

Topsoil and Subsoil Properties Influence Phosphorus Leaching from Four Agricultural Soils

Helena Andersson,* Lars Bergström, Faruk Djodjic, Barbro Ulén, and Holger Kirchmann

Eutrophication, a major problem in many fresh and brackish waters, is largely caused by nonpoint-source pollution by P from agricultural soils. This lysimeter study examined the influence of P content, physical properties, and sorption characteristics in topsoil and subsoil on P leaching measured during 21 mo in 1-m-long, undisturbed soil columns of two clay and two sandy soils. Total P losses during the period varied between 0.65 and 7.40 kg ha⁻¹. Dissolved reactive P was the dominant form in leachate from the sandy soils and one clay soil, varying from 48 to 76%. Particulate P dominated in leachate from the other clay soil, where low pH (5.2) in the subsoil decreased aggregate stability and thereby probably increased the dispersion of clay particles. Phosphorus leaching was small from soils with high P sorption index (PSI) and low P saturation (<10% of PSI) in the subsoil, even though extractable P (Olsen P) in the topsoil was high, and large from a soil with low sorption capacity and high P saturation (>35% of PSI) in the profile. High sorption capacity in the subsoil was more important for P leaching in sandy soils than in clay soils with macropore flow, where the effect of high sorption capacity was reduced due to less interaction between percolating water and the soil matrix. The results suggest that P leaching is greatly affected by subsoil properties and that topsoil studies, which dominate current research, are insufficient for assessing P leaching in many soils.

A MAJOR environmental problem in many freshwater bodies in Sweden and in the Baltic Sea is eutrophication, i.e., high concentrations of P and N that may cause harmful biological disturbances. In an international expert evaluation commissioned by the Swedish Environmental Protection Agency, P was identified as the limiting nutrient for algal growth in central and coastal parts of the brackish Baltic Sea (Boesch et al., 2006). The main diffuse P source in the Baltic Sea catchment area is agriculture (Helsinki Commission, 2011). In Sweden, agriculture is estimated to contribute 40% of the total anthropogenic net load of P to the surrounding coastal areas (Brandt et al., 2009). Similar situations can be found in other parts of the world, for instance in the brackish Chesapeake Bay on the U.S. East Coast, where large mitigation efforts have been undertaken in the last couple of decades to reduce agricultural P loads (Reckhow et al., 2011).

Surface runoff and erosion is considered to be the main pathway for P losses from arable fields in many areas (Sharpley et al., 1993). Extractable P (e.g., Olsen P and ammonium lactate P [P-AL]) in the topsoil is therefore considered a useful risk indicator of P losses in such areas (e.g., Heckrath et al., 1995; Maguire and Sims, 2002). However, leaching of P through the soil profile can be extensive in many flat areas (Algoazany et al., 2007; van der Salm et al., 2012) and is considered to be the main pathway for P losses in central Sweden (Ulén and Snäll, 2007). In such areas, information on topsoil characteristics has been shown to be insufficient for estimating P losses. For example, in a Swedish lysimeter study, Djodjic et al. (2004) found no significant correlation between extractable P (Olsen P and P-AL) in the topsoil and P concentrations in drainage water and concluded that subsoil properties were more important for P leaching from their soils than the P content in the topsoil. On comparing an intact fine loam soil column from a Danish agricultural field with a parallel topsoil study, Jensen et al. (1999) found that the subsoil had a large impact on P leaching. Similarly, in a Finnish study, the highest P sorption capacity was found at approximately the 30- to 70-cm depth, clearly affecting P leaching losses (Peltovuori, 2007). The importance of subsoil properties for P leaching has

Copyright © American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. 5585 Guilford Rd., Madison, WI 53711 USA. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

J. Environ. Qual. 42:455–463 (2013)
doi:10.2134/jeq2012.0224
Received 1 June 2012.

*Corresponding author (Helena.Andersson@slu.se).

H. Andersson, L. Bergström, B. Ulén, and H. Kirchmann, Dep. of Soil and Environment, Swedish Univ. of Agricultural Sciences, P.O. Box 7014, SE-750 07 Uppsala, Sweden; and F. Djodjic, Dep. of Aquatic Sciences and Assessment, Swedish Univ. of Agricultural Sciences, P.O. Box 7050, SE-750 07 Uppsala, Sweden. Assigned to Associate Editor Christian Stamm.

Abbreviations: AL, ammonium lactate; DPS, degree of phosphorus saturation; DRP, dissolved reactive phosphorus; PP, particulate phosphorus; PSI, phosphorus sorption index; TP, total phosphorus.

also been pointed out in studies conducted in the Netherlands (Schoumans and Groenendijk, 2000; van Beek et al., 2009).

Many laboratory and field studies have examined how soil properties affect P movement in soil, but few have focused on the subsoil. In a laboratory study, Hooda et al. (2000) found that the amount of extractable P in soil was less important for potential P release from soil than the degree of P saturation (DPS). The degree of P saturation is estimated by dividing the soil P content by the P sorption capacity (van der Zee et al., 1987). One single large addition of P, the single-point sorption index (PSI), can also be used as a quick estimate of the P sorption capacity (Bache and Williams, 1971). For Swedish soils, PSI values calculated from these single-point additions have been reported to be highly correlated with the maximum amounts of P that can be sorbed to the soil, as determined from sorption isotherms, and thus provide a good estimate of the P sorption capacity (Börling et al., 2001). Börling et al. (2004) concluded that the extractable soil P concentration, measured as P-AL or Olsen P, in relation to the P sorption index of the soil was a good indicator of DPS in Swedish noncalcareous topsoils. The ratio between extractable P and PSI has been well correlated to P extracted with CaCl_2 , which can be used as an extractant for determining P concentrations in the soil solution (McDowell and Sharpley, 2001).

Chemical properties of the topsoil, in addition to transport mechanisms, are important when studying P leaching in soils with macropore flow (Jarvis, 2007), whereas P leaching from soils without macropore flow may be better explained by P sorption and desorption in the subsoil (Schoumans and Groenendijk, 2000; van Beek et al., 2009). In soils where the sorption capacity is high in the subsoil, P losses are probably lower than in soils with lower sorption capacity, for which P leaching is often better correlated with P release in the topsoil. A number of P leaching studies have been conducted on soils with well-documented chemical characteristics of the topsoil. Although several researchers have pointed out the importance of the subsoil for P leaching (e.g., Djodjic et al., 2004; Peltovuori, 2007; van Beek et al., 2009), few studies have considered the actual P sorption and desorption properties of the topsoil and subsoil separately. Knowledge of chemical and physical soil properties in different profile horizons is essential in understanding P leaching from different soils. Therefore, in this study, P losses from intact soil columns (1-m length) were studied in relation to the characteristics of the topsoil and subsoil. Our specific objectives were to: (i) determine the P content, P binding, and P release in the topsoil and subsoil of four typical Swedish agricultural soils (two sandy soils and two clay soils); (ii) examine the variations in P leaching from these four soils; and (iii) discuss the influence of extractable soil P concentration and relevant topsoil and subsoil characteristics (chemical and physical) on P leaching.

Materials and Methods

Soil Description

Two sandy soils (Mellby: 56°29' N, 12°59' E; and Nântuna: 59°49' N, 17°41' E) and two clay soils (Lanna: 58°21' N, 13°07' E; and Bornsjön: 59°14' N, 17°41' E), located in agricultural areas in southern Sweden, were used in this experiment. The soils were chosen to represent Swedish agricultural soils with different physical and chemical characteristics. The Mellby sand has been classified as a Fluventic Haplumbrept (U.S. soil taxonomy) with

a sandy loam topsoil with weak coarse granular structure and a structureless sandy subsoil (Bergström et al., 1994). The Nântuna sand has a weakly aggregated loamy sand topsoil and a structureless sandy subsoil (Bergström et al., 1994) and has been classified as a Typic Udipsamment (U.S. soil taxonomy) (Kirchmann, 1985). The Lanna clay has been classified as an Udertic Haploboroll (U.S. soil taxonomy) with a silty clay topsoil with strong coarse subangular blocky structure and a clay subsoil with strong angular blocky structure (Bergström et al., 1994). The Bornsjön clay has a weakly aggregated clay topsoil and subsoil without any visible macropores. The soil can be classified as an Inceptisol (U.S. soil taxonomy) (a more detailed classification has not been made). More details about the physical properties of the soils are given in Table 1.

At the Mellby site, a perennial forage crop was grown for 20 yr before lysimeter collection and received no fertilizer during this period. The sampling site at Nântuna was covered with a perennial grass ley during the previous 10 yr, with an average P fertilization rate of 12 kg P ha⁻¹ yr⁻¹. The sampling site at Lanna was also covered with a perennial forage crop and received no fertilizer during the 12 yr before lysimeter collection. The Bornsjön field had been covered with perennial forage crops for 5 yr before lysimeter collection and had been fertilized with approximately 13 kg P ha⁻¹ yr⁻¹.

Soil Sampling and Analyses

At the time of lysimeter collection in autumn 2009, soil samples were taken from five locations at each site and at five different depths in the pits from which the lysimeters were taken (Mellby: 0–0.1, 0.1–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0 m; Nântuna, Lanna, and Bornsjön: 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, and 0.7–1.0 m). The sampling depths were chosen based on natural boundaries between topsoil and subsoil and to get an even distribution of soil samples within the subsoil. The 0- to 0.4-m (Mellby) and 0- to 0.3-m layers (Nântuna, Lanna, and Bornsjön) represented the topsoil, whereas the layers below to the 1-m depth represented the subsoil. The samples were air dried, crushed, and passed through a 2-mm sieve. Texture was determined by the pipette sedimentation procedure (Ljung, 1987). Soil pH was measured in water at a soil/water ratio of 1:5. Extractable P (P-AL) was determined according to the Swedish standard method in ammonium acetate lactate solution at a pH of 3.75 (Egnér et al., 1960). Iron and Al were extracted with ammonium oxalate (Fe-ox and Al-ox) (Schwertmann, 1964; van Reeuwijk, 2002). Concentrations of P in the AL extract and Fe and Al in the oxalate extract were determined by inductively coupled plasma analysis on a PerkinElmer Optima 7300 DV analyzer. Phosphorus extractable with 0.5 mol L⁻¹ NaHCO₃ at pH 8.5 (Olsen P) was determined according to Olsen and Sommers (1982) using flow injection analysis (Tecator AB; ADAS Method 59). Phosphorus present in the soil solution was analyzed after equilibration with 0.01 mol L⁻¹ CaCl₂ at a soil/solution ratio of 1:3 for 20 h at 21°C (CaCl₂-P). Phosphorus concentrations in the soil solution in Swedish soils are commonly low and this high soil/solution ratio, which is commonly used in Sweden (e.g., Börling et al., 2004), was therefore chosen to ensure P concentrations above the analytical detection limit. After extraction, samples were equilibrated for 1 h before being centrifuged and filtered through membranes with a 0.2- μm pore size. Dissolved reactive P (DRP) in the samples was then determined colorimetrically according to the molybdenum blue method as approved by the European Committee for Standardization (1996).

A single-point P sorption index (PSI_2 [$mmol\ kg^{-1}/\mu mol\ L^{-1}$]) was determined to get an estimate of the P sorption capacity of the different soils (Bache and Williams, 1971; Börling et al., 2001). In a study on Swedish soils, Börling et al. (2001) used two indices based on two P additions and found that the subsoil in some of the soils sorbed >90% of the P when the low P rate was applied ($19.4\ mmol\ P\ kg^{-1}\ soil = PSI_1$). Consequently, they recommended a higher addition of $50\ mmol\ P\ kg^{-1}\ soil$ (PSI_2) for both topsoil and subsoil to ensure that the P sorption maximum was exceeded. Thus, PSI_2 was chosen for this study. For this, 2 g of air-dried soil ($\leq 2\ mm$) was equilibrated with $50\ mmol\ P\ kg^{-1}\ soil$ in 20 mL of $0.01\ mol\ L^{-1}\ CaCl_2$. The PSI_2 was determined, according to Bache and Williams (1971), as

$$PSI_2 = \frac{X}{\log C} \quad [1]$$

where X is the amount of P sorbed by the soil ($mmol\ P\ kg^{-1}\ soil$) and C is the equilibrium P concentration in the solution ($\mu mol\ P\ L^{-1}$), determined colorimetrically. The calculation of PSI_2 corresponds to the Temkin isotherm model, where adsorption energy is stated to decrease linearly with increasing sorption. The value of C was logarithmically transformed to compensate for varying solution concentrations in the different soils (Bache and Williams, 1971).

The degree of P saturation (DPS) was estimated by dividing the extractable P (Olsen P) by the PSI_2 , as done in previous studies (e.g., Westermann et al., 2001; Börling et al., 2004):

$$DPS = \frac{\text{Olsen P}}{PSI_2} \cdot 100 \quad [2]$$

with all concentrations on a molar basis. The PSI_2 only gives an estimation of the amount of free sorption sites, however, without taking into account the amount of P already sorbed to soil particles. Hence, the ratio between Olsen P and PSI_2 should be considered an approximate value of DPS. Because Olsen P values in Swedish soils are commonly low, however, errors in the calculation of DPS as the ratio between Olsen P and PSI_2 are small.

Total C content (TC) in the soil was determined using a Leco CN 2000 analyzer. A parallel sample was combusted at $550^\circ C$ for 4 h and thereafter only the carbonate content (Carb-C) was measured, also using the Leco analyzer. The organic C content was calculated as the difference between TC and Carb-C.

More details about the soil chemical properties are given in Table 2.

Lysimeter Experiment

In autumn 2009, undisturbed soil columns were collected from the four sites in polyvinyl chloride pipes (1.18 m long, 0.295 m i.d.) using a drilling technique whereby a carved-out soil column is gently pushed into the pipe (Persson and Bergström, 1991). Three soil columns were collected at each site. After collection, the lysimeters were stored with sealed tops and bottoms in an unheated warehouse where the temperature occasionally fell below freezing ($0^\circ C$). The lysimeters were prepared for gravity

Table 1. Selected soil physical properties.

Soil	Depth	Clay†	Porosity	Bulk density	Saturated hydraulic conductivity	Water content at tensions		
						5 cm	100 cm	200 cm
	cm	%	$m^3\ m^{-3}$	$g\ cm^{-3}$	$mm\ h^{-1}$	$m^3\ m^{-3}$		
Mellby sand‡	0–10	7	0.47	1.32	–	0.438	0.231	0.214
	10–40	6	0.42	1.47	69.8	–	–	–
	40–60	1	0.38	1.63	75.7	0.413	0.132	0.100
	60–80	1	–	–	–	–	–	–
	80–100	2	0.38	1.65	–	–	–	–
Nåntuna sand§	0–10	11	0.45	1.43	290	0.427	0.180	0.168
	10–30	9	0.43	1.47	940	0.384	0.165	–
	30–50	2	–	–	–	–	–	–
	50–70	2	0.45	1.46	–	–	–	–
	70–100	6	–	–	50	0.385	0.065	–
Lanna clay¶	0–10	43	–	–	–	–	–	–
	10–30	45	0.52	1.24	1035.0	0.447	0.359	0.349
	30–50	56	0.48	1.43	330.0	0.419	–	–
	50–70	58	–	–	–	–	–	–
	70–100	61	0.47	1.46	35.0	0.442	–	–
Bornsjön clay#	0–10	60	0.53	1.21	50.4	0.505	0.412	–
	10–30	60	0.50	1.33	0.11	–	–	–
	30–50	59	–	–	–	–	–	–
	50–70	61	0.50	1.37	0.03	–	–	–
	70–100	54	0.53	1.30	0.23	–	–	–

† Particle size fraction $<0.002\ mm$, $n = 1$.

‡ Porosity, bulk density, and water content at three tensions, $n = 3$; saturated hydraulic conductivity, $n = 9$ (Bergström et al., 1994).

§ Porosity, bulk density, and water content at three tensions, $n = 6$ at 0–10 cm, otherwise $n = 3$ (Bergström et al., 1994); saturated hydraulic conductivity, $n = 4$ (Wiklert et al., 1983).

¶ $n = 2$ (Bergström et al., 1994).

Porosity, bulk density, and saturated hydraulic conductivity, $n = 8$ (Swedish University of Agricultural Sciences, 2010); water content at two tensions (Ulén, unpublished data, 2012).

drainage by removing approximately 0.08 m of soil at the bottom end and replacing it with gravel, two stainless steel meshes (pore size 0.5 mm) and a fiberglass lid (Fig. 1). The soil surface was approximately 0.05 m below the top of the plastic pipe, which prevented surface runoff from occurring. In March 2010, the lysimeters were placed in an outdoor station at the Swedish University of Agricultural Sciences, Uppsala, Sweden (59°49' N, 17°40' E), which is described in detail by Bergström (1992). One objective with this experiment was to study P leaching from different types of soils without the interference of crop uptake of water and P. For that reason, no crop was grown in the soil columns during the experiment. Despite this, the lysimeters were fertilized once with (NH₄)H₂PO₄ in April 2011 at a rate of 22 kg P ha⁻¹ to simulate common Swedish agricultural practices, where P is typically applied at that specific yearly rate, and also to study the possible effects of fertilization on P leaching. The soil surface was not managed apart from being manually weeded as required.

Water samples were collected for 21 mo on a weekly basis if drainage was available, or after each major drain-flow event, during the period August 2010 to April 2012. Before that, from April 2010 until the end of July, all water collected (15–55 mm) was discarded to minimize the influence of storage and disturbances during preparation of the soil columns. The concentration of total P (TP) was measured on unfiltered samples after digestion with potassium persulfate and DRP after filtration through membrane filters (Schleicher & Schüll GmbH) with 0.2-µm pore size. All analyses were made colorimetrically according to the molybdenum blue method as approved by the European Committee for Standardization (1996). Particulate P (PP) was calculated as the difference between TP in unfiltered and filtered water. Total loads for the period August 2010

to April 2012 were calculated by multiplying the concentration of the respective P fractions by the leachate volume during the same period and then summing the load for the 21 mo of the study. Due to the overrepresentation of autumn and winter compared with spring and summer in this study, loads for 2011 were also calculated to enable comparison with previous leaching studies for which annual loads are reported. Volume-weighted concentrations were calculated by dividing the total transport of the different P fractions by the total leachate volumes.

Temperature and precipitation data were obtained from the Ultuna climate station, which is equipped with standard meteorological instruments and is located approximately 300 m from the lysimeter station.

Statistical Analysis

All statistical analyses were performed in Minitab 16 (Minitab, 2010). Relationships were considered significant at $P < 0.05$.

Results and Discussion

Soil Characteristics

Selected soil chemical properties are shown in Table 2.

In the Nântuna sand, the degree of P saturation was high in the entire soil profile due to low P sorption capacity and frequent inputs of P fertilizers before this experiment, as can be seen from the extractable P concentrations (Table 2). The P sorption capacity (PSI₂) was higher in the Mellby sand than in the Nântuna sand due to the greater presence of both Fe and Al, especially in the subsoil. Extractable P (P-AL and Olsen P) in the Mellby sand was high in the topsoil and low in the subsoil,

Table 2. Selected soil chemical properties, including the pH, organic C (OC), CaCl₂-extractable P, NaHCO₃-extractable P (Olsen P), ammonium lactate extractable P (P-AL), oxalate-extractable Fe (Fe-ox), oxalate-extractable Al (Al-ox), the P sorption index (PSI₂), and the ratio of Olsen P to the PSI₂.

Site	Depth cm	pH†	OC %	CaCl ₂ -P	Olsen P	P-AL	Fe-ox	Al-ox	PSI ₂	Olsen P/PSI ₂ ‡
				mg kg ⁻¹			mmol kg ⁻¹ /µmol L ⁻¹ log(µmol L ⁻¹)100			
Mellby	0–10	5.8 ± 0.5§	3.3 ± 0.3	7.23 ± 2.28	91.0 ± 4.0	294 ± 10.2	1,979 ± 186	1,178 ± 67	3.9 ± 0.4	76 ± 6.7
	10–40	6.1 ± 0.2	2.1 ± 0.3	1.17 ± 0.3	77.8 ± 9.3	229 ± 47.0	1,996 ± 198	1,298 ± 168	4.6 ± 0.2	55 ± 7.3
	40–60	6.0 ± 0.1	0.3 ± 0.0	0.11 ± 0.01	8.0 ± 1.7	15 ± 3.0	1,805 ± 513	699 ± 131	3.6 ± 0.4	7.3 ± 2.0
	60–80	5.8 ± 0.1	0.4 ± 0.1	0.09 ± 0.01	5.7 ± 2.4	11 ± 4.8	3,960 ± 1,994	797 ± 211	4.3 ± 0.5	4.2 ± 1.4
	80–100	5.2 ± 0.4	0.4 ± 0.2	0.10 ± 0.01	10.3 ± 2.8	16 ± 4.9	1,727 ± 620	432 ± 134	3.3 ± 0.5	10 ± 3.9
Nântuna	0–10	7.0 ± 0.2	1.3 ± 0.2	3.35 ± 0.53	29.6 ± 2.9	164 ± 24.2	1,710 ± 203	802 ± 92	2.3 ± 0.7	44 ± 16
	10–30	7.5 ± 0.2	1.0 ± 0.1	1.88 ± 0.57	23.4 ± 2.8	126 ± 11.7	1,579 ± 102	768 ± 42	2.3 ± 0.5	35 ± 11
	30–50	7.6 ± 0.2	0.1 ± 0.0	1.88 ± 0.46	15.4 ± 2.1	52 ± 3.8	841 ± 179	491 ± 90	1.2 ± 0.4	48 ± 24
	50–70	7.6 ± 0.2	0.1 ± 0.0	1.38 ± 0.70	16.2 ± 3.0	55 ± 7.2	1,049 ± 128	465 ± 92	1.0 ± 0.3	55 ± 16
	70–100	7.6 ± 0.1	0.3 ± 0.4	1.34 ± 0.70	24.6 ± 9.5	76 ± 12.3	2,005 ± 426	619 ± 86	1.9 ± 0.2	44 ± 19
Lanna	0–10	6.1 ± 0.2	2.7 ± 0.2	0.30 ± 0.13	9.5 ± 3.7	33 ± 6.0	3,896 ± 475	1,798 ± 130	5.5 ± 0.3	5.7 ± 2.5
	10–30	6.4 ± 0.1	2.2 ± 0.1	0.19 ± 0.03	7.7 ± 1.5	31 ± 6.1	3,928 ± 361	1,848 ± 119	2.7 ± 0.3	4.4 ± 0.9
	30–50	6.8 ± 0.1	0.4 ± 0.0	0.10 ± 0.00	<4.0 ± 0.0¶	51 ± 24.5	3,729 ± 639	2,041 ± 259	7.7 ± 0.4	<1.7 ± 0.1
	50–70	7.0 ± 0.1	0.2 ± 0.0	0.10 ± 0.00	<4.0 ± 0.0¶	158 ± 5.4	3,076 ± 378	1,732 ± 199	6.9 ± 0.3	<1.9 ± 0.1
	70–100	7.2 ± 0.1	0.2 ± 0.4	0.10 ± 0.01	<4.0 ± 0.0¶	207 ± 15.5	2,245 ± 654	1,694 ± 223	6.0 ± 0.3	<2.2 ± 0.1
Bornsjön	0–10	6.0 ± 0.1	2.8 ± 0.1	0.29 ± 0.05	18.2 ± 1.3	44 ± 5.8	9,205 ± 1,283	3,140 ± 476	7.3 ± 0.4	8.1 ± 0.7
	10–30	6.2 ± 0.1	2.1 ± 0.3	0.24 ± 0.05	16.4 ± 2.6	32 ± 7.5	9,430 ± 611	2,869 ± 289	7.8 ± 0.3	6.8 ± 0.9
	30–50	6.6 ± 0.1	0.6 ± 0.0	0.12 ± 0.01	4.0 ± 0.0	9 ± 2.7	8,805 ± 2,770	1,919 ± 313	7.3 ± 1.0	1.8 ± 0.2
	50–70	6.5 ± 0.1	0.6 ± 0.0	0.12 ± 0.01	5.4 ± 2.1	12 ± 1.1	10,098 ± 6,485	2,069 ± 380	7.2 ± 1.4	2.4 ± 0.5
	70–100	5.2 ± 0.1	0.7 ± 0.1	0.13 ± 0.01	21.0 ± 5.3	31 ± 9.5	6,562 ± 831	2,387 ± 219	10.5 ± 0.6	6.4 ± 1.4

† Measured in water.

‡ The degree of P saturation (DPS) is commonly expressed as a percentage of the P sorption index (PSI₂) as an approximation.

§ Means ± SD, $n = 5$.

¶ Results were under the detection limit (<4.0 mg kg⁻¹).

resulting in high (36–55%) and low (2–6%) P saturation (estimated as Olsen P/PSI₂), respectively (Table 2).

Both clay soils had higher P sorption capacities and lower DPS ratios (Olsen P/PSI₂) than the two sandy soils (Table 2). Thus, the clay soils had greater potential to bind P than the sandy soils. The Borsnjön clay soil had a higher content of extractable P than the Lanna soil (topsoil and 70–100-cm layer) and also had a higher P sorption capacity due to higher concentrations of extractable Fe and Al acting as possible binding sites.

The concentration of P-AL in the Lanna soil increased with depth, whereas the P concentration decreased with depth when extracted with CaCl₂ (CaCl₂-P) or NaHCO₃ (Olsen P). In soils with a high pH, Ca-bound P may be present in significant concentrations and AL can dissolve Ca-bound P. Thus, discrepancies between P-AL and Olsen P values in the Lanna clay might indicate the presence of Ca phosphates. A mineralogical study of a similar clay soil near Lanna showed that P seemed to be bound to Ca complexes in the very fine clay fraction and that more P was bound to the clay fraction with increasing soil depth (Ulén and Snäll, 2007). Because P in these forms is easily dissolved with AL due to its low pH but may not be soluble under other conditions, P extracted from the soil with AL can be an overestimation of plant-available or leachable P. The reason for the increasing P-AL levels with depth in the Lanna clay was not further investigated in this study.

Limited preferential transport has been reported from leaching studies conducted on the Mellby sand (Bergström and Shirmohammadi, 1999) and the Nântuna sand (Bergström et al., 2011), although the clay content and saturated hydraulic conductivity (Table 1) of the latter indicate that there might be some water flow in preferential flow paths in the topsoil due to root and earthworm activities. In contrast, previous lysimeter studies have shown that macropore flow commonly occurs in the Lanna clay (Bergström, 1995; Bergström and Shirmohammadi, 1999; Djodjic et al., 1999). The high saturated hydraulic conductivity in this soil further indicates the presence of macropore flow (Table 1). Ulén et al. (1998) and Ulén and Persson (1999) showed that macropore flow is also a common flow process in the topsoil of the Borsnjön clay; however, only a very small part of the total soil area was reported as being hydraulically active at deeper depths (>30 cm) (Ulén and Persson, 1999). The reported saturated hydraulic conductivity of the topsoil (50.4 mm h⁻¹) and subsoil (<1 mm h⁻¹) further confirms the differences in macropore flow between topsoil and subsoil in the Borsnjön clay (Table 1).

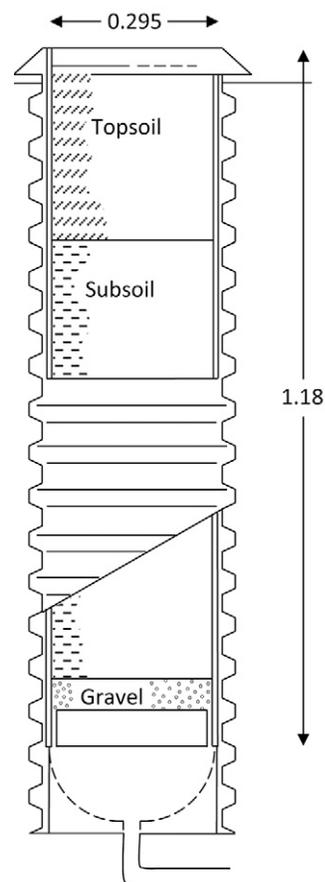


Fig. 1. Lysimeter placed in a belowground pipe (Bergström and Johansson, 1991).

Drainage Conditions

During the period August 2010 to April 2012, total precipitation was 977 mm, which is about normal for the area (Table 3). The mean air temperature was 5.5°C. There was more precipitation during January to April 2012 than during the same period in the previous year (Fig. 2); however, the winter of 2011 was much colder than that of 2012 and also had much thicker snow cover and thereby a thinner layer of frozen soil. Hence, when the snow melted in 2011, drainage amounts in the lysimeters increased rapidly in all soils and reached up to 111 mm during 3 wk in March and April (Fig. 3). In 2012, soil thawing resulted in a greater increase in drainage volumes from the clay soils than the sandy soils. These results are similar to those from another lysimeter study conducted on the Mellby sand and the Lanna

Table 3. Air temperature, precipitation, and drainage from the lysimeters.

Year	Month	Air temperature	Precipitation	Drainage			
				Mellby sand	Nântuna sand	Lanna clay	Borsnjön clay
		°C		mm			
2010	Aug.	16.5	89	74 ± 3†	90 ± 3	82 ± 5	86 ± 5
2010	Sept.–Dec.	1.8	197	98 ± 2	118 ± 1	101 ± 14	105 ± 18
2011	Jan.–Apr.	-0.1	79	119 ± 10	105 ± 43	125 ± 74	135 ± 23
2011	May–Aug.	15.8	217	13 ± 5	79 ± 2	67 ± 14	66 ± 11
2011	Sept.–Dec.	6.9	233	167 ± 9	191 ± 12	178 ± 9	193 ± 15
2012	Jan.–Apr.	0.4	162	89 ± 6	143 ± 11	119 ± 29	128 ± 26
Total			977	559 ± 28	725 ± 42	672 ± 136	714 ± 82

† Means ± SD, n = 3.

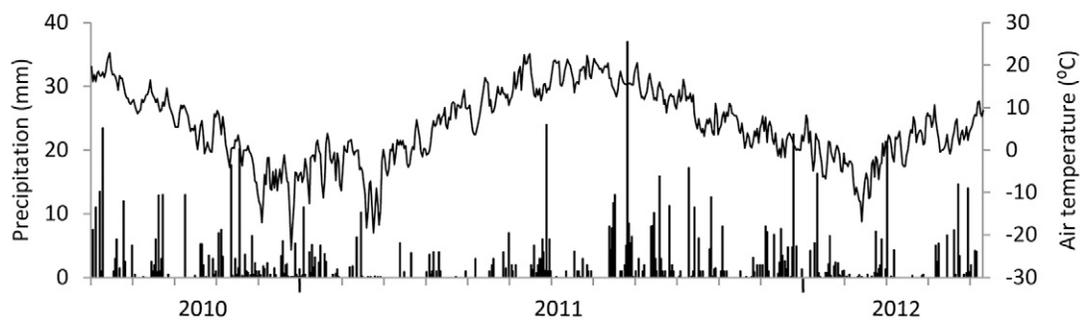


Fig. 2. Daily average precipitation (bars) and temperature (line) from August 2010 to April 2012.

clay, performed during a year with similar weather conditions to those in 2012, where drainage volumes after snowmelt increased faster in the clay soil than in the sandy soil (Bergström and Jarvis, 1993). This was probably due to the heterogeneity of the clay soil, where water in the finest pores is often unfrozen, water in the intermediate pores is frozen, and the largest pores are air

filled (Stähli et al., 1996). When the soil thawed, water may then have been transported downward through the air-filled pores at high velocity.

The amount of leachate in the lysimeters in relation to total precipitation was 73% in the Nântuna sand, 72% in the Bornsjön clay, 69% in the Lanna clay, and 57% in the Mellby

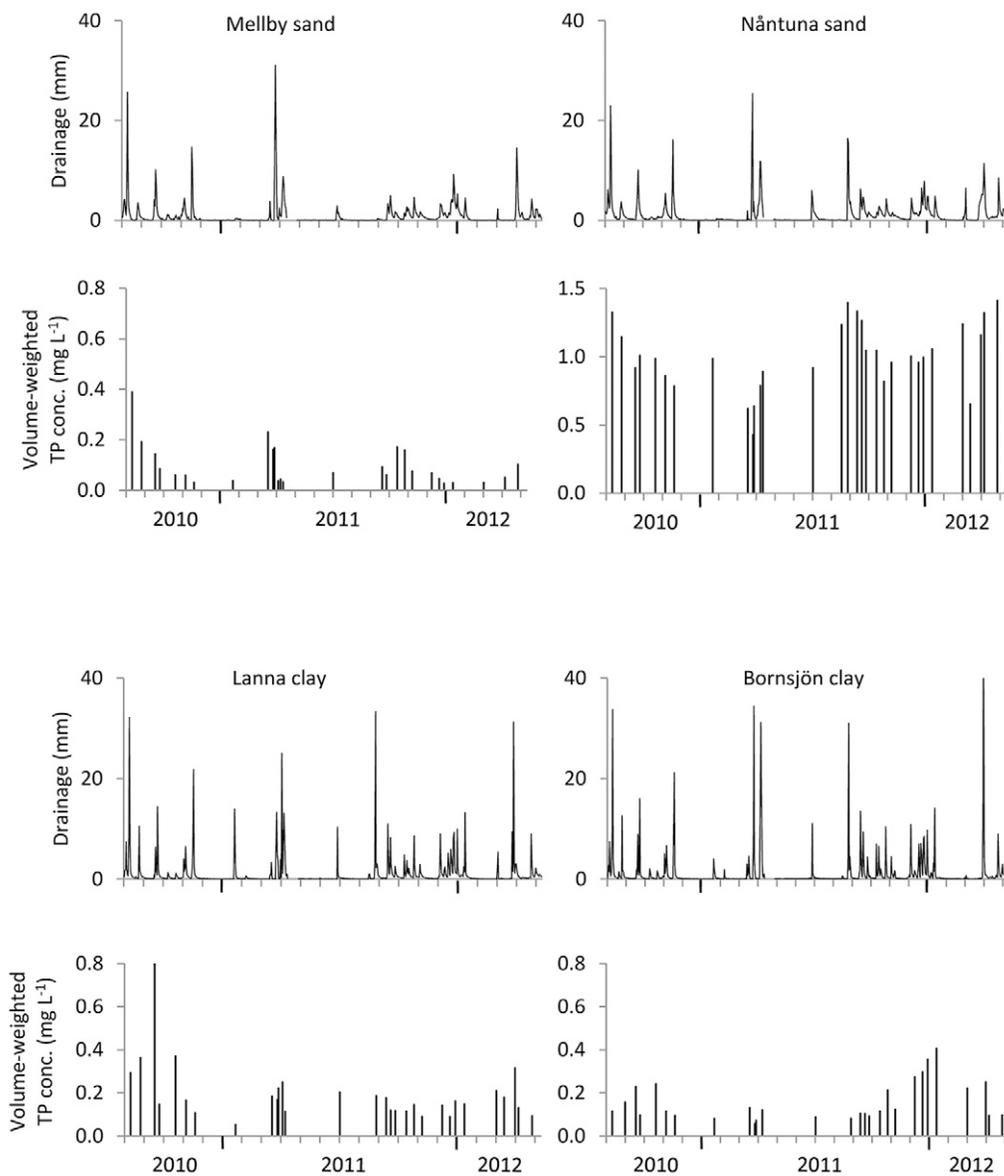


Fig. 3. Drainage volumes and volume-weighted total P (TP) concentrations from the soils from August 2010 to April 2012. (Note the different scale for TP concentrations in the Nântuna sand.)

sand. This is considerably higher than in other similar leaching studies performed in Sweden (e.g., Bergström and Jokela, 2001; Djodjic et al., 2004), mainly due to the lack of a crop on the lysimeters in this study. Despite the difference in drainage among the soils mentioned above, the total drainage amounts were not significantly influenced by soil type ($P > 0.05$). There were some differences in drainage amounts among individual soil columns of the same soil, however, with the clay soils showing larger variation among replicate soil columns than the sandy soils. This is probably due to the fact that sandy soils are usually more homogeneous than clay soils with macropores and therefore show less variability in flow processes (Bergström and Shirmohammadi, 1999).

Phosphorus Leaching in Relation to Soil Characteristics

Total leaching loads and volume-weighted concentrations of TP from the four soils followed the order: Nântuna sand > Lanna clay > Bornsjön clay > Mellby sand (Table 4).

The largest TP leaching loads from the Mellby sand, the Nântuna sand, and the Lanna clay during the study period occurred in August 2010. As indicated above, this was probably due to residual effects related to storage and preparation of the soil columns before the study. Phosphorus leaching losses were small from the Mellby sand, despite very high amounts of extractable P (Olsen P and P-AL) in the topsoil, due to the high P sorption capacity throughout the entire profile. Much of the P in this soil was sorbed in the topsoil, resulting in a lower degree of P saturation and much lower potential release of P ($\text{CaCl}_2\text{-P}$) to percolating water in the subsoil than the topsoil. Phosphorus losses were much larger from the Nântuna sand than from the Mellby sand, despite the fact that the Mellby sand had a much higher potential release of P to the soil solution ($\text{CaCl}_2\text{-P}$) in the topsoil. The high P losses from the Nântuna sand were caused by high amounts of extractable P (Olsen P and P-AL) and low P sorption capacity, especially in the subsoil. This resulted in a high degree of P saturation throughout the entire profile and thereby fewer free sorption sites being available for P retention. A similar pattern was shown in a study by Ulén (2006), where coarse-textured, tile-drained soils with a high degree of P saturation and low P sorption capacity (PSI) in the subsoil were prone to DRP leaching. The results of the present study are also in accordance with the findings of Djodjic et al. (2004), who showed that soils with high P sorption capacity in the subsoil (PSI) had reduced P concentrations in the soil solution (P extracted with distilled water), resulting in small P losses. They also found that soils with low P sorption capacity in the subsoil and high ability to release P had large P losses and concluded that the subsoil properties are critical for P leaching, making the subsoil act as either a source

(due to naturally high P concentrations) or sink for P. The lack of preferential flow reported in the two sandy soils studied here (Bergström and Shirmohammadi, 1999; Bergström et al., 2011) and the discrepancies found between the potential release of P to the soil solution ($\text{CaCl}_2\text{-P}$) in the topsoil and the actual P leaching loads emphasize the importance of chemical properties in sandy subsoils for P leaching.

The potential release of P to the soil solution ($\text{CaCl}_2\text{-P}$) was lower in the clay soils than in the Nântuna sandy soil, in both topsoil and subsoil. In the Bornsjön clay, the amount of extractable P (P-AL and Olsen P) was large in the topsoil and small in the subsoil, whereas extractable P (Olsen P) was small throughout the entire profile in the Lanna clay. The degree of P saturation (Olsen P/PSI₂) was lower but the P sorption capacity (PSI₂) was higher in the clay soils than in the sandy soils. The presence of continuous macropores in clay soils such as the Lanna clay, however, enables water and solutes to be rapidly transported through the soil, leading to a short contact time between the percolating water and the soil matrix and thus increasing P losses with increasing clay content, despite low P saturation (Djodjic et al., 2004). This means that chemical soil properties are commonly less important for P leaching in soils with macropores than in soils without. Saturated hydraulic conductivity (Table 1) and previous leaching studies performed on the Lanna clay (Bergström, 1995; Bergström and Shirmohammadi, 1999; Djodjic et al., 1999) and the Bornsjön clay (Ulén et al., 1998; Ulén and Persson, 1999) showed that macropore flow is more common in the Lanna clay than in the Bornsjön clay, especially in the subsoil. The lower water transport in macropores in the Bornsjön clay and its somewhat higher P sorption capacity may explain the smaller DRP leaching losses from the Bornsjön clay than from the Lanna clay.

In the sandy soils, drainage amounts were correlated to concentrations of TP ($r^2 = 0.93$, $P < 0.01$), DRP ($r^2 = 0.93$, $P < 0.01$), and PP ($r^2 = 0.83$, $P < 0.05$), although not if the soils were evaluated separately. Both the concentration (Table 5) and proportion (Table 6) of DRP to TP were lower in leachate from the Mellby sand than in leachate from the Nântuna sand due to the higher sorption capacity of the former. In the Mellby sand, the concentration of TP and the proportion of DRP to TP in the leachate were higher during the period January to April 2011 due to snowmelt (cf. Ulén and Snäll, 2007). During snowmelt, much water moves through the soil at high velocity (Fig. 3), giving less time for P released in the topsoil to be sorbed in the subsoil, leading to increased leaching of TP and especially DRP. In the Nântuna sand, however, TP leaching decreased slightly during the period January to April 2011, although the proportions of DRP and PP to TP remained the same. At snowmelt, P was

Table 4. Total load and average volume-weighted concentrations for the period August 2010 to April 2012 and annual load for 2011 of total P (TP), dissolved reactive P (DRP), and particulate P (PP).

Soil	Total load			Volume-weighted concentration			Annual load 2011		
	TP	DRP	PP	TP	DRP	PP	TP	DRP	PP
	kg ha ⁻¹			mg L ⁻¹			kg ha ⁻¹ yr ⁻¹		
Mellby sand	0.65 ± 0.27†	0.30 ± 0.16	0.07 ± 0.02	0.12 ± 0.05	0.05 ± 0.03	0.01 ± 0.00	0.28 ± 0.14	0.21 ± 0.13	0.02 ± 0.01
Nântuna sand	7.40 ± 1.11	5.43 ± 0.78	0.43 ± 0.06	1.03 ± 0.10	0.76 ± 0.07	0.06 ± 0.01	3.60 ± 0.68	2.80 ± 0.70	0.17 ± 0.02
Lanna clay	1.27 ± 0.50	0.89 ± 0.53	0.27 ± 0.16	0.19 ± 0.07	0.14 ± 0.09	0.04 ± 0.02	0.54 ± 0.20	0.38 ± 0.18	0.11 ± 0.09
Bornsjön clay	1.12 ± 0.28	0.34 ± 0.16	0.70 ± 0.09	0.16 ± 0.02	0.05 ± 0.02	0.10 ± 0.01	0.56 ± 0.05	0.17 ± 0.02	0.35 ± 0.03

† Means ± SD, $n = 3$.

Table 5. Mean concentrations of total P (TP), dissolved reactive P (DRP), and particulate P (PP) in leachate from the four soils ($n = 3$).

Year	Month	Mellby sand			Näntuna sand			Lanna clay			Bornsjön clay		
		TP	DRP	PP	TP	DRP	PP	TP	DRP	PP	TP	DRP	PP
mg L ⁻¹													
2010	Aug.	0.35	0.07	0.03	1.29	0.73	0.12	0.31	0.27	0.03	0.13	0.06	0.06
2010	Sept.–Dec.	0.07	0.03	0.01	0.89	0.64	0.06	0.20	0.14	0.03	0.12	0.06	0.04
2011	Jan.–Apr.	0.12	0.10	0.01	0.70	0.54	0.05	0.16	0.11	0.03	0.10	0.04	0.05
2011	May–Aug.	0.07	0.04	0.02	1.19	0.97	0.04	0.19	0.16	0.01	0.08	0.04	0.03
2011	Sept.–Dec.	0.08	0.05	0.01	1.04	0.80	0.04	0.13	0.08	0.04	0.21	0.05	0.15
2012	Jan.–Apr.	0.05	0.02	0.02	1.21	0.93	0.06	0.21	0.11	0.08	0.24	0.03	0.19
Mean		0.12	0.05	0.01	1.03	0.76	0.06	0.19	0.14	0.04	0.16	0.05	0.10

Table 6. Proportion of dissolved reactive P (DRP) and particulate P (PP) to total P in leachate, based on concentrations in the four soils ($n = 3$).

Year	Month	Mellby sand		Näntuna sand		Lanna clay		Bornsjön clay	
		DRP	PP	DRP	PP	DRP	PP	DRP	PP
%									
2010	Aug.	19	8	57	9	87	9	52	45
2010	Sept.–Dec.	38	14	72	7	74	14	55	37
2011	Jan.–Apr.	86	5	77	8	70	22	41	49
2011	May–Aug.	56	22	81	3	82	5	53	33
2011	Sept.–Dec.	67	12	76	4	62	29	24	71
2012	Jan.–Apr.	31	36	77	5	52	37	12	81
Mean		46	11	73	6	70	21	30	63

not released to the soil solution at a sufficiently high rate to match the increased water transport, which resulted in lower TP concentrations in the leachate during this period for the Näntuna sand. The same sudden increase in drainage volumes due to snowmelt as was seen in the period January to April 2011 did not occur in the sandy soils during the same period in 2012 (Fig. 3) due to the thicker soil frost layer in 2012.

During the entire study period, PP losses dominated in the leachate from the Bornsjön clay but not the Lanna clay, although both soils had similar clay contents. The Bornsjön soil is an old marine deposit with high organic C content (0.7%) and low pH (pH 5.2) in the 70- to 100-cm layer. Dispersion of clay particles is higher in soils with a pH of approximately 5 to 6 compared with that in soils with higher or lower pH (Haynes and Naidu, 1998; Kirchmann et al., 2013), which may explain the higher PP losses in the Bornsjön clay. The slightly higher sorption capacity and lower water flow in macropores in the Bornsjön subsoil than in the Lanna subsoil resulted in lower concentrations of DRP in the leachate. There was no correlation between TP, DRP, or PP concentrations in the drainage water and the drainage amount for the clay soils ($P > 0.05$), and changes in P concentration or P fractions in the leachate related to the intensive snowmelt in January to April 2011 were not seen in the clay soils. Total P leaching was higher in both clay soils, however, as well as in the Näntuna sand, in January to April 2012 compared with the same time period in 2011. During summer 2011, precipitation amounts were too small to result in increased P leaching due to the P fertilization at the end of April 2011. During autumn 2011 and winter to spring 2012, precipitation increased, which resulted in increased water velocities and amounts of water transported through the profiles (i.e., 334 mm for the Näntuna sand; Table 3), enabling leaching of fertilizer P that had not been sorbed to the soil. Still, no clear effect of the P fertilization in April 2011 on P leaching was seen for any of the soils.

Conclusions

The results presented here show that topsoil studies, which dominate current research, appear to be inadequate for determining P leaching in many soils. High sorption capacity in the subsoil was shown to be of greater importance for P leaching than P content in the topsoil, especially on sandy soils. The corresponding effect in clay soils with macropore flow in the subsoil was lower due to less contact between P in the soil solution and free sorption sites. Hence, chemical analyses may provide sufficient information to predict P leaching in sandy soils due to their structural homogeneity, whereas it is critical to consider transport mechanisms when studying P leaching in macroporous clay soils. More detailed studies on different subsoils are needed, however, to provide information about their role as sources or sinks for P leaching. Leaching loads of TP were more than 10-fold larger for one of the sand soils studied than for the other, despite similar textural composition and considerably lower TP (P-AL) content in the topsoil of the former. This suggests that leaching measurements in both subsoils and full-length profiles should be performed separately in future leaching studies. That would allow clearer identification of the causes behind P leaching and, ultimately, improve the possibility of designing proper mitigation strategies to reduce P losses.

Acknowledgments

This study was conducted with financial support from The Swedish Farmers' Foundation for Agricultural Research, to which we express our sincere thanks. We would also like to thank Göran Johansson and Ann Kristin Eriksson for their valuable help when collecting the soil columns and Gunnar Torstensson and Maria Blomberg for their help with the lysimeter station. Extra thanks to Ann Kristin for her help in the laboratory.

References

- Algoazany, A.S., P.K. Kalita, G.F. Czapar, and J.K. Mitchell. 2007. Phosphorus transport through subsurface drainage and surface runoff from a flat watershed in east central Illinois, USA. *J. Environ. Qual.* 36:681–693. doi:10.2134/jeq2006.0161

- Bache, B.W., and E.G. Williams. 1971. A phosphate sorption index for soils. *J. Soil Sci.* 22:289–301. doi:10.1111/j.1365-2389.1971.tb01617.x
- Bergström, L. 1992. A Swedish lysimeter test system suitable for studying fate and behaviour of pesticides in soils. In: F. Führ and R.J. Hance, editors, *Lysimeter studies of the fate of pesticides in the soil*. BCPC Monogr. 53. British Crop Protection Council, Farnham, UK.
- Bergström, L. 1995. Leaching of dichlorprop and nitrate in structured soil. *Environ. Pollut.* 87:189–195. doi:10.1016/0269-7491(94)P2606-A
- Bergström, L., E. Börjesson, and J. Stenström. 2011. Laboratory and lysimeter studies of glyphosate and aminomethylphosphonic acid in a sand and a clay soil. *J. Environ. Qual.* 40:98–108. doi:10.2134/jeq2010.0179
- Bergström, L., and N.J. Jarvis. 1993. Leaching of dichlorprop, betazon, and Cl-36 in undisturbed field lysimeters of different agricultural soils. *Weed Sci.* 41:251–261.
- Bergström, L., N. Jarvis, and J. Stenström. 1994. Pesticide leaching data to validate simulation models for registration purposes. *J. Environ. Sci. Health A* 29:1073–1104.
- Bergström, L., and R. Johansson. 1991. Leaching of nitrate from monolith lysimeters of different types of agricultural soils. *J. Environ. Qual.* 20:801–807. doi:10.2134/jeq1991.00472425002000040015x
- Bergström, L., and W.E. Jokela. 2001. Ryegrass cover crop effects on nitrate leaching in spring barley fertilized with ¹⁵NH₄ ¹⁵NO₃. *J. Environ. Qual.* 30:1659–1667. doi:10.2134/jeq2001.3051659x
- Bergström, L., and A. Shirmohammadi. 1999. Areal extent of preferential flow with profile depth in sand and clay monoliths. *J. Soil Contam.* 8:637–651. doi:10.1080/10588339991339513
- Boesch, D., R. Hecky, C. O'Melia, D. Schindler, and S. Seitzinger. 2006. Eutrophication of the Swedish seas. Rep. 5509. Swedish Environ. Protect. Agency, Stockholm.
- Börling, K., E. Otabbong, and E. Barberis. 2001. Phosphorus sorption in relation to soil properties in some cultivated Swedish soils. *Nutr. Cycling Agroecosyst.* 59:39–46. doi:10.1023/A:1009888707349
- Börling, K., E. Otabbong, and E. Barberis. 2004. Soil variables for predicting potential phosphorus release in Swedish noncalcareous soils. *J. Environ. Qual.* 33:99–106. doi:10.2134/jeq2004.0099
- Brandt, M., H. Ejhed, and L. Rapp. 2009. Nutrient loads to the Swedish marine environment in 2006. Rep. 5995. Swedish Environ. Protect. Agency, Stockholm.
- Djordjic, F., L. Bergström, B. Ulén, and A. Shirmohammadi. 1999. Mode of transport of surface-applied phosphorus-33 through a clay and sandy soil. *J. Environ. Qual.* 28:1273–1282. doi:10.2134/jeq1999.00472425002800040031x
- Djordjic, F., K. Börling, and L. Bergström. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. *J. Environ. Qual.* 33:678–684. doi:10.2134/jeq2004.0678
- Egnér, H., H. Riehm, and W. Domingo. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden: II. Chemische Extraktionsmethoden zur Phosphor und Kaliumbestimmung. *Lantbrukshoegsk. Ann.* 26:199–215.
- European Committee for Standardization. 1996. Water quality: Determination of phosphorus—Ammonium molybdate spectrometric method. European Standard EN 1189. Eur. Committee for Standardization, Brussels.
- Haynes, R.J., and R. Naidu. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutr. Cycling Agroecosyst.* 51:123–137. doi:10.1023/A:1009738307837
- Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. *J. Environ. Qual.* 24:904–910. doi:10.2134/jeq1995.00472425002400050018x
- Helsinki Commission. 2011. The Fifth Baltic Sea Pollution Load Compilation (PLC-5). *Baltic Sea Environ. Proc.* 128. Baltic Marine Environ. Protect. Commis., Helsinki.
- Hooda, P.S., A.R. Rendell, A.C. Edwards, P.J.A. Withers, M.N. Aitken, and V.W. Truesdale. 2000. Relating soil phosphorus indices to potential phosphorus release to water. *J. Environ. Qual.* 29:1166–1171. doi:10.2134/jeq2000.00472425002900040018x
- Jarvis, N.J. 2007. A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. *Eur. J. Soil Sci.* 58:523–546. doi:10.1111/j.1365-2389.2007.00915.x
- Jensen, M.B., H.C.B. Hansen, N.E. Nielsen, and J. Magid. 1999. Phosphate leaching from intact soil column in response to reducing conditions. *Water Air Soil Pollut.* 113:411–423. doi:10.1023/A:1005092704105
- Kirchmann, H. 1985. Losses, plant uptake and utilisation of manure nitrogen during a production cycle. Ph.D. diss. *Acta Agric. Scand., Suppl.* 24.
- Kirchmann, H., T. Kätterer, M. Schön, G. Börjesson, and K. Hamnér. 2013. Properties of soils in the Swedish long-term fertility experiments: VII. Changes in topsoil and upper subsoil at Örja and Fors after 50 years of nitrogen fertilization and manure application. *Acta Agric. Scand. B* (in press). doi:10.1080/09064710.2012.711352
- Ljung, G. 1987. Mekanisk analys. Beskrivning av en rationell metod för jordartsbestämning. *Commun.* 87:2. Dep. of Soil Sci., Div. of Agric. Hydrotechnics, Swedish Univ. of Agric. Sci., Uppsala.
- Maguire, R.O., and J.T. Sims. 2002. Soil testing to predict phosphorus leaching. *J. Environ. Qual.* 31:1601–1609. doi:10.2134/jeq2002.1601
- McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. *J. Environ. Qual.* 30:508–520. doi:10.2134/jeq2001.302508x
- Minitab. 2010. Minitab release 16.0. Minitab, State College, PA.
- Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. In: A.L. Page et al., editors, *Methods of soil analysis*. Part 2. 2nd ed. *Agron. Monogr.* 9. ASA and SSSA, Madison, WI. p. 403–430.
- Peltovuori, T. 2007. Sorption of phosphorus in field-moist and air-dried samples from four weakly developed cultivated soil profiles. *Eur. J. Soil Sci.* 58:8–17. doi:10.1111/j.1365-2389.2006.00789.x
- Persson, L., and L. Bergström. 1991. Drilling method for collection of undisturbed soil monoliths. *Soil Sci. Soc. Am. J.* 55:285–287. doi:10.2136/sssaj1991.03615995005500010050x
- Reckhow, K.H., P.E. Norris, J.R. Budell, D.M. Di Toro, J.N. Galloway, H. Greening, et al. 2011. Achieving nutrient and sediment reduction goals in the Chesapeake Bay: An evaluation of program strategies and implementation. *Natl. Res. Council*, Washington, DC.
- Schouman, O.F., and P. Groenendijk. 2000. Modeling soil phosphorus levels and phosphorus leaching from agricultural land in the Netherlands. *J. Environ. Qual.* 29:111–116. doi:10.2134/jeq2000.00472425002900010014x
- Schwertmann, U. 1964. Differenzierung der eisenoxide des bodens durch photochemische extraktion mit sauer ammoniumoxalalösung. *Z. Pflanzenenernaehr. Bodenk.* 105:194–202. doi:10.1002/jpln.3591050303
- Sharpley, A.N., T.C. Daniel, and D.R. Edwards. 1993. Phosphorus movement in the landscape. *J. Prod. Agric.* 6:492–500.
- Swedish University of Agricultural Sciences. 2010. Soil compaction. (In Swedish.) National data host, Dep. of Soil and Environ., Swedish Univ. of Agric. Sci., Uppsala. <http://www.slu.se/Global/externwebben/nl-fak/mark-och-miljo/jbhy/dokument/M%e3%96-10sammanst%e3%a4llning.pdf> (accessed 24 May 2012).
- Stähli, M., P.E. Jansson, and L.C. Lundin. 1996. Preferential water flow in a frozen soil: A two-domain model approach. *Hydrol. Processes* 10:1305–1316. doi:10.1002/(SICI)1099-1085(199610)10:10<1305::AID-HYP462>3.0.CO;2-F
- Ulén, B. 2006. A simplified risk assessment for losses of dissolved reactive phosphorus through drainage pipes for agricultural soils. *Acta Agric. Scand. B* 56:307–314.
- Ulén, B., and K. Persson. 1999. Field-scale phosphorus losses from a drained clay soil in Sweden. *Hydrol. Processes* 13:2801–2812. doi:10.1002/(SICI)1099-1085(19991215)13:17<2801::AID-HYP900>3.0.CO;2-G
- Ulén, B., A. Shirmohammadi, and L. Bergström. 1998. Phosphorus transport through a clay soil. *J. Environ. Sci. Health A* 33:67–82. doi:10.1080/10934529809376718
- Ulén, B., and S. Snäll. 2007. Forms and retention of phosphorus in an illite-clay soil profile with a history of fertilization with pig manure and mineral fertilisers. *Geoderma* 137:455–465. doi:10.1016/j.geoderma.2006.10.003
- van Beek, C.L., C. van der Salm, A.C.C. Plette, and H. van de Weerd. 2009. Nutrient loss pathways from grazed grasslands and the effect of decreasing inputs: Experimental results for three soil types. *Nutr. Cycling Agroecosyst.* 83:99–110. doi:10.1007/s10705-008-9205-z
- van der Salm, C., A. van den Toorn, W.J. Chardon, and G.F. Koopmans. 2012. Water and nutrient transport on a heavy clay soil in a fluvial plain in the Netherlands. *J. Environ. Qual.* 41:229–241. doi:10.2134/jeq2011.0292
- van der Zee, S.E.A.T.M., L.G.J. Fokkink, and W.H. van Riemsdijk. 1987. A new technique for assessment of reversibly adsorbed phosphate. *Soil Sci. Soc. Am. J.* 51:599–612. doi:10.2136/sssaj1987.03615995005100030009x
- van Reeuwijk, L.P., editor. 2002. *Procedures for soil analysis*. 4th ed. *Tech. Pap.* 9. Int. Soil Ref. Inf. Ctr., Wageningen, the Netherlands.
- Westermann, D.T., D.L. Bjorneberg, J.K. Aase, and C.W. Robbins. 2001. Phosphorus losses in furrow irrigation runoff. *J. Environ. Qual.* 30:1009–1015. doi:10.2134/jeq2001.3031009x
- Wiklert, P., S. Andersson, and B. Weidow. 1983. Studier av markprofiler i svenska åkerjordar. Del I. Ultunajordar. Rep. 132. Dep. of Soil Sci., Div. of Agric. Hydrotechnics, Swedish Univ. of Agric. Sci., Uppsala.