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Long-term measurements and model simulations of phosphorus leaching from a manured sandy soil

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Abstract: Cropping systems with high phosphorus (P) inputs may constitute a risk of P leaching, which contributes to eutrophication. The main objective of this study was to identify P leaching risks associated with three long-term fertilization regimes in separately tile-drained plots on a sandy soil in southwest Sweden. The three regimes resulted in different annual P surpluses of, on average, 16 kg P ha^{-1} (14 lb P ac^{-1}) in mineral form and 18 kg P ha^{-1} (16 lb P ac^{-1}) and 37 kg P ha^{-1} (33 lb P ac^{-1}) as pig slurry. The importance of different soil characteristics (soil P, iron, aluminum, and calcium content, and degree of P saturation [DPS]) and processes (water flow and P sorption/desorption) was examined using 15 years (1989 to 2003) of P leaching measurements and simulations with the ICECREAM model. Measurements of high soil P content and DPS values in the topsoil, in combination with high precipitation and rapid water flow, indicated a high potential for P losses, which was confirmed by the model simulations. However, the model considerably overestimated total P leaching by a factor of 5 to 9 since measured P leaching was small for all treatments. Measured mean annual total P leaching and total P concentration ranged respectively from 0.14 kg ha^{-1} (0.12 lb ac^{-1}) and 0.06 mg L^{-1} (3.75 × 10^{-6} lb ft^{-3}) at a high rate of slurry application to 0.20 kg ha^{-1} (0.18 lb ac^{-1}) and 0.08 mg L^{-1} (4.99 × 10^{-6} lb ft^{-3}) in the mineral P treatment. The differences in concentration were statistically significant ($p < 0.001$). A main conclusion from this 15-year study was that annual pig slurry application rates of 37 to 58 kg P ha^{-1} (33 to 52 lb P ac^{-1}) did not increase P leaching. High sorption capacity of the subsoil, caused by Fe, Al, and Ca, was obviously very important for controlling P losses. Thus, information on soil P content and fertilization must be supplemented with estimates of soil P sorption capacity when evaluating the risk of P leaching for different soils. This must also be considered in models used for assessment of P leaching from arable land. The current ICECREAM model does not include appropriate functions for describing P sorption/desorption processes in this type of soil and needs further development.

Key words: phosphorus application rate—phosphorus leaching—pig slurry—sorption/desorption processes—ICECREAM model

Agriculture is estimated to contribute roughly 40% of the phosphorus (P) loading to Swedish fresh waters and the Baltic Sea, which are threatened with accelerating eutrophication (Brandt and Ejhed 2003). The mechanisms and processes behind P transport from agricultural soils to water are complex. Topography, soil texture/structure, soil chemical properties, and precipitation are factors that determine the type of losses (i.e., surface runoff, erosion, or leaching) that dominate for a specific soil, which in turn determines how different management practices affect P losses. One of the most important factors is P fertilization, which can affect P losses in different ways depending on type of fertilizer (inorganic or organic), application rate and method (incorporation or not), and time of application.

Excessive applications of P, especially in areas with intensive livestock production, are receiving increasing attention in water quality management work (e.g. Sharpley et al. 2004a). This is largely due to the risk of long-term buildup of P in the soil, which has been observed in many agricultural areas. In Sweden, monitoring of agricultural soils has shown that about one-third of arable soils have what is considered a high plant-available P content (P-AL [P extracted with ammonium lactate and acetic acid solution] >8 mg 100 g^{-1} in soils) (Eriksson et al. 2010). According to Swedish official recommendations (Albertsson 2010), reduced P fertilization levels are recommended for such soils due to the higher risk of P leaching. A number of studies have observed a clear relationship between soil P content and potential release of dissolved reactive P (DRP) (Heckrath et al. 1995; Pote et al. 1999; Torbert et al. 2002; Börling et al. 2004). However, these studies also stress the importance of considering site-specific properties in order to make appropriate risk assessments, e.g., where measurements of soil P content are combined with measurements of other soil properties such as P sorption capacity.

Several methods to determine P sorption properties have been developed, among which estimating P sorption index is one widely accepted and used method (Bache and Williams 1971; Börling et al. 2001). For acid soils, where sorption of P mainly occurs on the surfaces of iron (Fe) and aluminum (Al) oxides and hydroxides, P sorption capacity of the soil can be calculated from the estimated Fe and Al contents. The degree of P saturation (DPS), interpreted as the percentage of a soil's P adsorption capacity already occupied by P, was developed by Van der Zee and Van Riemsdijk (1988) and has been used to predict the potential of the soil to adsorb and release P (Tarkalson and Mikkelsen 2004). DPS is commonly calculated as the relationship between the soil P content and the amount of Fe and Al. Another saturation index is expressed as soil P divided by P sorption index (Börling et al. 2004). However, the flow paths for water through soil may overshadow soil chemical properties, as shown for example by Pote et al. (1999) and Djodjic et al. (2004) for different types of soil.

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Table 1
Soil chemical properties in 1988, before the start of the study, for all plots. The different fertilization regimes are presented in table 2.

Properties	Fertilization regime					
	Low rate of slurry		High rate of slurry		Mineral P, no N	
	No CC	With CC	No CC	With CC	No CC	With CC
Total-C (%)						
0 to 0.3 m	3.1	2.9	3.2	3.5	2.6	3.3
pH						
0 to 0.3 m	5.7	5.9	6.2	6.2	6.0	5.8
0.3 to 0.6 m	5.6	5.9	6.2	6.4	6.0	6.0
0.6 to 0.9 m	5.9	6.1	6.1	6.4	5.6	6.3
P-AL (mg 100 g^{-1})						
0 to 0.3 m	23.2	22.3	26.4	32.4	24.2	28.2
0.3 to 0.6 m	2.7	2.6	2.6	4.4	3.2	5.8
0.6 to 0.9 m	2.2	3.9	2.6	5.4	3.2	4.4

Notes: Total-C = total carbon content. N = nitrogen. P = phosphorus. AL = extraction with ammonium lactate. CC = cover crop.

There is increasing interest in using mathematical simulation models to predict P loads to surface waters and/or groundwater and to evaluate the influence of various soil processes and management practices. Accordingly, a number of models with different emphases and limitations have been developed in recent years. In Sweden, P leached through the soil profile normally constitutes a large proportion of P losses. Hence, water and P transport processes through the soil have to be considered in any model used for Swedish conditions. The ICECREAM model (Rekolainen and Posch 1993; Larsson et al. 2007), which simulates surface and subsurface P losses in both dissolved and particulate forms, has been used for calculation of P leaching losses from Swedish agricultural soils at both regional and national scales (Johnsson et al. 2008). However, the model has not yet been thoroughly tested for field-scale applications.

In the present study, measurements and results simulated with the ICECREAM model were evaluated for a 15-year field leaching experiment on a sandy soil with different applications of liquid manure and mineral P fertilizer. The main objectives were to identify risks of P leaching associated with long-term use of pig slurry and to examine how soil characteristics (soil P, Fe, Al, and Ca [calcium] contents and DPS) and processes (water flow and P sorption/desorption) affected the P leaching patterns apparent in the measurements.

Materials and Methods

Site Description. The study was conducted in a long-term field experiment at the Swedish University of Agricultural Sciences' Mellby experimental site, located near Halmstad, southwest Sweden (56°29´ N, 13°00´ E). The soil profile is a Fluventic haplumbrept (Soil Survey Division Staff 1993), with 90 to 130 cm (35.4 to 51.1 in) sandy deposits overlying a glacifluvial clay. As indicated by ammonium lactate-soluble P (P-AL), the soil had a high P status in the topsoil, for which reduced P fertilization is recommended due to long-term manure application before the start of the experiment (table 1). The mean annual temperature in Halmstad from 1961 to 1990 was 7.2°C (45°F) and the mean annual precipitation was 803 mm (31.6 in). During the 15-year study period (1989 to 2003), mean annual precipitation was 722 mm (28.4 in), and mean annual temperature was 7.8°C (46°F). In 1982, 10 plots (30 × 30 m [98 × 98 ft]) were separately tile-drained. Drainage pipes with a diameter of 5.5 cm (2.2 in) were placed 7 m (23 ft) apart at about 90 cm (35.4 in) depth. Drainage water from each plot was routed in sealed pipes (7.5 cm [2.95 in] in diameter) to an underground measuring station that maintained a temperature below 10°C (50°F).

Table 2
Three fertilization regimes with different P application rates and P surpluses, calculated by deducting amounts of harvested P (including straw) from amounts of applied P. Annual mean values for 1989 to 2003.

Fertilization regime	Number of plots	Applied P (kg ha^{-1}) Pig slurry	Applied P (kg ha^{-1}) Mineral P	Harvested P (kg ha^{-1})	Surplus P (kg ha^{-1})
Low rate of slurry	2	28 (0)	9 (0)	19 (0.6)	18 (0.6)
High rate of slurry	2	56 (0)	2 (0)	20 (0.3)	37 (0.3)
Mineral P, no N	2	0 (0)	24 (0)	8.5 (1.1)	16 (1.1)

Note: Standard deviation given within parentheses. P = phosphorus. N = nitrogen.

Experimental Treatments. Six tile-drained plots were used in this study, with three pairs representing three fertilization regimes randomly distributed over the field. Pig slurry was applied at two rates corresponding to 28 and 56 kg P ha^{-1} y^{-1} (25 and 50 lb P ac^{-1} yr^{-1}) (table 2). The low-rate regime represented amounts produced on a farm with the maximum permitted animal density in Sweden. In the third treatment only mineral P was applied, with rates commonly used for the crops grown. Spring cereals were grown during 11 years of the 15-year experimental period (mainly oats [*Avena sativa* L.] and spring barley [*Hordeum vulgare* L.]), while spring oilseed rape (*Brassica napus* L.) and potatoes (*Solanum tuberosum* L.) were grown during two years each. The pig slurry and mineral P were applied and incorporated by harrowing before sowing in the spring of each year.

The experiment was originally designed for nitrogen (N) leaching studies, with the plots used for the mineral P treatment as control plots receiving no N fertilizer. This resulted in low crop yields in this treatment and a surplus of P similar to that in the treatment with the low rate of slurry (table 2). Each of the three fertilization regimes had two plots with identical fertilization, but one of the plots in each pair was stubble-cultivated after harvest in August to September and plowed in November, while the other had a cover crop during the fall and was plowed in the spring. Therefore, the fertilization regimes did not have true replicates, a factor that had to be considered in evaluation of the results.

Sampling and Measurements. Discharge rates from each plot were recorded with tipping buckets connected to a data logger, which stored accumulated daily amounts of drainage. Flow-proportional water samples of 15 mL (0.9 in^3) were taken using a peristaltic pump after every 0.2 mm (7.9 × 10^{-3} in) discharge. The samples were collected in individual polyethylene bottles for each plot, which were emptied every two weeks during drainage periods for analyses of DRP (only until 1999) and total P. Total P concentrations were determined on unfiltered samples and DRP on filtered samples (0.2 μm [7.9 × 10^{-6} in]) according to colorimetric methods issued by the European Committee for Standardization (ECS 1996).

The daily leaching loads of P were calculated by multiplying the concentration in each sample, which represented the two-week period before sampling, by the daily amount of drainage during that period. Annual values of leaching were obtained by adding up daily values during the period from April 1 to March 31 the following year, i.e., the time from sowing and fertilization of one crop until sowing of the next. The mean annual concentrations were obtained by dividing the accumulated annual load by the annual amounts of drainage from each plot.

To determine crop yields, three samples of grain/straw, oilseed, and potatoes were collected with common harvesting methods from each plot. The material was weighed, dried at 50°C (122°F), reweighed, and analyzed for P content by combustion on an elemental analyzer (Leco CNS-2000, Leco Corporation, St Joseph, Michigan).

Soil Chemical Properties. In order to identify soil chemical properties that may have affected P leaching from different plots, analyses were performed during 2010 on dry soil samples from the topsoil (0 to 0.3 m [0 to 11.8 in] depth) and subsoil (0.3 to 0.6 m [11.8 to 23.6 in] and 0.6 to 0.9 m [23.6 to 35.4 in] depths, respectively), which had been dried and stored since 2005. Measurements were made of P, Al, Fe, and Ca with ICP (inductively coupled plasma) spectrometry after extraction with 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). This is the method commonly used in Sweden for estimating plant-available P in soil. The concentration of DRP in the extract was analyzed after centrifugation and filtration (0.2 μm [7.9 × 10^{-6} in]) according to colorimetric methods issued by the European Committee for Standardization (ECS 1996), and values were converted to mg 100 g^{-1} soil. The Fe (Fe-AL, iron extracted with ammonium lactate) and Al (Al-AL, aluminum extracted with ammonium lactate) contents in the same extraction solution were analyzed in order to estimate the P sorption capacity of the soil. The DPS value (%) was calculated as the ratio between P-AL and Fe-AL + Al-AL, expressed on a molar basis (Ulén 2006). According to the same procedure, water-extractable phosphate-phosphorus (PO_4-P) was determined after extraction with distilled water at a soil: water ratio of 1:3.

Model Description. The ICECREAM model is a field-scale model for calculation of water discharge, erosion, and P losses. It is basically derived from the CREAMS model (Knisel 1980) and adjusted by incorporating snow and soil frost processes to suit Nordic conditions (Rekolainen and Posch 1993; Tattari et al. 2001). Preferential flow is also included to better describe flow processes in well-structured soils (Larsson et al. 2007).

The model runs on a daily time-step resolution with daily climate variables (temperature, precipitation, and cloudiness or solar radiation) and parameters related to crop management practices (type of crop, yields, fertilization, soil tillage operations, and dates for the different actions) as input to the simulations. In this study, the soil profile was divided into four layers (0 to 1 cm [0 to 0.4 in], 1 to 30 cm [0.4 to 11.8 in], 30 to 65 cm [11.8 to 25.6 in], and 65 to 100 cm [25.6 to 39.4 in]). The model simulates a full water balance including precipitation, evapotranspiration, surface runoff, and percolation between layers and out of the root zone. A modification of the Soil Conservation Service curve number method is used to partition the precipitation between surface runoff and infiltration (USDA-SCS 1972; Smith and Williams 1980). Percolation losses are partitioned between macropore flow (preferential flow) and matrix flow, and between losses through tile drains and deep percolation (Larsson et al. 2007). Downward water flow between layers in the micropore region is calculated with a storage-routing concept and occurs when the water content in a layer exceeds the storage capacity (i.e., field capacity minus wilting point) of that layer (Knisel 1980).

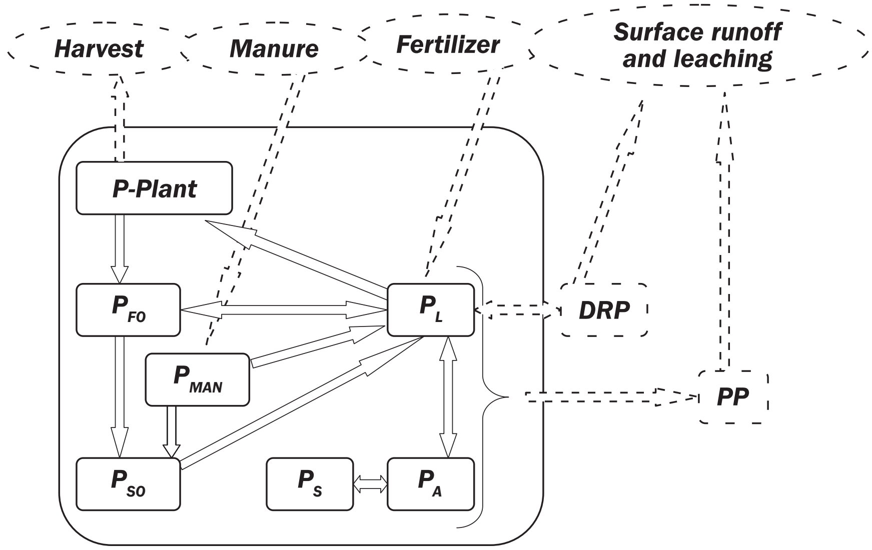
Preferential flow and transport are simulated through a short-circuit water flow pathway, corresponding to a macropore domain (Larsson et al. 2007). Water, suspended particles, and P entering the macropores are channeled directly to a groundwater reservoir assumed in the model, without interaction with the micropore region. Infiltration into macropores takes place if the moisture content of the two upper layers exceeds a given fraction of the field capacity. A soil-type dependent fraction (*Rf*) of infiltrating water is routed into macropores when infiltration exceeds a given threshold value (*Thresh_watin*). The groundwater reservoir receives percolating water and P from both the micropore and the macropore domain. From the groundwater reservoir, water and P can be routed either into tile drainage outflow or to deep percolation.

Phosphorus is added to the soil through fertilization with inorganic P or manure. Phosphorus is lost from the soil through harvest of plant biomass or through losses of particulate-bound P and DRP with surface runoff and percolating water. Losses of particulate-bound P through subsurface pathways occur only through macropores, while DRP is transported through both micropores and macropores.

Soil P is divided into six different pools (figure 1): three pools representing stable (P_S), active (P_A), and labile (P_L) inorganic P forms and three organic pools representing manure P (P_{MAN}), fresh organic matter P (P_{FO}), and slowly mineralizable humus P (P_{SO}). All soil P pools contribute to particulate-bound P losses. P_L is the source of DRP, which can be taken up by plants (P-PLANT) or immobilized into P_{FO} and lost through surface runoff and subsurface drainage. Additions of animal manure are placed into P_{MAN} and mineral-P fertilizer into P_L. Phosphorus is transferred to P_L from the organic-P pools through mineralization and from the mineral-P pools through sorption/desorption processes.

Figure 1

Phosphorus pools and flows in the ICECREAM model (Larsson et al. 2007).



Notes: DRP = dissolved reactive P. PP = particulate-bound P. P_S = stable inorganic P. P_A = active inorganic P. P_L = labile inorganic P. P_{MAN} = manure P. P_{FO} = fresh organic P. P_{SO} = slowly mineralizable humus P. P-Plant = P taken up by plants.

Table 3

Adjusted model parameter values differing from those used for the national calculations in Sweden (Johnsson et al. 2008).

Parameter	Adjusted values	Source for adjustment
Soil specific density (t m^{-3})	2.51, 2.55, 2.65, 2.66*	Measurement
Clay (m^3 m^{-3})	0.10, 0.10, 0.02, 0.01*	Measurement
Sand (m^3 m^{-3})	0.77, 0.77, 0.91, 0.86*	Measurement
Organic matter (m^3 m^{-3})	0.05, 0.05, 0.01, 0.005*	Measurement
Field capacity (m^3 m^{-3})	0.258, 0.227, 0.056, 0.079*	Measurement
Soil porosity (m^3 m^{-3})	0.418, 0.398, 0.324, 0.360*	Measurement
Wilting point (m^3 m^{-3})	0.079, 0.078, 0.014, 0.015*	Measurement
K1(% d^{-1})	0.83	Calibration
K2 (% d^{-1})	1.00	Calibration
Thresh_watin (m h^{-1})	0.0094	Calibration
R_f	0.5	Calibration
Soil P content		
Low rate of slurry (g kg^{-1})	1.017, 1.017, 0.307, 0.392*	Measurement
High rate of slurry (g kg^{-1})	1.155, 1.155, 0.274, 0.468*	Measurement
Mineral P, no N (g kg^{-1})	1.012, 1.012, 0.389, 0.454*	Measurement

Notes: K1 = percentage of drainage water from the micropore region in the groundwater reservoir ending up in tile drains. K2 = percentage of the rest of the micropore-generated water in the groundwater reservoir routed into deep percolation. Thresh_watin = infiltration threshold value. R_f = a soil-type dependent fraction of infiltrating water routing into macropores when infiltraton exceeds Thresh_watin. Soil P content = measured soil P-HCl values multiplied by 1.44. P = phosphorus. N = nitrogen.

* The four values are for layer 1 (0 to 1 cm), layer 2 (1 to 30 cm), layer 3 (30 to 65 cm), and layer 4 (65 to 100 cm), respectively.

A sorption distribution coefficient (k_{dl}) determines the P sorption/desorption between P_L and P_A and between P_A and P_S. Several options are available for calculating k_{dl} (Sharpley and Williams 1990). In this study we used an option presented by Siimes et al. (1998), derived from 18 long-term field experiments on Finnish soils, where k_{dl} is a function of pH (*pH*), degree of base saturation (*bsat*), and clay content (*solcly*):

$$k_{dl} = 0.0025\ solcly\ (0.46 - 0.0916\ log(100\ solcly) + (0.35 - 0.0025\ solcly)\ (0.0054\ bsat + 0.116\ pH - 0.73). \quad (1)$$

The distribution of P between P_L and DRP is described by a linear sorption isotherm assuming instantaneous equilibrium and, with the sorption distribution coefficient (k_{dw}), which is given as a function of the clay content (Knisel 1993):

$$k_{dw} = 100 + 250\ solcly. \quad (2)$$

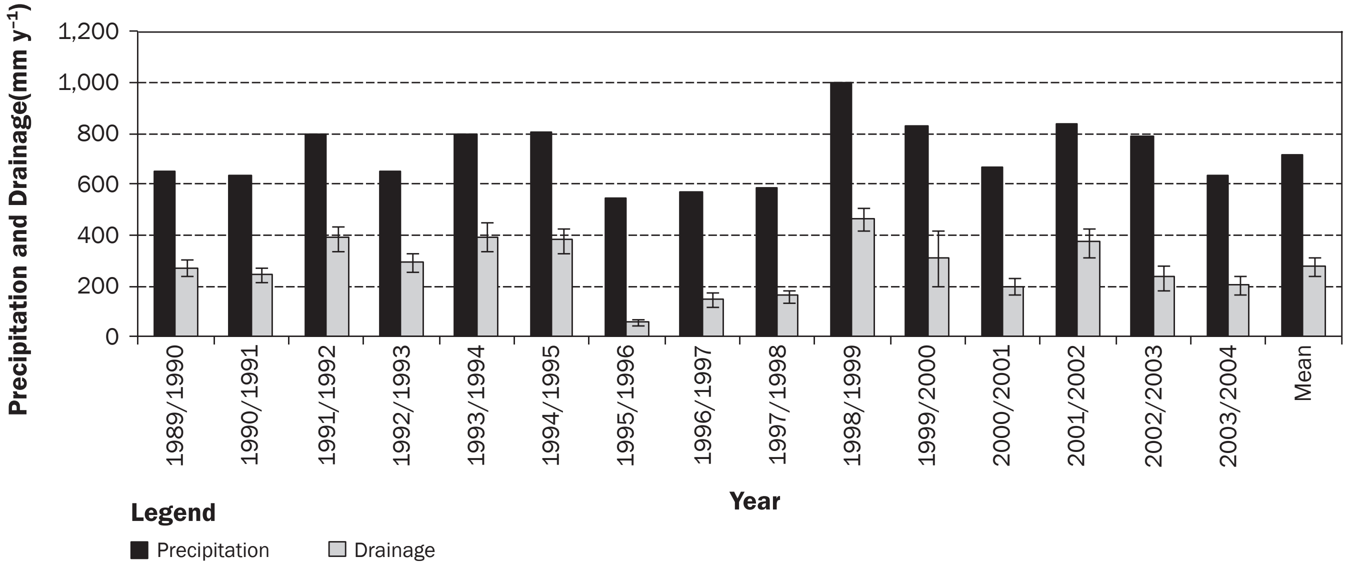
Simulation Procedure, Parameterization, and Input Data. The simulations were carried out in three steps. The hydrological part of the model was first calibrated to get good agreement with both measured annual accumulated drainage and daily drainage dynamics. Thereafter, P leaching dynamics were simulated with parameterization of P pools based on measured soil P properties to estimate the potential P leaching as given by the soil P content. Finally, to test the effect of sorption/desorption, simulations were run with the soil P pools initially set to zero.

Model parameterization was mainly based on parameters used for sandy loam soils in national calculations of P losses from Swedish agricultural soils (Johnsson et al. 2008). Some soil physical and chemical parameters were set according to measurements from the experimental site or obtained by calibration (table 3). Measured climate data and observed crop management and agricultural practices from the experimental site were used for the simulations.

The plot with a high rate of manure application and without a cover crop had the measured cumulative drainage and total P leaching that was closest to the average values for all plots and was therefore selected for calibration of the hydrological part of the model. In order to replicate measured cumulative drainage, the partitioning of drainage losses through tile drains from the micropore

Figure 2

Measured annual precipitation and mean annual drainage amounts for all plots. Bars show standard deviations.



region (*K1*) was calibrated to correspond to 83% of total drainage. The remaining 17% was lost as deep percolation in the simulations. This calibration agreed with earlier findings by Torstensson and Aronsson (2000), who concluded that about 20% of percolating water bypassed the tile drains through deep percolation at this site. Drainage partition between tile drainage and deep percolation in the macropore region was not calibrated due to its minor influence on the cumulative drainage volume in this particular soil.

Although preferential flow is generally not expected to occur to any large extent in a sandy soil, the model components (*Thresh_watin* and *Rf*) describing this process were important for calibration in order to replicate the measured daily water dynamics in simulations. This indicated that fast nonequilibrium flow behavior occurs in this soil, probably as a result of water repellency caused by high organic matter content (Larsson et al. 1999).

Phosphorus leaching was simulated for the three fertilization regimes without cover crops as in the field experiment. Initial mineral P contents were estimated from measured soil P values (P-HCl multiplied by 1.44) for each treatment (table 3).

Statistical Calculations. Analysis of variance was carried out using the General Linear Model procedure (SAS program, version 9.1) to test differences ($\alpha = 0.05$) in drainage, P losses, and soil chemistry between different fertilization regimes, and also for comparisons of plots with and without cover crop/fall tillage. The data were checked for normality, and P concentrations and P leaching were transformed before analysis in order to give a normal distribution.

The model efficiency in simulating drainage dynamics was evaluated by calculating the Nash-Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970; Moriasi et al. 2007). The calculation was based on monthly sum of drainage volume as shown in equation 3:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2}, \qquad (3)$$

where Y_i^{obs} is the i^{th} monthly sum of observed drainage, Y_i^{sim} is the i^{th} monthly sum of simulated drainage, Y^{mean} is the mean of the monthly sum of observed drainage, and n is the total number of monthly sums.

Equation 3 was also used to evaluate the model efficiency in simulating monthly total P and DRP transport. In addition, the agreement in dynamics between simulated monthly P transport and measured values was determined by calculating the correlation coefficient.

Results and Discussion

Soil Chemical Properties. Despite surplus P addition in all treatments, measured P-AL, P-HCl, and water-extractable PO_4-P showed no significant increases in soil P content (tables 1 and 4) during the experimental period. The values of these parameters for the topsoil tended to be highest in the treatment with high rates of pig slurry ($p = 0.08$ for P-AL). Overall, soil P contents were higher in the topsoil than in the subsoil, and the whole profile had considerable amounts of Fe and Al. The degree of P saturation (DPS) was high in the topsoil (30% to 60%), and lower in the subsoil (4% to 21%) due to the lower content of P. Although not included in the calculations of DPS, Ca may participate in the P sorption capacity of the soil. In the plots with high rates of pig slurry, the Ca-AL content of the topsoil was significantly larger than when low rates of pig slurry had been applied ($p = 0.02$). The measured chemical properties showed large variations between individual plots, and it was not possible to find correlations with measured P leaching.

Drainage and Precipitation Conditions. Measured mean annual drainage during the 15-year period amounted to 280 mm and occurred mainly during the period from October to April. Differences in drainage between years were significant (60 to 470 mm [2.4 to 18.5 in]; $p < 0.001$) due to weather variations (figure 2). There were some differences in drainage between individual plots (figure 2), but differences between the plot pairs with different fertilization regimes were not significant (table 5). However, differences in drainage between years were statistically significant ($p = 0.007$). Moreover, the presence of a cover crop during the fall and winter probably increased evapotranspiration, causing somewhat reduced drainage, but when the two groups of plots with and without a cover crop were compared, these differences (on average 16 mm [0.6 in]) were not significant.

Table 4
Soil chemical properties in soil samples from 2005.

Properties	Fertilization regime					
	Low rate of slurry		High rate of slurry		Mineral P, no N	
	No CC	With CC	No CC	With CC	No CC	With CC
Total-C (%)						
0 to 0.3 m	2.6	2.5	3.1	3.6	2.2	3.3
pH						
0 to 0.3 m	6.2	6.4	6.6	6.5	6.4	6.4
0.3 to 0.6 m	5.8	5.5	6.3	6.6	6.2	6.4
0.6 to 0.9 m	5.9	6.4	6.2	6.6	5.7	6.4
WEP (mg 100 g^{-1})						
0 to 0.3 m	0.46	0.33	0.60	0.91	0.44	0.74
0.3 to 0.6 m	0.03	0.03	0.02	0.10	0.04	0.02
0.6 to 0.9 m	0.02	0.01	0.03	0.03	0.12	0.03
P-HCl (mg 100 g^{-1})						
0 to 0.3 m	68.7	72.5	73.0	87.4	66.9	73.6
0.3 to 0.6 m	19.3	23.3	15.3	22.7	22.2	31.8
0.6 to 0.9 m	28.1	26.4	34.9	30.1	21.2	41.9
P-AL (mg 100 g^{-1})						
0 to 0.3 m	23.3	22.5	30.7	34.1	24.0	28.6
0.3 to 0.6 m	3.0	2.7	2.6	6.5	5.3	2.0
0.6 to 0.9 m	1.4	1.7	1.9	2.0	2.8	2.3
Ca-AL (mg 100 g^{-1})						
0 to 0.3 m	108	126a	176	191b	139	173ab
0.3 to 0.6 m	34.0	45.9	48.5	81.2	70.2	57.0
0.6 to 0.9 m	36.1	70.0	44.8	35.9	45.7	48.6
Fe-AL +Al-AL (mg 100 g^{-1})						
0 to 0.3 m	65.7	63.8	67.7	53.1	61.6	57.2
0.3 to 0.6 m	28.8	42.7	75.7	39.4	58.5	26.5
0.6 to 0.9 m	14.0	27.6	46.8	20.8	70.6	13.7
DPS (%)						
0 to 0.3 m	33.6	30.3	43.0	59.6	34.6	43.9
0.3 to 0.6 m	8.8	5.6	3.7	14.0	8.1	6.2
0.6 to 0.9 m	21.2	7.1	4.0	8.4	4.4	19.7

Notes: CC = cover crop. C = carbon. WEP = water extractable PO_4^-P(phosphate-phosphorus). HCl = hydrochloric acid. P = phosphorus. Ca = calcium. Fe = Iron. Al = aluminum. The index –AL refers to extraction with ammonium lactate. DPS = degree of phosphorus saturation. Letters (a, b) show significant differences between fertilization regimes (α = 0.05).

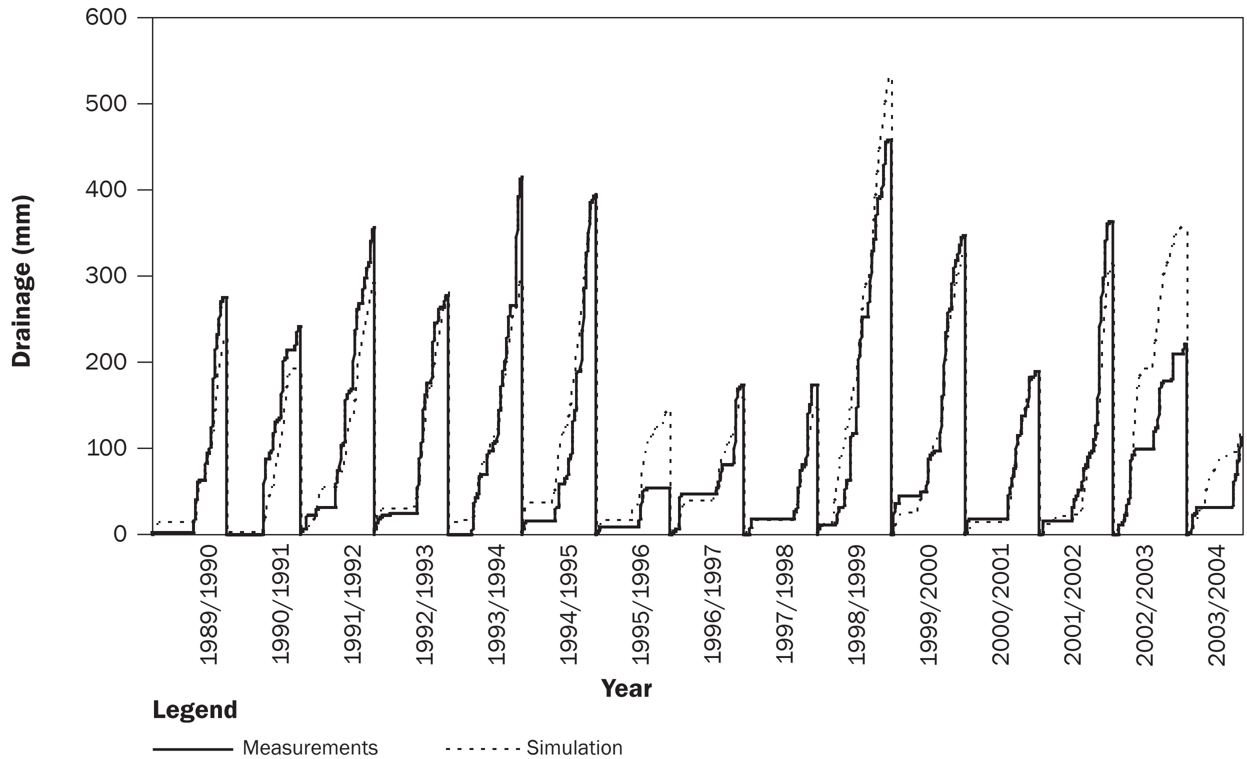
Table 5
Mean annual values for the period from 1989 to 2003 of drainage amounts, concentrations of total phosphorus (total P) in drainage water, and leaching losses in all plots.

Properties	Fertilization regime								
	Low rate of pig slurry			High rate of pig slurry			Mineral P, no N		
	No CC	With CC		No CC	With CC		No CC	With CC	
Drainage (mm)	340	259	a	274	264	a	244	288	a
Total P (kg ha^{-1})	0.14	0.19	a	0.14	0.14	a	0.24	0.16	a
Total P (mg L^{-1})	0.04	0.07	a	0.05	0.06	a	0.10	0.05	b
DRP/total P*	0.22	0.32	a	0.55	0.48	a	0.38	0.67	a

Notes: Letters (a, b) indicate significant differences between the plot pairs with different fertilization regimes (α = 0.05). P = phosphorus. N = nitrogen. CC = cover crop. DRP = dissolved reactive phosphorus.

* For the period 1990 to 1999, which was the only period when DRP was analyzed in drainage water.

Figure 3
Simulated and measured annual (1 April to 31 March) accumulated drainage for the period 1989 to 2003 (ending on December 1, 2003).



The simulated cumulative drainage was 4,070 mm (160 in) for the 15-year period, which was 70 mm (2.8 in) (< 2%) lower than measured drainage. In figure 3, simulated cumulative drainage is compared with measured drainage on a yearly basis. Generally, the model accurately simulated cumulative drainage for most years, except for overestimations in 1995 to 1996 and 2002 to 2003, which is an indication that the model responded in a reasonable way to weather data. The model was also generally able to simulate the drainage dynamics for a shorter time step resolution. The NSE coefficient value was 0.54 for the evaluated monthly sum of drainage. This model performance is satisfactory according to the recommendations for the monthly time step made by Moriasi et al. (2007).

Measured Phosphorus Concentrations in Drainage Water and Phosphorus Losses. With respect to Swedish conditions, leaching losses of total P and P concentrations in drainage water were low in this soil (table 5). For all plots, mean annual P leaching and concentrations for the 15-year period were 0.17 kg ha^{-1} (0.15 lb ac^{-1}) and 0.06 mg L^{-1} (3.75 × 10^{-6} lb ft^{-3}), respectively. The measured concentrations were sufficiently high (> 0.03 mg L^{-1} [1.87 × 10^{-6} lb ft^{-3}]) to be considered as contributing to eutrophication of surface waters (Sawyer 1947), but they were in the lower range of values (0.06 to 0.17 mg L^{-1} [3.75 × 10^{-6} to 1.06 × 10^{-5} lb ft^{-3}]) estimated for drainage water from arable land in Sweden (Johnsson et al. 2008). There was no correlation between drainage amounts and total P concentrations in drainage water, but during 1995 to 1996, when there were very small drainage losses, the highest total P concentrations in drainage water were measured in all treatments (figure 4).

Since this study contained few repetitions of fertilization regimes, no real replicates, and a considerable variation between individual plots, the results should be viewed with caution, but some deserve attention. For example, the results indicate that application of pig slurry did not constitute an increased risk of P leaching from this soil, even at a considerable P surplus (37 kg ha^{-1} y^{-1} [33 lb ac^{-1} yr^{-1}]) resulting from application rates (58 kg ha^{-1} [52 lb ac^{-1}]) more than double those recommended for the crops grown. In fact, the treatment with high rates of pig slurry had the smallest measured P leaching (table 5), although not significantly ($p = 0.07$) lower than in the other treatments. Furthermore, both treatments involving application of pig slurry had significantly lower P concentrations in the drainage water than when only mineral P was applied ($p < 0.001$; table 5 and figure 4). For even higher P application rates, the results might be different, but other studies have also shown that large applications of manure do not increase P leaching or even result in reduced P losses (Sharpley et al. 1998; Bergström and Kirchmann 2006). Sharpley et al. (2004b) suggested that long-term manure application may change P sorption characteristics, due to increased Ca content in the soil, resulting in smaller amounts of water-extractable PO_4-P. In the present study, the higher Ca-AL content in the treatment with a high rate of pig slurry may support these findings (table 4).

In contrast, mineral P applications without any N fertilizer at all resulted in the highest mean P concentrations in drainage water (figure 4). Poor crop development resulted in a considerable surplus of P in this treatment, which may have contributed to P leaching. The yields of cereal crops in the mineral P

Figure 4

Measured mean annual concentrations of total P in drainage water in different years and mean values for the whole period. Letters (a, b) indicate significant differences between the different treatments.

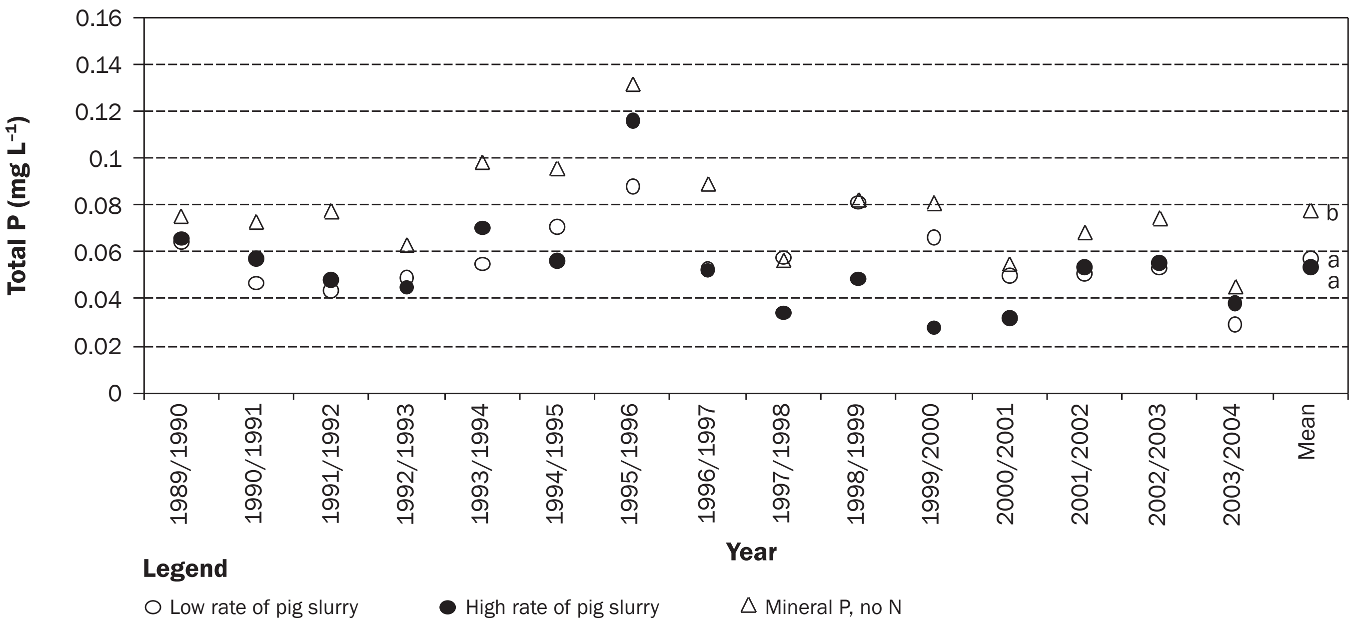


Table 6

Simulated mean annual phosphorus (P) flows and leaching losses with different initial P pools. Phosphorus flows included P applied in the form of pig slurry or mineral fertilizer, P removed by crop harvest, and overall P losses to water through runoff or leaching. Phosphorus leaching is illustrated in terms of total P, dissolved reactive P (DRP), and other P (defined as the difference between total-P and DRP).

P pools	Fertilization regime	Applied P (kg ha^{-1})	Harvested P (kg ha^{-1})	Overall P losses (kg ha^{-1})	Total P leaching (kg ha^{-1})	DRP leaching (kg ha^{-1})	Other P leaching (kg ha^{-1})
Actual P pools	Low rate of slurry	37	15.4	1.09	0.84	0.50	0.34
	High rate of slurry	58	14.6	2.00	1.27	0.99	0.28
	Mineral P, no N	24	7.6	1.16	0.91	0.57	0.34
Zero P pools	Low rate of slurry	37	15.4	0.22	0.13	0.01	0.12
	High rate of slurry	58	14.6	0.24	0.15	0.02	0.13
	Mineral P, no N	24	7.6	0.22	0.14	0.02	0.12

treatment were only about 40% of those in the other treatments (2,000, 5,200, and 4,900 kg ha^{-1} [1,780, 4,640, and 4,370 lb ac^{-1}] after mineral fertilizer, low, and high slurry P rates, respectively). In the long-term, no N fertilization and poor crop growth will also result in depletion of soil organic matter (Persson and Kirchmann 1994). This may affect soil physical and biological properties, which may in turn affect P mobilization and transport. Excluding N fertilization may have had a greater influence on P leaching than the P fertilization regime had. Similar results, with increased P leaching when N fertilization was excluded, were reported by McDowell and Monaghan (2002). However, Williams and Young (1994) observed a decrease in P leaching when N fertilization was excluded.

The results also indicated that the cover crops did not seem to influence drainage amounts or P concentrations in this study since no correlations were found between plots with a cover crop and these variables. However, the possibility cannot be excluded that there may have been interactions between different management practices. For soils with macropores, excluding tillage during fall in combination with crop growth has been shown to reduce the risk of erosion losses of P but to increase the ratio of dissolved/particulate P in drainage water (Bechmann et al. 2005; Ulén et al. 2010). However, in recent two-year studies on a sandy soil close to the Mellby site, time of tillage and/or use of cover crops did not affect P leaching (Aronsson et al. 2011).

Measurements of DRP during 10 of the 15 years (table 5) showed that 30% to 80% of P was present in forms other than DRP, but this could not be related to the different types of fertilizer treatments or to growth of cover crops. The water samples were mostly very clear and without visible particles, which indicated that particulate-bound P was not a main contributor. One possible explanation for the difference between DRP and total P could be P bound to dissolved organic matter, which can be present at considerable concentrations after application of organic manures, as shown by McGechan and Hooda (2010).

Simulated Phosphorus Leaching. The simulations showed higher P leaching from the plots with the high application rate of pig slurry than those with low slurry application rate and mineral P fertilizer (table 6). The difference was mainly due to differences in DRP. This result is logical with regard to the constitution of the model, i.e., with equilibrium between the pools so that high P input results in higher amounts of easily dissolved P. In the model, P in manure is added to the P_{MAN} pool, which partly transforms to stable organic P and partly to labile P as the source for DRP leaching. However, the simulated result was in conflict with the measured data, which did not show significant P transport differences between different fertilization regimes and had much smaller P leaching in all regimes. Although the model overestimated P leaching, the correlations between simulated and measured monthly transport were significant for DRP ($r^2 = 0.156$, $p < 0.0001$) and for total P ($r^2 = 0.274$, $p < 0.0001$). This indicates that the model managed to simulate the P transport dynamics pattern quite well and shows the importance of water dynamics for P losses.

The simulations with actual P pools considerably overestimated total P leaching, by a factor of 5 for the treatments with mineral P and low application rate of slurry and a factor of 9 for the high application rate of slurry (tables 5 and 6). This overestimation resulted in unsatisfactory NSE coefficients calculated for monthly transport of DRP (−21) and total P (−26). In contrast, simulations with initial P pools set to zero gave similar total P leaching loads (on average 0.14 kg P ha^{-1} y^{-1} [0.12 lb P ac^{-1} yr^{-1}]) to measurements (on average 0.17 kg ha^{-1} y^{-1} [0.15 lb ac^{-1} yr^{-1}]). In this scenario, the DRP in drainage water changed from 60% to 80% to only about 10% of total P leaching losses, which was mainly due to the reduced P desorption capacity from the P pools.

These results indicate that the model does not describe the sorption/desorption processes in an accurate manner for the Mellby soil. In a similar study with the ICECREAM model on a Swedish clay soil (Larsson et al. 2007) using the same equation for calculating the P sorption distribution coefficient as was used in this study, the model in general simulated DRP leaching satisfactorily, although with overestimation for some simulation periods. The authors attributed the overestimation to underestimation of P adsorption caused by not considering free Fe and Al oxides present in soil. In addition, Yli-Halla et al. (2005) suggested that Fe and Al oxides be considered when estimating the sorption/desorption capacity of Finnish soils.

The strong overestimation of P leaching was mainly assumed to result from high desorption from the more stable P pools, while both the mineralization of P from the organic pools and the water transport dynamics were reasonable. The Mellby soil is rich in Fe and Al oxides, and their strong sorbing capacity is believed to be a major explanation for the low P leaching from this soil. The functions for sorption/desorption processes in the current version of the model are based on pH, clay content, and degree of base saturation. For this soil with low clay content, this function does obviously not reflect what really happens. For further use on soils rich in Fe and Al oxides, their sorption/desorption capacity should be considered in the model.

Summary and Conclusions

In this study, measurements and model simulations were used to test the effect of different factors on P leaching: P fertilization regime, soil P content, transport/water flow, and sorption/desorption of P. According to the results, sorption/desorption seems to be the most important factor controlling P leaching from this soil, overshadowing the effects of transport processes, soil P content, and manure application. Although a high soil P content and a large surplus of P in the topsoil, each in combination with rapid water flow, indicated that P leaching could be expected to be considerable, P was efficiently sorbed, and measured P leaching was small.

The net release of P from the large soil P pool was very small in this soil, which resulted in measured total P leaching that was 5 to 9 times smaller than potential leaching. This was probably the main reason why large applications of manure did not result in increased P leaching. In other words, when managing manure application and designing mitigation strategies, measurements of soil P content need to be supplemented with estimations of the site-specific P sorption capacity and/or degree of P saturation in order to accurately evaluate the risk of P leaching. On the other hand, although P leaching was small in this field, the large amount of P retention in soil may greatly contribute to the build-up of soil P pools, which could pose a threat to future water quality if the high applications of pig slurry continue.

The ICECREAM model does not include appropriate functions for describing sorption/desorption processes of P as affected by Fe, Al, and Ca in the soil. Since sorption/desorption are obviously key processes for P leaching in agricultural soils, leaching models need to be expanded to include such processes. This is especially critical in the case of the ICECREAM model because it is widely used for large-scale calculations of P leaching from Swedish arable soils, which are known to be rich in Fe and Al oxides.

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