Phosphorus losses from agricultural land to surface waters
– Impact of grazing and trampling by horses

Mohammed Masud Parvage

Abstract

The number of horses in Sweden has increased in recent decades, reaching over 300,000 in 2009. The horses are kept on 300,000 ha representing 10% of total agricultural land in Sweden. This study characterised the potential risk of phosphorus (P) losses from a heavy clay soil used for horse grazing and feeding (paddock) and compared the losses with nearby arable land managed conventionally and losses from ungrazed pasture. Water-soluble phosphorus (WSP) concentration in surface soil (0-10 cm) from the paddock areas (mean 0.62 mg 100 g^{-1} soil) did not differ significantly from that in arable land, but differed very significantly ($p<0.001$) from reference areas with ungrazed pasture. Phosphorus extracted in acid lactate (P-AL value) in the topsoil of paddock (mean 14.7 mg 100 g^{-1} soil) differed significantly both from arable land and ungrazed pasture ($p=0.031$ and 0.033, respectively). Total phosphorus extracted with nitric acid (P-HNO_3) in topsoil of paddock areas (mean 117.3 mg 100 g^{-1} soil) did not differ significantly from arable land ($p=0.08$) but was significantly higher ($p<0.001$) than in ungrazed pasture. Paddock soils with high levels of different P forms, thus, pose a high risk of P losses. Aluminium and iron content in acid extract (Al-AL and Fe-AL) were found to be highly correlated to P-AL (r=0.76, $p<0.001$; r=0.75, $p<0.001$, respectively), indicating no significant difference for the dominance of Al over Fe for P availability in the fields studied. No good correlation was found with Ca (r=0.26, $p=0.03$) but soil C content was found to be correlated with P-AL (r=0.46, $p<0.001$). In the past 8 years, high P concentrations (up to 1.5 mg L^{-1}), mainly in dissolved reactive form, have been recorded in drainage water from the catchment (30 ha). Therefore, we concluded that horse grazing at high stocking rates (>2.5 livestock units ha^{-1}) may pose a risk of high P losses to nearby water bodies.

Key words*: phosphorus, surface water, horse paddock, animal grazing, clay soil, agricultural land*

List of Contents

1. Introduction

Phosphorus (P) is one of the most important nutrients for plant growth and is therefore frequently used by farmers as a fertiliser to increase crop yields (Steegen *et al*., 2001). Pasture also receives significant amounts of P through direct manure deposition by grazing animals (Parkyn and Wilcock, 2004). There is strong evidence of P losses from agricultural land throughout the world, but few developed countries have studied grazing land and compared the risk of P losses with those from arable land (Hart *et al*., 2004). While P is regarded as the key limiting factor for eutrophication in most lakes, rivers and freshwater bodies (Schindler, 1977), and grazing land has higher P inputs (Nash *et al*., 2000) and P losses (Ebeling *et al*., 2002), grazing land may also contribute to deterioration of surface water quality.

In agricultural systems, especially grazing systems, P may come from fertilisers (inorganic and/or organic), plants, animal waste, and from soil. Atmospheric deposition (dry deposition or via rainfall) also contributes 1-2 kg ha^{-1} yr^{-1} (Greenhill *et al*., 1983b). Different sources of P and their contribution to P losses from intensively grazed pasture are quite large (Dougherty *et al*., 2004). The proportion of P lost from an intensively managed grazed land is reported to be 10-15% from fertiliser, 15-20% from plants, 25-30% from dung, and 30-40% from the soil itself (McDowell *et al*., 2007).

Regarding the P load from grazed lands to streams and lakes, different factors have been identified, such as different sources and transport pathways of P (Gburek *et al*., 2000; Sharpley and Tunney, 2000). Like other nutrients, P can be lost in water as soluble forms and as suspended soil (as P is attached to eroding soil particles) (Nash and Halliwell, 1999). Heathwaite *et al*. (1997) found that almost 50% of organic P was lost through subsurface drainage pathways. He also found that organic P losses though surface runoff accounted for at least 33% of total P losses. A recent study by Dougherty *et al*. (2008) showed that most P losses from grazed land occurred as water-soluble P (around 90%) and only 10% as particulate P. The main form of P in cattle manure is orthophosphate (>80%) (McDowell and Stewart, 2005b) that can be bound to colloidal particles and loss through runoff. About 10% of the P in manure may end up in sediments and increase the amount of P lost as water-soluble P during the rainy season (McDowell, 2006).

The topography of the landscape and water movement on the soil surface or within the soil profile influence the load of P lost from grazed catchments to water courses. The solubility of P and the detachability of P-containing sediments from aggregates to soil solution are the mechanisms linking sources and P transport (McDowell *et al.*, 2001) as P is transported from soil in both dissolved and particulate forms (Haygarth and Sharpley, 2000). Particulate-bound P is associated with soil minerals and organic matter. Organic P generally accounts for 20-80% of total P in topsoil (0-20 cm depth), which amounts to about 5-20 kg P ha^{-1} yr^{-1}, and is readily transformed and adsorbed by plants (Brady and Weil, 2002). Problems arise if dissolved P and particulate-bound P are transported from the grazing system to water courses and P is released from the suspended particles.

The proportion of dissolved reactive P (DRP) and particulate-bound P (PP) in runoff water from grazing land varies depending on the nature of the animal manure (time of deposition, *i.e.* fresh or dry, and type of livestock), soil texture and structure, dominant clay mineral in the soil and hydrological conditions (Jordan and Smith, 1985; Hooda *et al.*, 1999; Simard *et al.*, 2000; Uusitalo *et al.*, 2001; McDowell, 2006). Losses are exacerbated during intensive precipitation with fresh dung on the field and higher clay content in soils.

In Sweden, 300,000 ha, or about 10% of total agricultural land are used for around 300,000 horses (6.3% of total grazing animals) (Hedberg, 2009). The total number of grazing animals other than horses is 4,500,000 (Swedish Agricultural Board, 2009). These include cows, heifers, bulls, steers, calves, sheep, and different types of pigs.

A few studies conducted in Sweden on nutrient losses from grazing land have focused on N as the main nutrient, ignoring P or making it a lower priority (Dahlin and Johansson, 2008). However, both P and N losses must be considered if Sweden is to achieve its goal of zero eutrophication by 2015.

The aims of this study were to determine the potential risk of P leaching from small areas intensively grazed and trampled by horses through i) characterising the important P forms in terms of P leaching and erosion compared with ungrazed pasture; and ii) comparing P concentrations in drainage water from areas with horses with those in drainage water from ungrazed arable land.

2. Materials and Methods

2.1 Site description

The investigation was carried out in an agricultural area 30 km south of Stockholm (coordinates as 59°14'2.47"N, 17°42'44.82"E), close to Lake Bornsjön (Figure 1). The area comprised 7.2 ha, of which 4.43 ha was arable land, 0.09 ha was ungrazed meadow with grass and the rest (2.67 ha) was used as exercise and grazing for horses (paddock). The horse paddock has been managed for the past 30 years and had a mean livestock density of 3.75 animal units per hectare receiving 15 kg P ha^{-1} yr^{-1} after deposition of fresh faeces and urine. The arable land has P imports of P 12 kg ha^{-1} yr^{-1} either as mineral fertiliser or as manure. The farmer usually broadcasts the fertiliser or manure at some time during May. Several long, narrow horse paddocks that are not grazed continuously year around but provide rotational grazing during the growing season receive no inputs of P other than horse manure deposition.
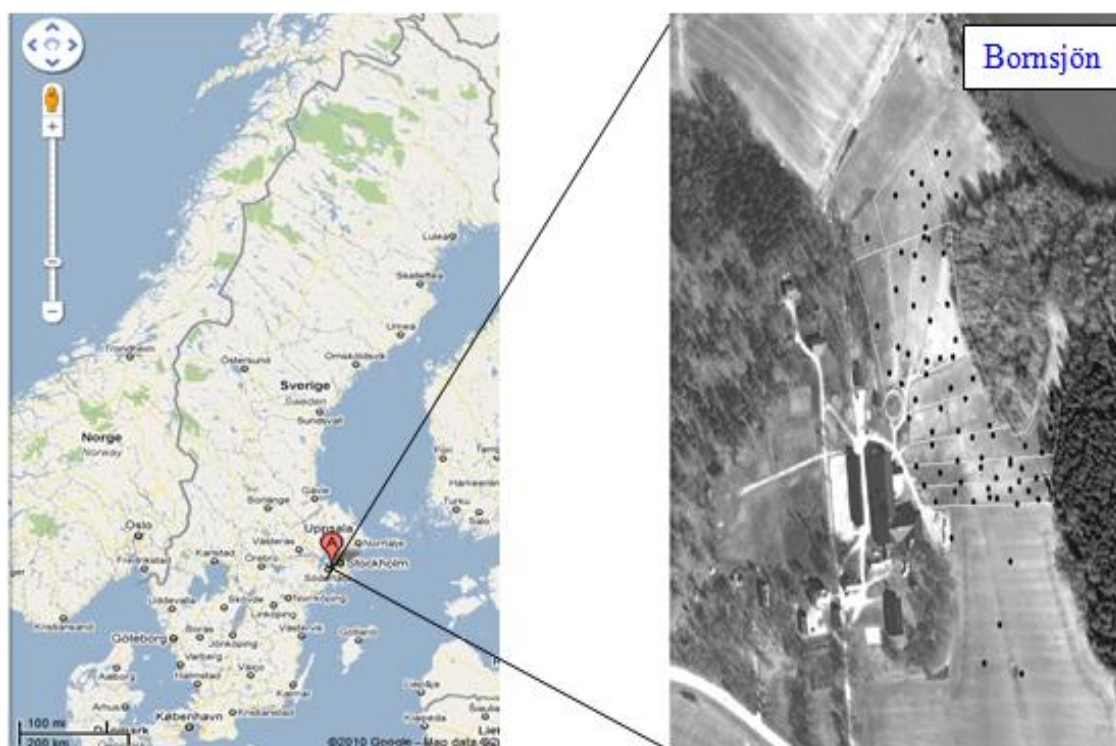

Figure 1. Location of the study site (published with permission of Swedish Land Surveyor Gävle 1 2010/0050). Black dots on the right-hand picture are the sampling points.

Another important source of P import to grazing land is year-around feed supply to horses (especially during winter). One of the paddocks was not used for horse-keeping in recent years and covered by uncut meadow-grass, was used as a reference area for the study and referred to as ungrazed pasture. The topsoil texture at the site was a heavy clay classified as a Eutric Cambisol (Ule´n & Persson, 1999) under the FAO Soil Classification. The slope of the study area was ca. 5%. Drainage water is collected in a culvert that runs directly to Lake Bornsjön, 50 m from the lowest horse paddock.

2.2 Soil sample collection and preparation

Soil samples were collected in grids with similar sampling density (i.e. samples per ha) used for the grazing folds and the ungrazed pastures. The arable land was represented by just a few samples because the variation in soil P concentration was found to be smaller (<15%) (B. Ule´n, pers. comm.). At each sampling point, eight sub-samples were collected by augur, mixed thoroughly and prepared as one bulk sample. The total number of samples taken in the grazing paddock, arable land and ungrazed pasture (reference land) was 69, 5 and 2, respectively. Samples were oven-dried at 60^0C within 24 h, milled and sieved through a 2-mm mesh. Soil particles that passed through the sieve were taken for further analysis. Fresh samples were used for determination of WSP.

2.3 Soil analysis

Water Soluble Phosphorus (WSP) from fresh and dry soil: To measure the water-soluble phosphorus content, 6 g fresh sample were dispersed in 18 ml distilled water in a plastic centrifuge tube. The suspension was shaken for one minute and then centrifuged for 20 minutes at 3000 rpm. The filtrate was extracted and analysed colorimetrically (Murphy and Riley, 1962) by atomic absorption spectrophotometer (AAS). In order to evaluate the effect of drying the soil, WSP was also analysed on dry samples. In that case the WSP was determined by the same method as for fresh soil, but the shaking time was 20 hours.

Phosphorus Sorption Index (PSI): Phosphorus concentration in the soil solution (which was also determined both colorimetrically and with inductively coupled plasma-atomic emission spectrophotometer, ICP-AES) and calculation of PSI were carried out as described by Bache and Williams (1971) and Börling *et al.* (2001) using

the equation $PSI = X / \log C_P$, where X represents the amount of P adsorbed by the soil (mmol kg^{-1} soil) and C_P the P concentration in the solution (μmol L^{-1}). Here, the ratio (w/v) of soil to extractant (0.01 M CaCl$_2$ containing 50 mmol P kg^{-1} soil) was 1:10. KH$_2$PO$_4$ was used as the source of phosphorus. The shaking and centrifuging procedure used was the same as for determination of water-extractable P in dry soil.

Ammonium acetate lactate (AL) extraction: Plant available P, aluminium (Al), iron (Fe) and calcium (Ca) were extracted with ammonium acetate lactate (Egne´r et al., 1960) at pH 3.75 and analysed by ICP-AES.

Acid Oxalate Extraction (pH 3) of P, Fe and Al: These were determined according to Reeuwijk (1995). The ratio of soil to extractant (a mixture of 0.2 M (NH$_4$)$_2$C$_2$O$_4$*H$_2$O and 0.2 M H$_2$C$_2$O$_4$* H$_2$O by 1:4 ratio) used here was 1:50. The concentrations of Fe and Al were analysed by ICP-AES.

Carbon and Nitrogen: The amount of carbon and nitrogen was determined according to LECO Cooperation (2003). In brief, 1 g dry soil was combusted at 1050 °C for 5 minutes and the percentage of C and N in the vapour was measured using a LECO CN2000 analyser.

Degree of Phosphorus Saturation (DPS): DPS for both ammonium lactate (DPS-AL) and oxalate (DPS-OX) was calculated as a ratio on a molar basis. The equation used for this calculation was $DPS = (P / Fe + Al)*100$ (Börling, 2003). The concentrations of P, Fe and Al were expressed as mmol kg^{-1} soil.

Soil pH: Soil pH was determined on dry soil samples mixed with distilled water at a ratio (w/v) of 1:5. The suspension was shaken for 5 minutes, left overnight and again shaken for 5 minutes. After shaking, the sample was left for a few minutes to resettle the sediments and finally the pH in the water phase was measured with a pH meter.

Total P: Soil samples were digested with 7 M HNO$_3$ and P was determined with ICP-AES in accordance with Swedish Standards-028311 (SIS, 1997) by a commercial soil laboratory.

Data on nutrient concentrations in drainage water were obtained from manual water sampling at the end of the culvert and from regular flow-proportional water sampling of a reference 4.4 ha arable field carried out by Stockholm Water Company. Analyses (dissolved reactive phosphorus, DRP and total phosphorus) were carried out at the Water Laboratory of Stockholm Water and at the Department of Soil and Environment, SLU. Drainage discharge data and the corresponding P concentrations were taken from Ulén (pers. commun). Based on measurements on a few occasions, relative discharge from the culvert and horse-grazed area was found to be similar to water discharge from the reference field.

2.4 Statistical analysis

Comparisons of P contents between different land uses were performed by two sample (unpaired) t-tests. Correlations between different P forms and their characteristic element were determined by Pearson correlation (R) test. Linear regression was used to determine the existence of relationships. Comparisons between different extraction methods were made by pair-wise simple regression. The level of significance ($\propto$) for all cases was set to 0.05. All statistical analyses were performed by MINITAB 15, but standard deviation was calculated from EXCEL 2003.

3. Results

3.1 Different soil P forms and their distribution

Table 1 gives an overview of the different forms of P, PSI and DPS that were found in different types of land studied. Water-soluble phosphorus (WSP) from fresh soil, the main constituent of environmental risk assessment, was highest for grazed land (0.62 m 100 g^{-1} soil), followed by arable land (0.52 m 100 g^{-1} soil), and was very low in ungrazed pasture (0.04 mg 100 g^{-1} soil). Similar trends were found for dry soil samples. High variability was observed between different sampling points (see Appendix I) for both fresh and dry soil from grazed plots, probably the effect of uneven distribution of P-rich dung patches. The results were statistically analysed by t-test (CI-95%) to determine whether the differences were significant. Although the numerical value of WSP for grazed land (n=69) and arable land (n=5) differed, with difference was not statistically significant (*p*=0.69). However, WSP in grazed land and ungrazed pasture (n=2) differed significantly (*p*<0.001). Concentrations of P-AL, P-HNO$_3$ and DPS-AL values were generally higher for grazed land and very low for

ungrazed pasture and arable land being intermediate. Analysis by two-sample t-test revealed that the P-AL value of grazed land were significantly higher than from both of the arable land and ungrazed pasture (p=0.031 and p=0.033, respectively). Concentrations of P-HNO$_3$ in grazed land did not differ significantly from arable land (p=0.08), but were significantly higher than in the ungrazed pasture (p<0.001).

In the case of P-OX and DPS-OX, the values for grazed land were also high. Phosphorus sorption index (PSI) values were lowest for grazed land (4.6), intermediate for ungrazed pasture (5.3) and highest for arable land (5.6) (Table 1).

Table 1. Characterisation of soil P in different land uses (arithmetic mean ± standard deviations). Water-soluble P (WSP); ammonium lactate (AL) extractable P; acid oxalate (OX) extractable P; nitric acid (HNO$_3$) digested P; P sorption index (PSI); and degree of P saturation (DPS)

	WSP fresh soil	WSP dry soil	P-AL	P-OX	P-HNO$_3$	PSI	DPS-AL	DPS-OX
Land use			mg 100g^{-1}			mmol kg^{-1}	%	
Grazed land	0.62 (±0.5)	0.43 (±0.4)	14.7 (±12.3)	19.2 (±5.1)	117.3 (±25.4)	4.6 (±0.6)	7.4 (±4.7)	7.4 (±2.02)
Arable land	0.52 (±0.2)	0.37 (±0.3)	8.6 (±4.1)	13.7 (±5.6)	106.7 (±9.2)	5.6 (±0.8)	4.9 (±1.6)	4.8 (±1.5)
Ungrazed pasture	0.04 (±0.03)	0.04 (±0.01)	6.6 (±2.1)	18.7	98.2 (±2.2)	5.3 (±0.1)	2.6 (±0.4)	6.4

3.2 Distribution of characteristic components of soil P sorption

Elements that are closely associated with soil P are listed with their quantities and land use type in Table 2. Here, the values were not as clearly distributed as for P. Carbon (C) and nitrogen (N) content were highest for grazed land (an indication of higher organic matter), calcium (Ca) was highest for arable land and iron (Fe) was highest for ungrazed pasture. Depending on the extraction method used, Al content was highest in arable land (Al-OX) or ungrazed pasture (Al-AL).

3.3 Total soil P content

Based on a bulk density of 1.35 g cm^{-3}, which is common for most mineral soils (Brady and Weil, 2002), total P in different forms for the surface soil layer (0-10 cm) was calculated (Table 3). Since fresh soil more closely resembles natural conditions, WSP determined in fresh soil samples was considered for this calculation.

Table 2. Characteristic components of soil P analysed for different land uses (arithmetic mean ± standard deviations). Aluminium, iron and calcium in ammonium lactate extract (Al-AL, Fe-AL and Ca-AL); aluminium and iron acid oxalate extract (Al-OX and Fe-OX); total organic carbon (C) and nitrogen (N)

Land use	pH	Tot-C	Tot-N		Ca-AL	Al-AL	Al-OX	Fe-AL	Fe-OX
		%		C/N			mg 100g^{-1}		
Grazed land	6.1 (±0.3)	3.6 (±1.2)	0.4 (±0.1)	10.2 (±0.6)	350 (±60.3)	37.6 (±5.4)	50 (±8.2)	84.2 (±21.4)	120.4 (±15.8)
Arable land	6.3 (±0.1)	2.6 (±1.7)	0.3 (±0.2)	10.4 (±0.1)	434.7 (±56.7)	46.4 (±7.6)	72.8 (±0.4)	72.4 (±16.1)	119.6 (±17.9)
Ungrazed pasture	5.9 (±0.2)	3.3	0.3	10.1	289.5 (±104.2)	51.4 (±5.7)	51.1	115.3 (±22.9)	137.6

Grazed land had a significantly higher P content than arable land, with an additional 1.5 kg WSP, 85 kg P-AL and 125 kg P-HNO$_3$ per hectare. These values increased to 8 kg, 110 kg and 250 kg per hectare, respectively, when grazed land was compared with ungrazed pasture.

Table 3. Phosphorus content in soil for the surface layer (0-10 cm) under the three different types of land use studied

Land Use	WSP fresh soil	P-AL	P-HNO$_3$
		kg ha^{-1}	
Grazed land	8.5	200	1575
Arable land	7.0	115	1450
Ungrazed pasture	0.5	90	1325

3.4 Total (Tot-P) and dissolved reactive phosphorus (DRP) in drainage water from catchment with horses and from a reference arable field

Drainage water from the culvert in the 2.67 ha horse grazing area was attributed to the whole 7.2 ha study area. Phosphorus concentrations (both total P and DRP) in drainage water from the site were found to be very high during summer and autumn, reaching over 0.5 mg L^{-1} during the study (Figure 2). However total P and DRP in the drainage water from the horse paddocks reached over 2 mg L^{-1} on some occasions during the study years. These very high concentrations pose real risks of water quality degradation through eutrophication because summer is the best time for the growth of organisms, especially algae, if sufficient quantities of P are supplied.
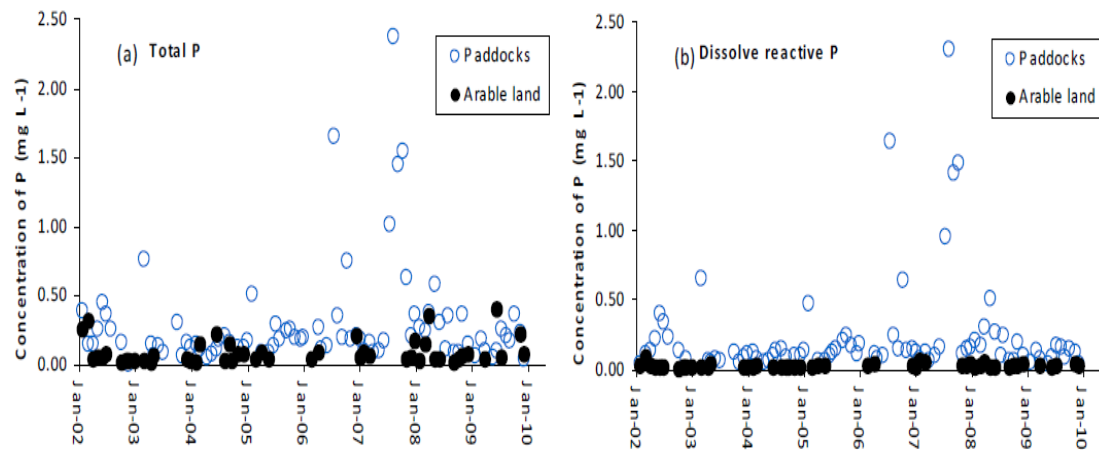
Figure 2. Phosphorus concentration (mg L^{-1}) in drainage water (a) total P and (b) dissolved reactive P (DRP) from two different types of land use systems.

3.5 Distribution of different P forms and parameters important for P sorption among the grazed plots

Soil data from the different paddock plots are shown in Table 4. Generally, the plots were rich in the elements analysed and except for WSP (in fresh soil) and pH, there were significant variations. One notable finding was that samples from the plots nearer the stable had higher P and organic C content than those farther away. Horses are often kept in the paddock area closest to the stable for ease of management, which caused higher P and C content there. For example, extractable P values in plots B and C close to the stable (21 and 23 mg P 100 g^{-1} soil, respectively) were significantly higher ($P < 0.001$) than those in remote plots E, F, G, I and J (10, 9, 11, 8 and 7 mg P 100 g^{-1} soil, respectively).

3.6 Relationship between forms of P and other soil parameters

Water soluble P (analysed from dry soil) was highly correlated with DPS-AL (r=0.77, $p<0.001$) but had no significant correlation with DPS-OX (r=0.09, $p=0.5$). Degree of P saturation in AL extract was highly correlated with P-HNO$_3$ (r=0.93, $p<0.001$) compared with DPS-OX (r=0.37, $p=0.005$). Concentrations of P-AL showed a higher correlation (r=0.96, $p<0.001$) with P-HNO$_3$ than with P-OX (r=0.61, $p=0.005$). Furthermore, WSP was found to be correlated with P-AL (r=0.78, $p<0.001$) and had no correlation with P-OX (r=0.02, $p=0.6$) but with Al-AL. Schematic presentations of these findings are given in Figure 3. These results clearly show that WSP is highly correlated with P-AL and also show the superiority of ammonium lactate (AL) extractant over oxalate extractant (OX) for environmental risk assessment of P losses.

12

Table 4. Mean concentration of soil P forms and other soil characteristics of the grazed paddocks: 'n' is the number of samples; water-soluble P (WSP); ammonium lactate extract (AL), phosphorus (P), aluminium (Al), iron (Fe) and calcium (Ca); nitric acid (HNO_3) digested P; P sorption index (PSI); degree of P saturation (DPS); total organic carbon (C) and nitrogen (N). Means that do not share the same letter are significantly different ($p<0.05$)

Plots	Distance from stable, m	WSP fresh soil	WSP dry soil	P-AL	HNO_3-P	PSI	DPS-AL	Organic C	Total N	pH	AL extractable Al	Fe	Ca
		mg 100g^{-1}				mmol kg^{-1}	%			pH	mg 100g^{-1}		
A (n=7)	31	0.5a	0.6ab	20ab	129abc	4.5ab	8.9ab	4.0ab	0.4bc	6.1a	35b	99a	319bc
B (n=7)	44	0.5a	0.4ab	21a	123abc	4.9a	7.9ab	3.7ab	0.4ab	6.1a	34b	93ab	338abc
C (n=7)	45	0.8a	0.7a	23a	146a	4.1b	11.1a	4.8a	0.5a	6.0a	36ab	95ab	405a
D (n=7)	52	0.9a	0.6a	20ab	129abc	4.6ab	10.46a	3.6ab	0.4bc	6.3a	35b	89ab	361ab
E (n=7)	70	0.7a	0.3ab	10bc	102c	4.6ab	5.7ab	3.3abc	0.3bc	6.2a	41ab	72ab	377ab
F (n=7)	76	0.4a	0.1b	9c	100c	4.7ab	5.7ab	2.9bc	0.3bc	6.3a	39ab	69ab	351abc
G (n=7)	77	0.4a	0.6ab	11bc	121abc	4.9a	5.2b	2.1c	0.3c	6.0a	40ab	96ab	275c
H (n=7)	78	0.5a	0.3ab	14abc	115bc	4.8ab	7.3ab	3.2abc	0.4bc	6.2a	38ab	77ab	363ab
I (n=7)	79	0.5a	0.4ab	8c	105c	4.7ab	4.7b	2.9bc	0.3c	5.9a	43a	74ab	338abc
J (n=6)	134	0.9a	0.5ab	7c	98c	4.7ab	4.5b	3.0bc	0.3bc	6.0a	40ab	68b	339abc

In terms of the element in soil minerals responsible for P binding at exchangeable sites, the results showed that P-AL was correlated with Al-AL (r=0.76, $p<0.001$) and Fe-AL (r=0.75, $p<0.001$) in contrast to Ca (r=0.26, $p=0.03$) (Figure 3b). This indicates the dominance of both Al and Fe in determining the availability of P in the fields studied, while Ca has a negligible effect in non-calcareous soil. P-AL was also found to be highly correlated with soil C content (r=0.46, $p<0.001$), which was higher in grazed land (mean 3.6%) than in the other two land uses studied here (2.6% in arable land and 3.3% in ungrazed pasture).

4. Discussion

The grazed land in the study area has been grazed for at least the last 30 years and has received almost 220 tons of horse manure, which has enriched the soil P pools. Russell et al. (2008) found that one horse excretes 4.8 kg P per year, which would amount to 1.4 tons of P for 10 horses over 30 years. Assuming that half of this (P) value had been deposited on the grazing sites, they were enriched with 0.7 tons of P

Figure 3a. Regression plots for selected soil parameters and phosphorus indices (a) water-soluble P (WSP) vs ammonium lactate (AL) extractable P, (b) WSP vs AL extractable aluminium (Al), (c) WSP vs total organic carbon (Tot-C), and (d) WSP vs Al-AL & Tot-C.

over the 30-year period. The WSP content in such soil is directly associated with the solubility of organic P (Shober and Sims, 2007). Available soil P content tends to increase by two folds within 2 years having an animal density of 3.13 ha^{-1} yr^{-1} (Roquette *et al*., 1973). Sharpley *et al*. (2004) reported that soils receiving animal manure have higher P and organic C content. Furthermore, Hart *et al*. (2004) reported that P losses from grazed land are even higher than those from intensively managed paddy fields. Figure 4 shows how different fractions of P from different land uses contributed to the total and highlight the fact that the grazed land had a higher P content than arable land and/or ungrazed pasture.

Concentration of P in the horse manure at the study site was 3.7 g P-AL and 6.25 g P-HNO$_3$ per kg of total solids (Ulén, pers. comm.). Another study by Caselles *et al*. (2002) found the tot-P content (P-HNO$_3$) of horse manure to be 7.6 (range 6.1-9.3) g kg^{-1} (dry weight basis), while that of sheep and cattle manure was 5.7 (4.2-7.9) and 3.1 (1.2-4.1) g kg^{-1} dw, respectively. Thus the manure deposited by horses at the study

site has higher potential for P input and subsequent losses compared with manure from sheep or cattle.

Djodjic *et al*. (2004) found no good correlation between leaching losses of P and soil test P for agricultural soils, which was explained by the subsoil making a great difference. However, the form in which mobilised P is present (as dissolved inorganic, organic or particle-bound P) is important for leaching (Haygarth and Sharpley, 2002), but their proportions vary, mainly with soil texture and hydrological characteristics (He *et al*., 2006). A study on grazed plot lysimeters by Heathwaite *et al*. (1997) revealed that soluble (<0.45 μm) inorganic forms of P are the dominant form of P lost by leaching from pasture. Other forms are organic and particulate P, which also contribute significantly to losses through subsurface drainage.
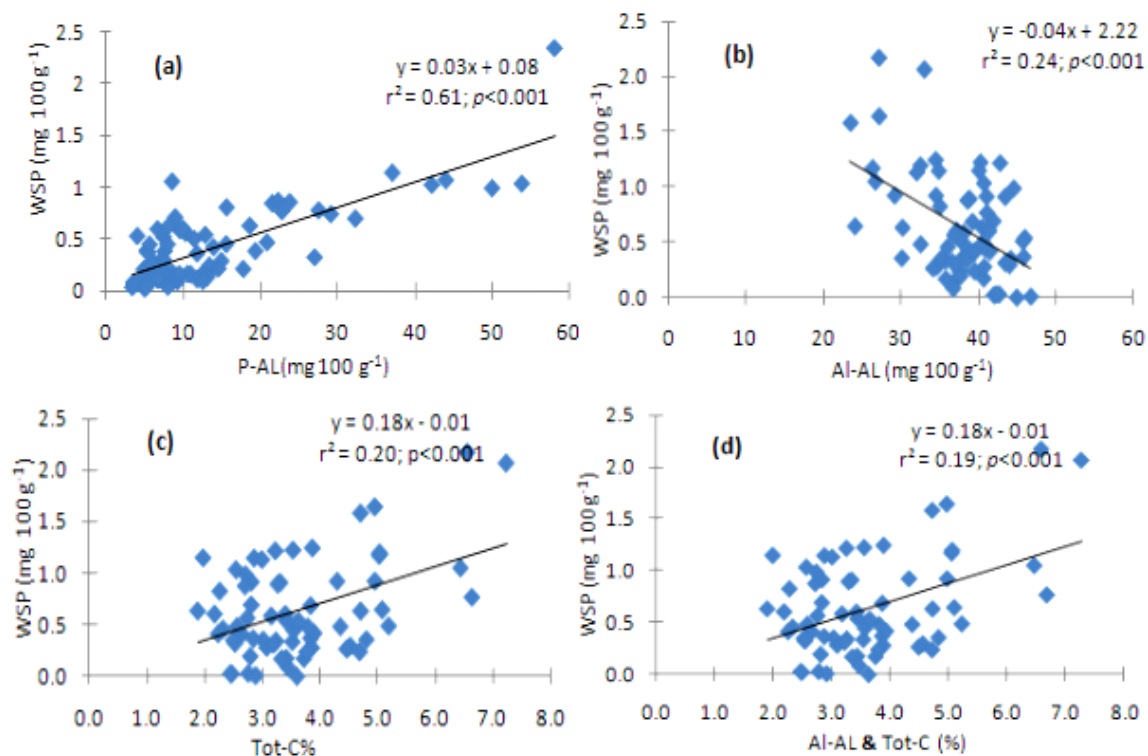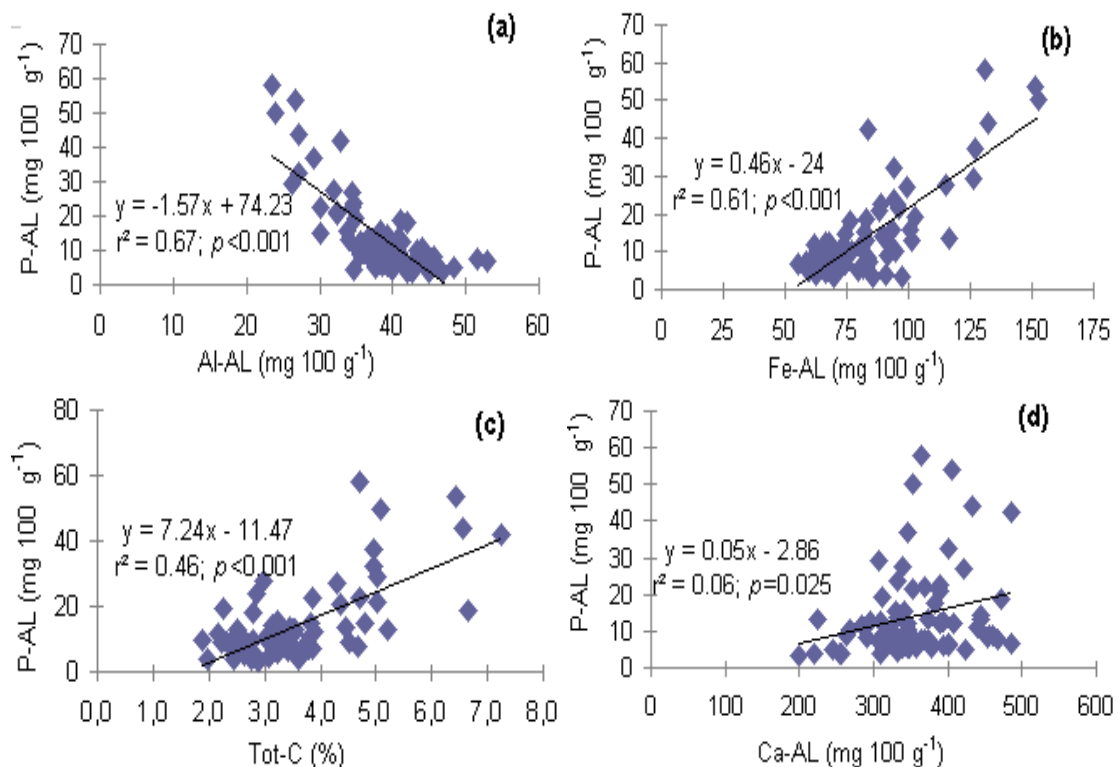

Figure 3b. Regression plots for selected soil parameters and phosphorus indices (a) ammonium lactate (AL) extractable P vs AL extractable aluminium (Al), (b) P-AL vs AL extractable iron (Fe), (c) P-AL vs total organic carbon (Tot-C), and (d) P-AL vs AL extractable calcium (Ca).
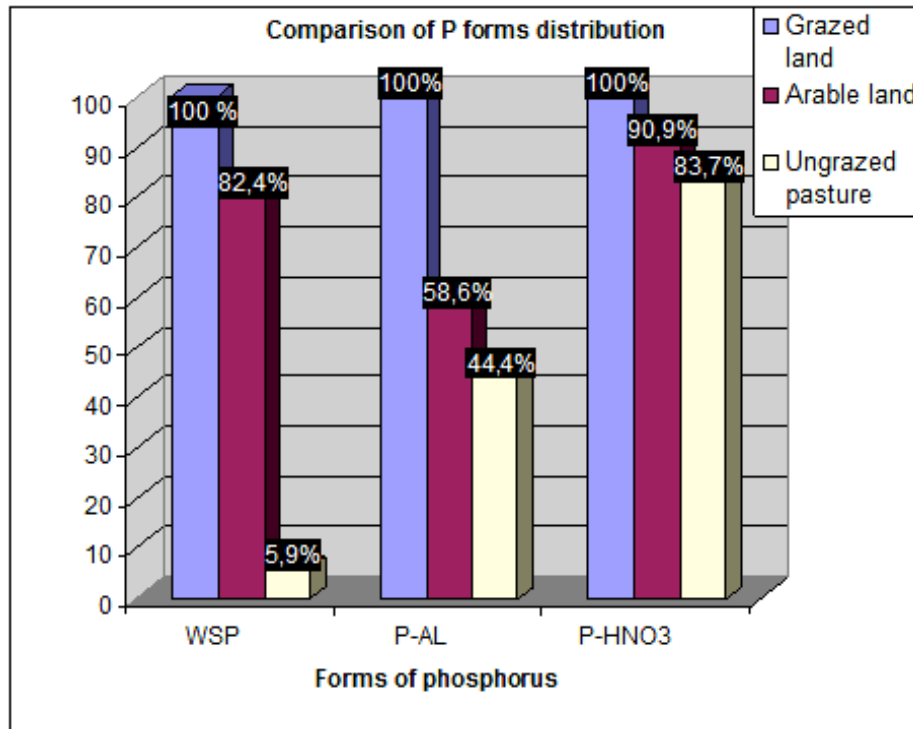
Figure 4. Different fractions of P and their comparative distribution (%) for the three different land uses studied.

A study by Kleinman *et al*. (2005) identified WSP in manure as the main form of P losses through runoff from grazed land. It is therefore important to have an idea about the threshold limit of WSP value concerning P losses. Recent studies by Pöthig *et al*. (2010), based on different types of soils in Germany and Switzerland, concluded that soils with WSP concentrations exceeding 0.5 mg 100 g^{-1} soil can be regarded as having a high risk of P losses from soil to water. The mean values of WSP for our study area were 0.62, 0.52 and 0.04 mg 100 g^{-1} soil for grazed land, arable land and ungrazed pasture, respectively, indicating that grazed land has the highest potential risk of P losses, followed by arable land. Based on analyses of dry soil the difference between the three land uses was less, 0.43, 0.37 and 0.04 mg 100 g^{-1} soil respectively. Ungrazed pasture has a negligible risk of P losses. Casson *et al*. (2006) also found soils that exceeded WSP of 1 mg L^{-1} had a potential risk of P losses from the system, meaning that our grazed plot had a higher risk of P losses than arable land (Figure 2).

The different forms of P in animal manure vary between animal species (Sharpley and Moyer, 2000; Kleinman *et al*., 2002a; Vadas *et al*., 2004), but there is very little variation for the same animal species even when the dietary composition is changed

16

(Leytem *et al*., 2004). Animal manure has a low N:P ratio (almost 1:1) but common agricultural plants absorb N and P in a ratio of 8:1, leaving 7 units of P to the soil system per unit taken up in plants and making manure a potential source of P losses (Zhang *et al*., 2009). Higher soil OM results in more water-soluble complex C, which can reduce the soil adsorption and/or absorption sites for P and result in more P losses from the profile. On the other hand, P associated with OM may be lost through soil macropores and cracks to the drainage system by means of preferential flow (Tarkalson and Leytem, 2009). Inversely, soil organic matter is responsible for higher P sorption within the profile by means of complex formation (Bloom, 1981; Niskanen, 1990a; Börling *et al*., 2001) and by favouring the formation of amorphous hydroxides, which subsequently increase P sorption (Borggaard *et al*., 1990; Niskanen, 1990a). Aluminium, which is strongly associated with soil organic matter, has a pronounced effect on the formation of amorphous Al oxides, which in turn favours higher P sorption capacity (Niskanen, 1990b; Lookman *et al*., 1996; Börling *et al*., 2001). This could be the cause of the higher WSP and P-AL in grazed land.

Dissolved P concentration in drainage water is significantly related to the P concentration of the surface soil (Sharply *et al*., 1986). Therefore, higher P content in the topsoil carries a risk of higher P losses (Börling *et al*., 2004). However, when considering leaching losses we need to know the fate of the P forms that travel through the soil (Djodjic *et al*., 2004). Even at low concentrations, long-term application of P reduces the capacity of the soil to adsorb additional P and therefore the P level can cross the threshold limit for losses (Sharpley, 1995). This was probably the cause of the higher P concentration (both WSP and P-AL) in our grazed field.

Because of its saturation of negative charges on the clay surface, soil with higher DPS shows a lower affinity for P (Ulén, 2006) and releases more desorbed P to the soil solution, resulting in higher P losses (Beauchemin and Simard, 1999). Sorption and desorption of P is mainly attributed to the saturation of oxides and hydroxides of Al and Fe (Uusitalo and Tuhkanen, 2000; Börling, 2003; Leytem *et al*., 2005; Mamo and Wortmann, 2009). Our results show that both Fe and Al have a good correlation with soil P content but that Al has a significantly stronger relationship compared with Fe which suggests that Al-oxides and hydroxides probably have better influence on

excess P losses to the aquatic environment. Our findings confirm those of Borggaard *et al*. (1990), who found higher specific surface for Al-oxides than Fe-oxides, resulting in higher P sorption to Al. Soil clay particles often tend to be coated by a thin film of Al-hydroxides, whereas Fe-oxides and hydroxides occur as patches, giving Al more opportunities for P sorption than Fe (Ulén, 2006). Phosphorus solubility increases in more reducing chemical conditions (Zhang *et al*., 2010).

Since the soil at our study site is of heavy clay type, it probably has a higher potential of P losses to the receiving lake. Concentration of soil P and characteristics of surface soil are important parameters for understanding of P losses from topsoil of a clay soil through vertical flow or by surface runoff (Djodjic, 2001). Along with macropores, continuous cracks through the soil column caused by drying events enable deeper root penetration in drained clay (Kirchmann, 1991), making more openings through the profile. Such macropores and cracks reduces the contact time between runoff water and the P adsorbing surfaces. This results in higher P losses, despite the high adsorbing capacity of the subsoil (Djodjic *et al*., 2004).

Higher P sorption capacity in non-calcareous soil is well documented for the presence of amorphous Al-oxide and hydroxide (Bloom, 1981; Borggaard *et al*., 1990; Niskanen, 1990a; Börling *et al*., 2001; Zhang *et al*., 2009). A study by Djodjic *et al*. (2002) showed that P losses from clay soils strongly increased, from 0.16 to 0.91 kg ha^{-1}, with an increase in clay content from 46.5 to 60.6%, even though the soil had low DPS. Our study area has a clay content of 61.25% (Ulen *et al*., 2001), making this area at higher risk of P losses.

Based on the extraction methods of WSP, P-AL, P-OX and P-HNO$_3$, land intensively grazed by horses was found to have higher P content of all forms compared with arable land, and both grazed land and arable land had higher P content than ungrazed pasture. The higher P content in grazed land put this land use ahead of the other two land uses studied for potential risk of P losses. These losses are attributed to WSP and P-AL content of topsoil for the clay soil, since losses by surface runoff and preferential flow through cracks and macropores were evident. The higher P in grazed land is probably because of direct deposition of large quantities of horse manure over the years. Both Fe and Al are regulating factors in soil P release, with Al having a greater impact on P solubility at our study site. Animal manure favours the formation

of amorphous Al and Fe oxides and hydroxides, thereby increasing P sorption. However, coating clay particles with organic matter reduces adsorption sites during subsurface flow and could cause higher P losses to drainage water.

5. Summary and conclusions

This study revealed potentially high losses of P from grazing land for horses, which represents only 10% of Swedish agricultural land. Detailed investigations are needed on different grazing animals before grazing land (as a whole) can be identified as a potential hotspot for high P losses. In parallel to research on arable land, research on P losses from grazing systems and remedial measures for these should be introduced before it is too late. Possible remedial measures include decreased animal density per hectare, no imported feed inside grazing fields, fencing animals away from streams, daily removal of manure from outdoor animal grazing areas, construction of wetlands downslope from the grazing field to remove excess nutrients, etc. To have safe, non-polluted surface water, we must decrease P losses from catchments putting grazing land for horses above arable land for any remediation measures.

References

Bache, B. W. and E. G. Williams. 1971. A phosphate sorption index for soils. *J. Soil Sci.* 22:289-301.

Beauchemin, S. and R. R. Simard. 1999. Soil phosphorus saturation degree: Review of some indices and their suitability for P management in Québec, Canada. *Canadian J. Soil Sci.* 79:615-625.

Bloom, P. R. 1981. Phosphorus adsorption by an aluminium-peat complex. *Soil Sci. Soc. Am. J*. 45: 267-272.

Borggaard, O. K., S. S. Jorgensen, J. P. Moberg and B. R. Lange. 1990. Influence of organic matter on phosphate adsorption by aluminium and iron oxides in sandy soils. *J. Soil Sci.* 41:443-449.

Börling, K., E. Otabbong and E. Barberis. 2001. Phosphorus sorption in relation to soil properties in some cultivated Swedish soils. *Nutr. Cycl. Agroecosys.* 59:39-46.

Börling, K. 2003. Phosphorus sorption, accumulation and leaching - effect of long-term inorganic fertilization of cultivated soils. *Doctoral thesis Agraria no 428*, Swedish University of Agricultural Sciences, Uppsala. ISSN 1401-6249. ISBN 91-576-6466-8.

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.

Brady, N. C. and R. R. Weil. 2002. Soil phosphorus and potassium. In: *The Nature and Properties of Soils* .13th ed. Pearson Education Ltd, New Jersey. 449-495. ISBN: 0-13-016763-0

Caselles, J. M., M. Raul, M. P. Murcia, A. P. Espinosa and B. Rufete. 2002. Nutrient value of animal manures in front of environmental hazards. *Communications in Soil Sci. and Plant Analysis* 33 (15):3023-3032.

Casson, J. P., D. R. Bennett, S. C. Nolan, B. M. Olson and G. R. Ontkean. 2006. Degree of phosphorus saturation thresholds in manure-amended soils of Alberta. *J. Environ. Qual.* 35: 2212-2221.

Dahlin, S. and G. Johansson. 2008. Environmental impact of horse keeping – nitrogen and phosphorus accumulation and distribution in outdoor areas for horses. *SLU, Dept of Soil Sci. Div. Soil Fertility Report 216*.

Djodjic, F. 2001. Displacement of Phosphorus in Structured Soils. *Doctoral thesis Agraria 283*. Swedish University of Agricultural Sciences. Uppsala. Sweden.. ISSN 1401-6249. ISBN 91-576-5826-9.

Djodjic, F., L. Bergström and B. Ulén. 2002. Phosphorus losses from a structured clay soil in relation to tillage practices. *Soil Use Manage.* 18:79-83.

Djodjic, F., K. Börling and L. Bergström. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. *J. Environ. Qual.* 33:678-684.

Dougherty, J. W., N. K. Fleming, J. W. Cox and D. J. Chittleborough. 2004. Phosphorus transfer in surface runoff from intensive pasture systems at various scales: A review. *J. Environ. Qual.* 33:1973-1988.

Dougherty, J. W., P. J. Nicholls, P. J. Milham, E. J. Havilah and R. A. Lawrie. 2008. Phosphorus fertilizer and grazing management effects on phosphorus in runoff from dairy pastures. *J. Environ. Qual.* 37:417-428.

Egnér, H., H. Riehm, and W. R. Domingo. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteiling des Nährstoffzustandes der Böden. II Chemische Extrationsmethoden zur Phosphor- och Kaliumbestimmung. *Kungliga Lantbrukshögskolans Annaler 26*, 199-215. (In German).

Ebeling, A. M., L. G. Bundy, J. M. Powell and T. W. Andraski. 2002. Dairy diet phosphorus effects on phosphorus losses in runoff from land-applied manure. *Soil Sci. Soc. Am. J.* 66: 284-291.

Gburek, W. J., A. N. Sharpley, L. Heathwaite and G. J. Folmar. 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index. *J. Environ. Qual*. 29:130-144.

Greenhill, N. B., K. H. Fung, K. I. Peverill and G. P. Briner. 1983b. Nutrient content of rainwater in Victoria and its agricultural significance. *Search* 14**:**46-47.

Hart, M. R., B. F. Quin and M. L. Nguyen**.** 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. *J. Environ. Qual*. 33:1954-1972.

Haygarth, P. M. and A. N. Sharpley. 2000. Terminology for phosphorus transfer. *J. Environ. Qual*. 29:10-15.

Heathwaite A. L., P. Griffiths, P. M. Haygarth. S. C. Jarvis and R. J. Parkinson. 1997. Phosphorus loss from grassland soils: implications of land management for the quality of
receiving waters. In: *Freshwater Contamination*, Proc. Rabat Symp. IHAS Publ. No 243. 177-186.

He, Z. L., M. K. Zhang, P. J. Stoffella, X. E. Yang and D. J. Banks. 2006. Phosphorus concentration and loads in runoff water under crop production. *Soil Sci. Soc. Am. J.* 70:1807-1816.

Hedberg, A. 2009. Horse breeding as a land use and agricultural activity. In: *EU Equus*. Ministry of Agriculture, Sweden.

Hooda, P. S., M. Moynagh, I. F. Svoboda, A. C. Edwards, H. A. Anderson and G. Sym. 1999. Phosphorus loss in drain flow from intensively managed grassland soils. *J. Environ. Qual.* 28:1235-1242.

Jordan, C. and R. V. Smith. 1985. Factors affecting leaching of nutrients from an intensively managed grassland in County Antrim, Northern Ireland. *J. Environ. Manage*. 20:1-15.

Kleinman, P. J. A., A. M. Wolf, A. N. Sharpley, D. B. Beegle and L. S. Saporito. 2005. Survey of water-extractable phosphorus in livestock manures. *Soil Sci. Soc. Am. J*. 69: 701-708.

Kleinman, P. J. A., A. N. Sharpley, B. G. Moyer and G. F. Elwinger. 2002a. Effect of mineral and manure phosphorus sources on runoff phosphorus. *J. Environ. Qual*. 31:2026-2033.

Kirchmann, H. 1991. Properties and classification of soils of the Swedish long-term fertility experiments. I. Sites at Fors and Kungsängen. *Acta Agriculturae Scandinavica, Section B 41*: 227-242.

LECO Cooperation. 2003. *Organic Application Note, LECO CN2000* (brochure), St. Joseph, Michigan. U.S.

Leytem, A. B., B. L. Turner, V. Raboy and K. L. Peterson. 2005. Linking manure properties to phosphorus solubility in calcareous soils: importance of the manure carbon to phosphorus ratio. *Soil Sci. Soc. Am. J.* 69:1516-1524.

Leytem, A. B., B. L. Turner and P. A. Thacker. 2004. Phosphorus composition of manure from swine fed low-phytate grains: Evidence for hydrolysis in the animal. *J. Environ. Qual.* 33:2380-2383.

Lookman, R., K. Jansen, R. Merckx and K. Vlassak. 1996. Relationship between soil properties and phosphate saturation parameters. A transect study in northern Belgium. *Geoderma* 69:265-274.

Mamo, M. and C. Wortmann. 2009. Phosphorus sorption as affected by soil properties and termite activity in Eastern and Southern Africa. *Soil Sci. Soc. Am. J.* 73 (6):2170-2176.

McDowell, R. W., A. N. Sharpley and G. Folmar. 2001. phosphorus export from an agricultural watershed: Linking source and transport mechanisms. *J. Environ. Qual.* 30:1587-1595.

McDowell, R. W. and I. Stewart. 2005b. Phosphorus in fresh and dry dung of grazing dairy cattle, deer, and sheep: Sequential fractionation and phosphorus-31 nuclear magnetic resonance analysis. *J. Environ. Qual.* 34:598-607.

McDowell, R. W. 2006. Phosphorus and sediment loss in a catchment with winter forage grazing of cropland by dairy cattle. *J. Environ. Qual.* 35:575-583.

McDowell, R. W., D. M. Nash and F. Robertson. 2007. Sources of phosphorus lost from a grazed pasture receiving simulated rainfall. *J. Environ. Qual.* 36:1281-1288.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Analy. Chimica Acta.* 27:31-36.

Nash, D. M. and D. J. Halliwell. 1999. Fertilisers and phosphorus loss from productive grazing systems. *Aust. J. Soil Res.* 37:403-429.

Nash, D. M., M. Hannah, D. J. Halliwell and C. Murdoch. 2000. Factors affecting phosphorus export from a pasture-based grazing system. *J. Environ. Qual.* 29:1160-1166.

Niskanen, R. 1990a.Sorption capacity of phosphate in mineral soils. I Estimation of sorption capacity by means of sorption isotherms. *J. Sci. Agri. Soc.Finland* 62:1-8.

Niskanen, R. 1990b. Sorption capacity of phosphate in mineral soils. II Dependence of sorption capacity on soil properties. *J. Sci. Agri. Soc. Finland* 62:9-15.

Parkyn, S. and R. Wilcock. 2004. Impacts of agricultural land use. In: *Freshwaters of New Zealand,* J. Harding, P. Mosley, C. Pearson and B. Sorrell (eds)., New Zealand Hydrol. Soc., New Zealand Limnol. Soc., Caxton Press, Christchurch, New Zealand. 34.1–34.16.

Pöthig, R., H. Behrendet, D. Optiz and G. Furrer. 2010. A universal method to assess the potential of phosphorus loss from soil to aquatic ecosystem. *Environ. Sci. Pollut. Res.* 17:497-504.

Reeuwijk, L. P. V. 1995. *Methods of Soil Analysis*. International Soil Reference and Information Centre. Wageningen, Netherlands.

Roquette, F. M. J., J. E. Matocha and R. L. Duble. 1973. Recycling and recovery of nitrogen, phosphorus and potassium by coastal bermudagrass. II. Under grazing conditions with two stocking rates. *J. Environ. Qual.* 2:129-132.

Russell, M., D. E. Weller, T. E. Jordan, K. J. Sigwart, and K. J. Sullivan. 2008. Net anthropogenic phosphorus inputs: Spatial and temporal variability in the Chesapeake Bay region. *Biogeochemstry* 88:285-304.

Schindler, D. W. 1977. Evolution of phosphorus limitation in lakes. *Science* 184:897-899.

Sharpley, A. N. 1995. Soil phosphorus dynamics: Agronomic and environmental impacts. *Ecol. Engineering*. 5:261-279.

Sharpley, A. N. and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. *J. Environ. Qual*. 19:1462-1469.

Sharpley, A. N., S. J. Smith and R. G. Menzel. 1986. Phosphorus criteria and water quality management for agricultural watersheds. *Lake Reserv. Managt.* 2: 177-182.

Sharpley, A. N. and H. Tunney. 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. *J. Environ. Qual*. 29:176-181.

Sharpley, A. N., R. W. McDowell and P. J. A. Kleinman.. 2004. Amounts, forms, and solubility of phosphorus in soils receiving manure. *Soil Sci. Soc. Am. J.* 68:2048-2057.

Shober, A. L. and J. T. Sims. 2007. Integrating phosphorus source and soil properties into risk assessments for phosphorus loss. *Soil Sci. Soc. Am. J.* 71:551-560.

Simard, R. R., S. Beauchemin and P. M. Haygarth. 2000. Potential for preferential pathways of phosphorus transport. *J. Environ. Qual*. 29:97-105.

Steegen, A., G. Govers, I. Takken, J. Nachtergaele, J. Poesen and R. Merckx . 2001. Landscape and watershed processes: Factors controlling sediment and phosphorus export from two Belgian agricultural catchments. *J. Environ. Qual*. 30:1249-1258

SIS. 1997. Soil analysis - Determination of trace elements in soils - Extraction with nitric acids. *Swedish Standard* SS 28311. Stockholm, Sweden.

Swedish Agricultural Board. 2009. List of Livestock in Sweden. www.jordbruksverket.se Accessed 2010-01-25.

Tarkalson, D. D. and A. B. Leytem. 2009. Phosphorus mobility in soil columns treated with dairy manures and commercial fertilizers. *Soil Science* 174:73-80.

Ulén, B. Personal communication. Associate professor and senior researcher, Department of soil and environment. Swedish University of Agricultural Sciences. Ulls väg 17, Uppsala 750 07, Sweden.

Ulén, B. 2006. A simplified risk assessment for losses of dissolved reactive phosphorus through drainage pipes from agricultural soils. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science* 56 (4):307–314.

Ulén, B., G. Johansson and K. Kyllmar. 2001. Model predictions and long-term trends in
phosphorus transport from arable lands in Sweden. *Agricultural Water Management* 49:197-210.

Ulén, B. and K. Persson. 1999. Field-scale phosphorus losses from a drained clay soil in Sweden. *Hydrol. Process.* 13:2801-2812.

Uusitalo, R., E. Turtola, T. Kauppila and T. Lilja. 2001. Particulate phosphorus and sediment in surface runoff and drainflow from clayey soils. *J. Environ. Qual*. 30:589-595.

Uusitalo, R. and H. R. Tyhkanen. 2000. Phosphorus saturation of Finnish soils: evaluating an easy oxalate extraction method. *Agric. Food Sci. Finland* 9:61-70.

Vadas, P. A., P. J. A. Kleinman and A. N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface applied manures. *J. Environ. Qual.* 33:749-756.

WFD. 2000. Establishing a framework for Community action in the field of water policy. In: *Directive 2000/60/Ec of the European Parliament and of the Council.* http://eur-lex.europa.eu Accessed 2010-03-12

Zhang, H., G. Johnson and M. Fram. 2009. Managing phosphorus from animal manure. *Oklahoma Cooperative Extension Service, PSS-2249*.

Zhang, W., J. W. Faulkner, S. K. Giri, L. D. Geohring and T. S. Steenhuis. 2010. Soil and water management and conservation: Effect of soil reduction on phosphorus sorption of an organic-rich silt loam. *Soil Sci. Soc. Am. J.* 74:240-249

Appendix I

Soil Analyses data- water-soluble P (WSP); ammonium lactate (AL) extractable phosphorus (P), aluminium (Al), iron (Fe) and calcium (Ca); nitric acid (HNO_3) digested P; P sorption index (PSI); degree of P saturation (DPS)

Sample No	pH	WSP*, fresh soil	WSP*, dry soil	P-AL*	Ca-AL*	Al-AL*	Fe-AL*	PSI***	DPS-AL**	P-HNO3*
Date of analysis: 2009/06/23										
A1	6.00	0.34	0.18	12.76	308.40	35.67	90.83	3.65	6.55	117.6
A2	5.60	0.03	0.07	3.71	254.80	42.58	90.67	5.12	1.85	95.94
A3	5.70	0.46	0.10	9.30	347.00	35.97	75.50	4.70	5.55	113
A4	6.00	0.18	1.06	8.61	455.60	40.58	64.72	4.55	5.66	98.9
A5	6.30	2.07	1.02	42.18	484.80	32.93	83.33	3.34	23.57	171.2
A6	6.00	0.30	0.11	8.84	461.00	43.93	73.58	5.02	5.17	114.8
A7	6.20	0.93	0.33	27.04	422.40	34.43	99.67	3.02	12.90	154.2
A8	6.40	2.18	1.07	44.00	433.00	27.07	132.50	2.78	16.76	186
A9	6.30	1.06	1.04	53.82	406.40	26.60	151.50	4.53	18.16	190
A10	5.90	0.77	0.63	18.64	472.00	41.00	82.98	4.55	10.06	140.6
B1	5.80	0.03	0.09	3.62	255.40	41.92	69.52	4.67	2.23	92.74
B2	5.90	0.03	0.11	4.92	244.00	42.25	79.53	4.91	2.73	101.2
B3	5.80	0.28	0.11	4.59	331.60	34.57	66.30	4.33	3.07	98.34
B4	6.10	0.18	0.16	7.54	332.20	37.17	84.33	4.64	4.09	111
B5	6.30	0.37	0.17	11.00	439.20	38.00	69.82	4.73	6.92	103.6
B6	6.10	0.27	0.20	13.42	373.40	34.05	90.83	4.40	6.94	123.8
B7	6.50	1.65	0.70	32.30	401.60	27.10	94.17	4.35	16.70	137.6
B8	6.30	1.18	0.74	29.14	307.60	26.25	126.50	7.45	11.61	149
B9	6.30	0.65	0.99	49.98	353.40	23.97	152.33	4.62	16.91	177.4
C1	5.50	0.01	0.04	3.47	198.40	46.68	97.17	5.52	1.61	87.38
C2	5.60	0.00	0.06	3.64	219.80	44.87	85.83	5.47	1.88	86.18
C3	5.80	0.09	0.25	13.42	224.80	36.67	116.50	4.90	5.55	122
C4	6.00	0.17	0.18	8.67	312.40	35.70	83.28	4.41	4.78	113.6
C5	6.20	0.36	0.29	14.98	338.00	30.02	81.92	4.00	8.62	119.8
C6	6.10	0.49	0.47	20.88	390.40	32.43	88.00	4.03	11.17	133
C7	6.20	0.49	0.14	13.16	443.40	40.60	82.58	4.79	7.14	131
C8	6.20	1.20	0.85	21.54	352.80	32.43	96.33	4.29	10.67	137.6
C9	6.40	0.93	1.14	37.10	346.20	29.10	126.67	4.28	14.62	173.6
C10	6.60	1.59	2.34	58.04	365.00	23.40	130.83	3.54	22.65	187
D1	6.10	0.02	0.03	5.04	363.20	47.45	99.17	5.35	2.29	96.66
D2	5.80	0.07	0.05	8.06	215.80	55.45	131.50	5.26	2.82	99.78
E1	5.90	0.64	0.87	22.32	369.40	30.10	88.67	4.48	11.99	131.8
E2	6.10	0.24	0.19	7.71	363.40	37.50	61.95	4.60	5.34	108.6
E3	6.20	1.25	0.77	22.80	389.20	34.38	95.67	4.58	11.26	131.8
E4	6.50	0.70	0.22	17.82	382.60	41.87	76.52	4.32	10.22	121.4
E5	6.40	1.15	0.86	23.82	332.20	34.78	94.17	4.96	11.91	136.2
E6	6.50	1.14	0.78	27.56	338.60	31.95	115.17	4.57	11.70	141.8
F1	6.10	0.36	0.17	10.64	345.40	35.12	68.70	4.52	6.89	112
F2	6.00	0.28	0.11	7.38	374.60	40.67	58.57	4.96	5.23	100.6
F3	6.30	0.42	0.15	12.38	407.80	41.38	67.95	4.98	7.81	118.2
F4	6.20	0.35	0.45	15.62	330.20	38.42	93.33	4.76	7.74	118.6
F5	6.50	0.83	0.39	19.38	311.40	34.95	102.83	4.63	8.98	121.4
G1	6.50	0.20	0.04	5.29	357.40	37.62	71.97	5.05	3.26	92.98
G2	6.20	0.48	0.11	6.78	309.60	38.12	67.30	4.73	4.39	92.1
G3	6.30	0.61	0.12	11.86	389.20	37.10	61.75	4.39	8.26	106.6
G4	6.00	0.24	0.30	7.15	327.40	39.42	64.87	4.51	4.73	95.94

G5	6.30	0.45		0.10	12.60	394.20	40.73	66.55	5.08	8.10	108.8
G6	6.20	0.64		0.17	9.55	328.20	40.42	82.22	4.63	5.20	106.2
H1	5.80	0.41		0.39	5.31	339.80	39.35	59.05	4.68	3.78	89.7
H2	6.20	1.23		0.36	11.86	346.40	40.18	73.53	4.58	7.08	113.6
H3	6.10	0.54		0.14	6.23	400.60	45.92	72.18	3.30	3.66	88.82
H4	6.30	0.69		0.22	14.60	444.00	39.13	74.32	5.42	8.69	110
H5	6.10	0.51		0.15	6.45	399.80	45.65	70.72	4.89	3.86	101.8
H6	6.40	0.59		0.43	13.96	331.80	38.02	89.33	4.89	7.19	111.8
I1	5.70	0.61		0.52	7.53	373.00	41.32	60.15	4.60	5.22	102
I2	6.00	0.37		0.23	5.46	377.20	45.75	71.77	4.74	3.23	97.22
I3	6.10	0.32		0.39	7.63	317.80	43.38	83.02	4.94	4.07	111.6
I4	5.90	0.49		0.50	11.48	283.40	40.32	80.22	4.30	6.39	108.8
J1	6.20	0.33		0.54	12.90	295.00	36.55	101.17	4.66	6.02	122.6
J2	5.80	0.35		0.56	10.34	267.60	44.08	94.83	5.10	4.94	125.6
J3	6.00	0.42		0.71	9.02	263.40	39.32	91.67	4.82	4.52	113.4
K1	5.50	1.22		0.29	6.03	393.40	42.70	67.02	5.02	3.81	87.38
K2	6.30	0.92		0.59	9.60	340.60	40.95	69.80	4.63	5.95	104.6
K3	6.20	0.92		0.60	10.02	323.40	43.35	77.05	4.21	5.67	101.8
K4	5.70	0.99		0.37	5.49	347.40	44.48	81.90	4.86	2.94	103.4
K5	6.10	0.90		0.31	7.50	369.20	38.75	62.95	4.50	5.09	98.82
K6	5.90	0.54		0.60	6.73	341.20	37.45	55.17	4.37	5.09	102.6
K7	6.00	0.88		0.45	5.71	345.00	38.50	62.32	4.57	3.91	99.14
K8	6.40	1.04		0.17	6.50	325.80	40.62	74.38	5.18	3.83	91.7
K9	5.80	1.15		0.53	4.11	309.20	39.98	62.43	5.15	2.79	83.22
K10	6.20	0.57		0.63	8.15	291.20	36.78	65.73	4.73	5.41	107.8
L1	6.20	0.57		0.81	15.66	342.00	33.80	100.50	4.35	7.43	121.6
L2	6.10	0.39		0.21	4.97	424.20	48.45	60.05	6.67	3.30	98.34
L3	6.40	0.78		0.26	7.49	468.20	51.62	64.82	5.48	4.63	109.2
L4	6.30	0.34		0.12	6.83	486.60	52.82	68.92	5.80	4.01	101.6
L5	6.30	0.53		0.45	8.03	452.60	45.57	67.72	5.86	4.96	102.8

* mg 100 g^{-1} soil; ** % (molar weight basis)

Appendix II

Soil analysis data- acid oxalate (OX) extractable phosphorus (P), aluminium (Al), and iron (Fe); degree of P saturation (DPS); total organic carbon (C) and nitrogen (N)

Date of analysis: 2010/03/16						
Sample No	P-OX*	Al-OX*	Fe-OX*	DPS-OX**	Tot-C %	Tot-N %	C/N
A1	17.12	44.12	116.23	6.90	3.52	0.33	10.63
A2	14.12	45.73	121.96	5.44	2.75	0.27	10.19
A3	12.73	46.72	113.81	5.18	2.31	0.23	9.87
A4	14.90	53.58	106.05	6.26	3.72	0.37	10.00
A5					7.24	0.63	11.47
A6	17.18	61.48	111.41	6.75	4.52	0.47	9.58
A7	21.99	52.34	123.99	8.17	4.30	0.43	10.08
A8	29.06	36.46	109.43	12.69	6.56	0.62	10.61
A9	36.64	35.19	137.46	13.16	6.44	0.59	10.97
A10	20.25	42.42	93.69	9.83	6.64	0.60	11.10
B1	12.21	42.75	101.52	5.54	2.46	0.23	10.51
B2	15.05	45.89	115.13	6.08	2.44	0.24	10.31
B3	13.49	45.33	114.75	5.47	3.07	0.29	10.78
B4	14.64	42.64	106.56	6.39	3.41	0.32	10.55
B5	16.44	53.91	101.75	7.13	3.83	0.38	10.01
B6	19.29	52.04	116.71	7.54	4.46	0.44	10.24
B7	23.32	45.36	110.78	9.75	4.95	0.48	10.42
B9	34.58	35.99	138.74	12.29	5.08	0.48	10.69
C1	10.91	35.82	91.42	5.57	2.88	0.29	9.92
C2					3.60	0.33	11.00
C3	21.10	42.37	126.56	7.96	3.45	0.33	10.54
C4	19.91	51.73	140.18	6.68	3.33	0.32	10.47
C5	21.30	49.78	137.42	7.31	4.81	0.45	10.68
C6	23.57	49.44	118.43	9.19	4.35	0.43	10.24
C7					5.19	0.47	11.07
C10	23.77	21.19	85.53	13.76	4.70	0.41	11.44
D1	18.70	51.13	137.61	6.39	3.33	0.33	10.12
E1	16.12	48.64	115.95	6.41			
E2					4.69	0.46	10.24
E3					3.86	0.39	9.93
E4	19.71	49.58	99.77	8.83	2.80	0.30	9.25
E6	30.15	46.00	142.92	10.13	2.99	0.29	10.34
F1	19.55	53.02	141.32	6.50	3.01	0.30	10.10
F2	16.31	55.60	117.82	6.25	3.85	0.40	9.68
F3	19.74	56.00	107.98	8.11	3.90	0.38	10.18
F4	19.25	47.70	102.74	8.49	3.23	0.34	9.43
F5	23.01	48.71	126.41	8.51	2.26	0.22	10.44
G1	14.72	50.02	125.12	5.47	2.79	0.27	10.21
G2	17.59	52.84	141.55	5.84	3.79	0.39	9.79
G3	18.92	53.49	127.76	6.83	2.16	0.24	9.09
G4					3.77	0.37	10.10
G5	20.51	58.34	115.65	7.91	3.54	0.36	9.72
G6	19.00	52.50	121.08	7.20	1.87	0.19	9.74
H1	12.85	57.08	109.59	5.20	2.64	0.27	9.80
H2	16.60	59.43	117.98	6.28	3.53	0.35	10.16
H3	17.20	62.95	124.07	6.18	3.41	0.36	9.52
H4	19.62	58.97	119.93	7.33	3.84	0.39	9.83

H5	18.61	64.77	127.06	6.52	3.58	0.38	9.50
H6	23.03	58.50	149.09	7.20	3.15	0.32	9.91
I1	16.55	57.53	118.67	6.27	3.39	0.34	10.10
I2					2.84	0.31	9.27
I3	21.66	65.22	157.14	6.37	3.19	0.27	12.00
I4	21.56	52.23	153.03	6.71	2.56	0.27	9.43
J1	19.42	47.29	135.29	6.81			
J2	21.09	51.51	141.88	7.01	2.49	0.26	9.76
J3	17.06	48.11	131.90	6.10	2.23	0.22	9.95
K1	13.55	56.67	106.89	5.60	3.22	0.29	11.11
K2	16.11	54.86	114.53	6.34	2.81	0.26	10.83
K3	16.19	49.32	106.42	6.89	3.31	0.31	10.64
K4	16.56	52.76	120.74	6.28	2.70	0.27	10.09
L2	9.69	73.09	106.99	3.78	1.44	0.14	10.43
L3	17.63	72.56	132.29	5.84	3.79	0.37	10.30

* mg 100 g^{-1} soil; ** % (molar weight basis)