P loadings to water bodies. Previous reports of an increased risk of P leaching from soils with high soil test P were confirmed in this study, although a wide variation in the relationship was observed across soils. Phosphorus leaching was low at long-term fertilization rates equivalent to P removal with harvested products, which stresses the importance of long-term P balance to limit P leaching losses. Such a fine-tuned strategy also requires determination of P removal with harvested products, which in the Swedish long-term fertility experiments has been less than the national limit for P application, 22 kg P ha^{-1} yr^{-1}, set through animal density regulations.

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Figure captions

Fig. 1 Timeline showing rainfall simulations and manure application. Manure was only applied to soil columns from the manured cropping system (MCS). Simulated rainfall was applied only three times (25 mm per event) to soil columns from the unmanured cropping system (UMCS).

Fig. 2 Relationships between ammonium lactate (AL) extractable P and concentration of dissolved reactive phosphorus (DRP) and total phosphorus (TP) in leachate from the three rainfall simulations in experiment 1. Each dot represents the mean of the three rainfall simulations and four soil columns from the same P-level, cropping system and soil. Error bars with standard deviation. Data transformed with the natural logarithm.

Fig. 3 Relationship between ammonium lactate (AL)-extractable P in the soil (data transformed with the natural logarithm) and the percentage of dissolved reactive P (DRP) in total P (TP) in leachate. Error bars with standard deviation. See Tables 4-7 for more information about the relationships.

Fig. 4 Increase in concentration of dissolved reactive phosphorus (DRP) and total phosphorus (TP) in leachate after manure application related to ammonium lactate (AL)-extractable P. Each dot represents the mean of four soil columns from the same P level, cropping system and soil. Error bars with standard deviation.

Tables

Table 1 Application rates of P to field plots, in relation to P removed with harvest

P level	P application rate (kg ha yr^{-1})	
	Fjärdingslöv, Ekebo	Bjertorp, Klostergården, Högåsa
Low	0	0
Medium	Replacement	Replacement
High	Replacement + 15	Replacement + 20
Very high	Replacement + 30	Replacement + 30

Table 2 Texture and concentration of ammonium lactate-extractable P (mg kg^{-1}) at different P levels in field plots. Results from composite topsoil samples (0-20 cm depth) taken in the autumn 2007

		Manured cropping system (MCS)				Unmanured cropping system (UMCS)			
	Texture	Low	Medium	High	Very high	Low	Medium	High	Very high
Bjertorp	Silty clay loam	19	24	70	101	18	28	87	123
Ekebo	Loam	36	70	164	236	24	46	109	173
Fjärdingslöv	Sandy loam	26	58	132	208	15	23	111	183
Högåsa	Loamy sand	29	42	80	133	18	26	84	116
Klostergården	Silty clay loam	23	29	100	121	34	47	117	152

Low, medium, high and very high refer to P levels with varied P application in relation to P removed with harvested products, see Table 1. Börling et al. (2001) reported P-AL for the low P level with standard deviations <1 mg kg^{-1}.

Table 3 Selected chemical and physical properties of soils used in the experiment. Degree of P saturation using ammonium lactate-extractable Fe, Al and P (DPS-AL) calculated according to Ulén (2006) on data from topsoil samples taken in 2010 in the high P level treatment in the unmanured cropping system (Anders E Lindsjö, personal communication)

	Texture[a]	PSC_{max}[b] (mmol kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Porosity (%)	pH[a]	Organic C[e] (%)	Ca (cmol kg^{-1})	PBC[a] (l kg^{-1})	Fe_{ox}+ Al_{ox}[b] (mmol kg^{-1})	DPS-AL (%)
Bjertorp	Silty clay loam	8.8	nd	nd	30[a]	nd	6.6	1.8	nd	4.7	111	22
Ekebo	Loam	10.2	47[d]	36[d]	18[d]	44[d]	6.5	2.2	7.9[d]	5.3	108	13
Fjärdingslöv	Sandy loam	6.0	62[d]	24[d]	14[d]	35[d]	7.5	1.2	11.3[d]	3.2	70	29
Högåsa	Loamy sand	10.0	77[c]	15[c]	7[c]	46[c]	5.8	1.8	3. 8[c]	4.7	116	18
Klostergården	Silty clay loam	6.9	9[c]	44[c]	48[c]	45[c]	6.9	1.8	21.3[c]	3.9	89	33

Topsoil samples were taken from the unmanured cropping system (low P level).

PSC_{max}: maximum P sorption capacity; Fe_{ox}+ Al_{ox}: ammonium oxalate-extractable Al and Fe ; PBC: P buffering capacity ; nd: not determined.

[a] Börling et al. (2001), [b] Börling et al. (2004), [c] Kirchmann et al. (2005), [d] Kirchmann et al. (1999), [e] Börjesson (2012), [f] Djodjic et al. (2004)

Table 4 Main effects and interactions (p-values) from the statistical analyses of P leaching, before recent manure application, at different concentrations of AL-extractable P. Dissolved reactive P, TP, percentage DRP in TP and leachate volume were used as dependent variables. Data on DRP, TP and AL-extractable P were transformed with the natural logarithm in the analysis

	Dependent variable (p-value)			
	DRP	TP	% DRP in TP	Leachate volume
CS	0.3	0.007	0.3	0.8
AL-P	<0.0001	<0.0001	<0.0001	0.6
Soil	0.006	<0.0001	0.1	0.04
AL-P * CS	0.9	0.2	0.05	0.9
AL-P * Soil	<0.0001	<0.0001	0.09	0.5
Soil * CS	0.008	0.002	0.2	0.8
AL-P * Soil * CS	0.07	0.03	0.1	0.8

DRP: Dissolved Reactive Phosphorus; TP: Total Phosphorus; CS: Cropping System; AL-P: Ammonium Lactate extractable P

Table 5 Estimates of least squares means and slopes with p-values, for P leaching before recent manure application. Leachate volume, DRP and TP were used as dependent variables in the statistical analysis. The LS means are mean values of leachate concentration or leachate volume, from three 25 mm rainfall simulations and from four soil columns. Values of DRP, TP and AL-extractable P were transformed with the natural logarithm, and the unit before transformation was mg L^{-1} for DRP and TP. In a, slopes with p-values for DRP and TP and LS means of leachate volumes for the different soils are shown. In b, LS means for DRP and TP of different soils and cropping systems are shown separately. Back-transformed geometric means are given within brackets. In c, comparisons between cropping systems for each soil are shown.

Soil	——— DRP ———		——— TP ———		Leachate volume (mm)	
a)						
	Slope	p-value	Slope	p-value	LS Mean	SEM
Bjertorp	2.2 c	<0.0001	1.3 b	<0.0001	28 c	1.6
Ekebo	1.2 a	<0.0001	0.58 a	<0.0001	17 a	1.6
Fjärdingslöv	1.6 b	<0.0001	1.2 b	<0.0001	19 a, b	1.5
Högåsa	2.1 b, c	<0.0001	1.6 c	<0.0001	27 c	1.5
Klostergården	2.9 d	<0.0001	2.1 d	<0.0001	24 b, c	1.5
b)						
	LS Mean	SEM	LS Mean	SEM		
Manured cropping system (I)						
Bjertorp	-1.4 (0.25) c	0.20	-0.83 (0.44) d	0.11		
Ekebo	-4.0 (0.019) a	0.22	-3.0 (0.05) a	0.12		
Fjärdingslöv	-2.6 (0.072) b	0.19	-2.0 (0.14) b	0.10		
Högåsa	-2.5 (0.083) b	0.18	-1.5 (0.23) c	0.094		
Klostergården	-1.5 (0.22) c	0.19	-0.63 (0.53) d	0.097		
Unmanured cropping system (II)						
Bjertorp	-1.2 (0.30) c	0.19	-0.52 (0.59) c	0.098		
Ekebo	-3.4 (0.033) a	0.18	-2.6 (0.08) a	0.095		
Fjärdingslöv	-1.5 (0.22) c, b	0.18	-1.0 (0.35) b	0.095		
Högåsa	-1.7 (0.18) c, b	0.19	-1.1 (0.33) b	0.10		
Klostergården	-2.4 (0.093) b	0.19	-1.3 (0.28) b	0.099		
c)						
Comparisons of LS Means between cropping systems (p-values shown)						
Bj I vs. Bj II	0.9		0.5			
Ek I vs. Ek II	0.6		0.3			
Fj I vs. Fj II	0.01		<0.0001			
Hö I vs. Hö II	0.2		0.2			
Kl I vs. Kl II	0.09		0.004			

Values within columns and sections with different letters are significantly different.
DRP: Dissolved Reactive Phosphorus; TP: Total Phosphorus; SEM: Standard Error of the Mean

Table 6 Main effects and interactions (p-values) from the statistical analyses of P leaching, after recent manure application, at different concentrations of AL-extractable P in five soils

	Dependent variable (p-value)		
	Increase DRP	Increase TP	% DRP in TP
Soil	0.05	0.03	<0.0001
AL-P	<0.0001	0.003	<0.0001
AL-P*Soil	0.0003	0.009	0.2

DRP: Dissolved Reactive Phosphorus; TP: Total Phosphorus; AL-P: Ammonium Lactate extractable P

Table 7 Estimates of least squares means and slopes for each soil from the statistical analysis of increase in P leaching after recent manure application. Increase in dissolved reactive P (DRP), increase in total P (TP), and percentage DRP in TP were used as dependent variables

	Increase DRP (mg L^{-1})					Increase TP (mg L^{-1})					% DRP in TP			
Soil	LS Mean	p-value	SEM	Slope	p-value	LS Mean	p-value	SEM	Slope	p-value	LS Mean	SEM	Slope	p-value
Bjertorp	1.7 d	<0.0001	0.1	0.17 c	<0.0001	2.0 c	<0.0001	0.2	0.17 b	0.0006	0.82 d	0.02	0.11	0.0004
Ekebo	0.0098 a	0.9	0.08	0.00054 a	0.9	0.2 a, b	0.2	0.1	0.0047 a	0.8	0.15 a	0.02	0.048	0.1
Fjärdingslöv	0.95 c	<0.0001	0.07	0.042 b	0.002	1.6 c	<0.0001	0.1	0.047 a	0.02	0.58 c	0.02	0.13	<0.0001
Högåsa	-0.042 a	0.6	0.07	-0.0076 a	0.68	-0.13 a	0.3	0.1	-0.026 a	0.4	0.40 b	0.02	0.15	0.0001
Klostergården	0.44 b	0.0002	0.08	0.040 a, b	0.04	0.54 b	0.002	0.1	0.030 a	0.3	0.58 c	0.02	0.12	0.0003

Values within columns with different letters are significantly different.

SEM: Standard Error of the Mean

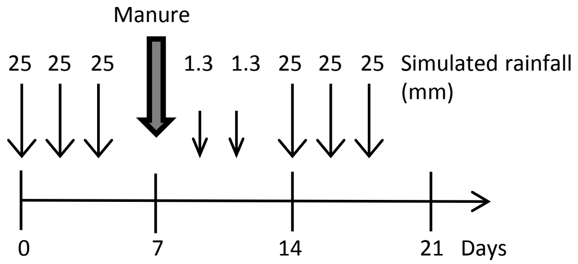

Figure 1.
Annika Svanbäck, Barbro Ulén, Ararso Etana, Lars Bergström, Peter Kleinman and Lennart Mattsson.
Influence of soil phosphorus and manure on phosphorus leaching in Swedish topsoils.

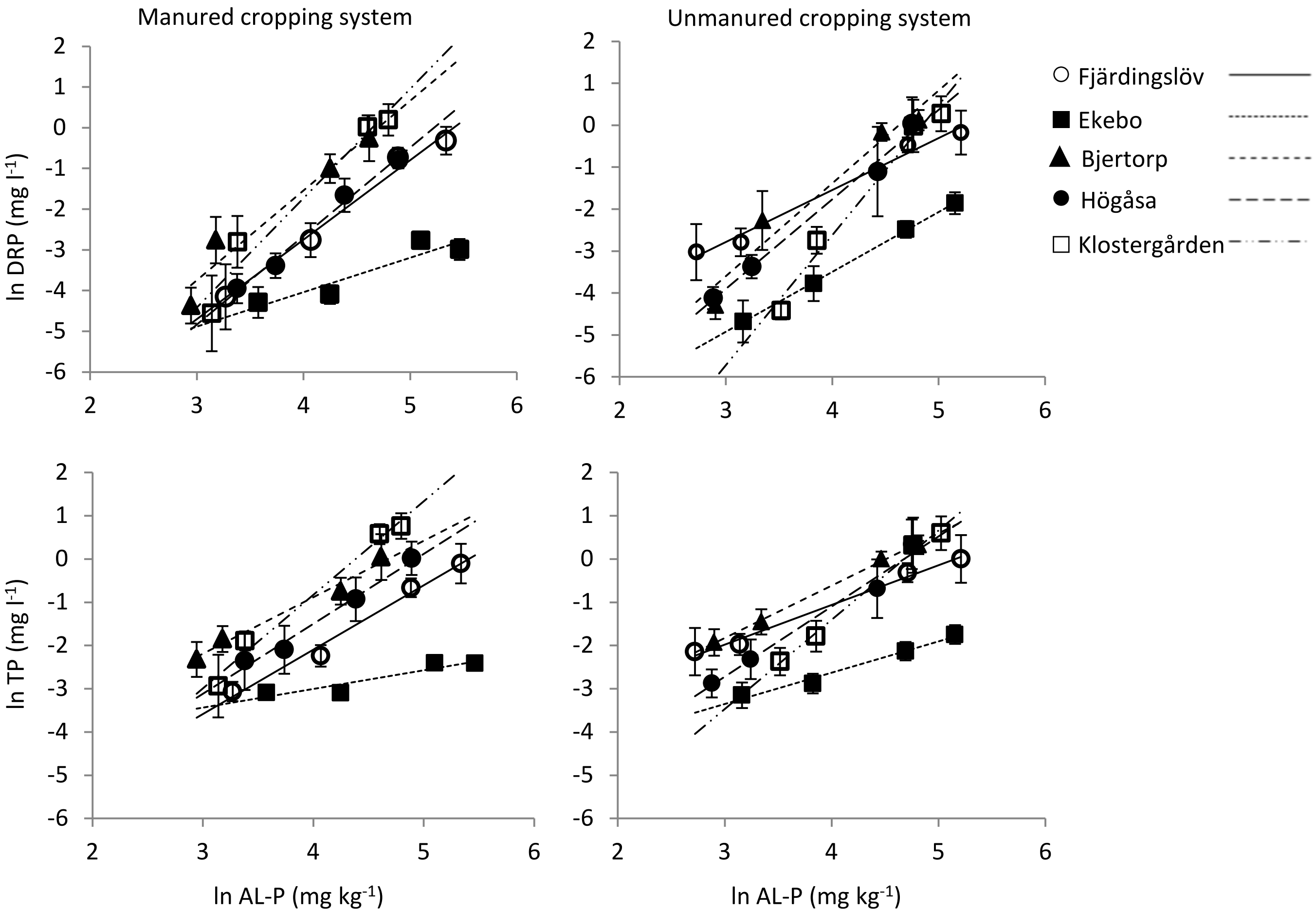

Figure 2.

Annika Svanbäck, Barbro Ulén, Ararso Etana, Lars Bergström, Peter Kleinman and Lennart Mattsson.
Influence of soil phosphorus and manure on phosphorus leaching in Swedish topsoils.

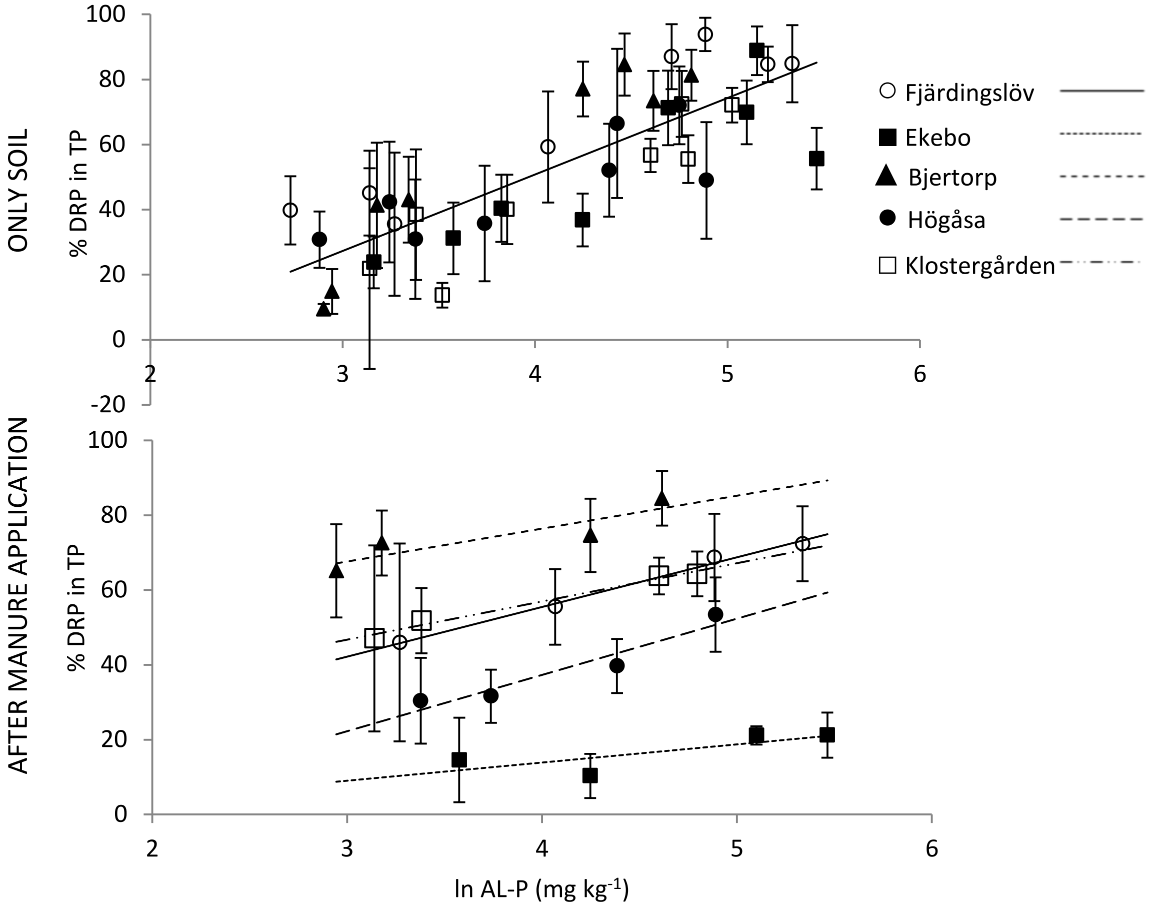

Figure 3.

Annika Svanbäck, Barbro Ulén, Ararso Etana, Lars Bergström, Peter Kleinman and Lennart Mattsson. Influence of soil phosphorus and manure on phosphorus leaching in Swedish topsoils.

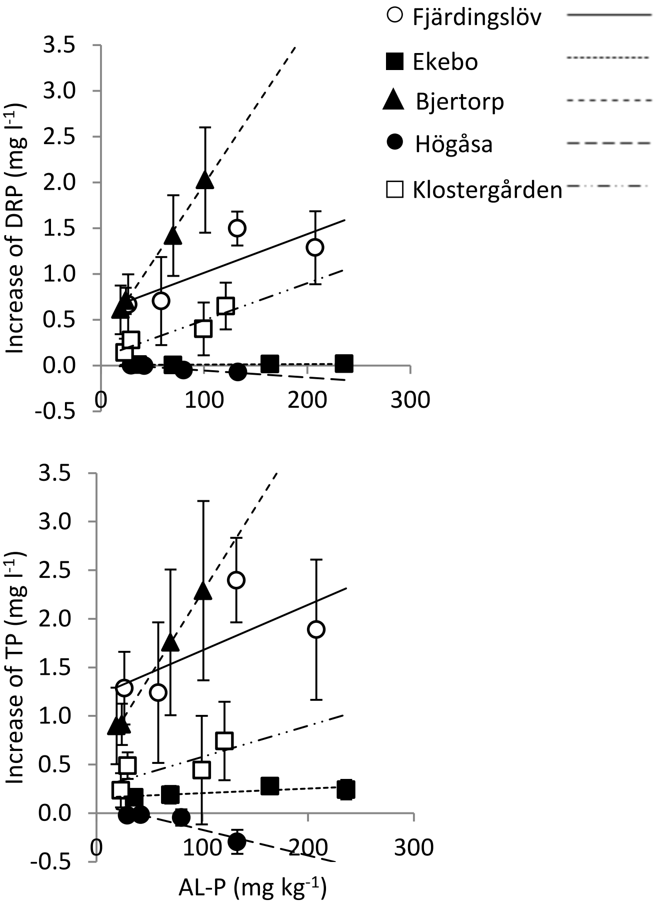

Figure 4.

Annika Svanbäck, Barbro Ulén, Ararso Etana, Lars Bergström, Peter Kleinman and Lennart Mattsson.

Influence of soil phosphorus and manure on phosphorus leaching in Swedish topsoils.