Impact of Horse-keeping on Phosphorus (P) Concentrations in Soil and Water

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Cover: Paddock outlooks during spring at a site used for the survey study
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Abstract

Agricultural sources contribute significantly to the high phosphorus (P) loads in water, causing eutrophication in many of Europe's water bodies. Consequently, priority has been given to reducing P leakage from sources, including soils used for animal farming. Horse farms use about 4 % of the total agricultural land in the EU, but have not so far been investigated thoroughly with regard to their impact on water quality. This study characterised the potential risk of P leaching losses from Swedish horse paddocks in a three-stage investigation of the soil and water P status. The study began with an analysis of eight years of drainage P data from a small catchment, a so called – 'observation field', dominated by horse paddocks (Paper I). In the following study (Paper II), soil P status was examined in different parts of the horse paddocks (feeding, grazing and excretion areas) to identify potential hotspots for high P losses within the paddock. In the third experiment (Paper III), topsoil columns (0 - 20 cm) from different segments of the paddock (feeding, grazing, and excretion area) were isolated and potential leaching losses of P from the soil columns were measured during simulated rainfall in the laboratory. The studies showed that: i) horse paddocks can pose a potential threat to water quality *via* leaching of excess P, ii) feeding and excretion areas are potential hotspots for significantly high leaching losses, and iii) paddocks established on sandy soils are particularly vulnerable to high P losses.

Besides identifying P leaching problems, additional investigations were carried out to mitigate P losses from paddocks using organic bedding materials (*e.g.* wheat straw, wood chips and peat) (Paper IV) and to determine an environmentally safe load of horse manure for arable soils (Paper V). The main findings of these studies were: iv) of the three bedding materials, only wood chips could reduce P losses while the other two enhanced leaching losses, and v) the addition of composted horse manure up to 36 Mg ha^{-1} (22 kg P ha^{-1}) did not increase P leaching from organic soil, but from the mineral soils, while 90 - 100 % of the added P from the compost was retained in the soils.

Finally, proposals for better paddock management were outlined and the need for national rules/regulations for horse paddocks were stressed to avoid nutrient build-up and to reduce losses. In addition, to strengthen the understandings and conclusions, more field studies were suggested for future research.

Keywords: Animal grazing, Bedding materials, Composted manure, Eutrophication, Horse paddocks, Mineral soil, Leaching losses, Organic soil, Phosphorus, Water quality

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Dedication

To my parents and to the proletariat farmers

Nothing goes unpaid in the nature - a common saying

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Parvage, M.M., Kirchmann, H., Kynkäänniemi, P. & Ulén, B. (2011) Impact of horse grazing and feeding on phosphorus concentrations in soil and drainage water. Soil Use and Management 27 (3), 367–375.

II Parvage, M.M., Ulén, B. & Kirchmann, H. (2013) A survey of soil phosphorus (P) and nitrogen (N) in Swedish horse paddocks. Agriculture, Ecosystems and Environment 178, 1-9.

III Parvage, M.M., Ulén, B. & Kirchmann, H. (2015) Are horse paddocks threatening water quality through excess loading of nutrients? Journal of Environmental Management 147, 306-313.

IV Parvage, M.M., Ulén, B. & Kirchmann, H. (2015). Wood chips, peat and wheat straw as manure phosphorus binding agent to reduce leaching losses from horse paddocks (manuscript).

V Parvage, M.M., Ulén, B. & Kirchmann, H. (2015). Nutrient retention and leaching potential from three contrasting agricultural top soils in Sweden amended with composted horse manure (submitted).

Papers I-III are reproduced with the permission of the publishers.

The contribution of Mohammed Masud Parvage to the papers included in this thesis was as follows:

I Took part in planning together with third and last co-authors. Performed the experimental work, data analysis, data interpretation and writing with frequent assistance from all co-authors.

II Planned the study together with all co-authors. Performed the experimental work, data analysis, data interpretation and writing with frequent assistance from all co-authors.

III Planned the study together with all co-authors. Performed the experimental work, data analysis, data interpretation and writing with frequent assistance from all co-authors.

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Abbreviations

AL	Ammonium acetate lactate
DM	Dry matter
DOP	Dissolved organic phosphorus
DPS	Degree of phosphorus saturations
DRP	Dissolved reactive phosphorus (in water/leachate sample)
EU	European union
FIA	Flow injection analyser
LSU	Livestock unit
PO_4^{3-}	Phosphate
PP	Particulate phosphorus
SD	Soil with dung on the top
SPD	Soil with 5 cm peat and dung on the top
SWCD	Soil with 5 cm wood chips and dung on the top
SWSD	Soil with 5 cm wheat straw and dung on the top
TOC	Total organic carbon
TP	Total phosphorus (in water/leachate sample)
WHC	Water holding capacity
WSP	Water soluble phosphorus

1 Introduction

With a growing population, rising urbanisation and increased incomes, the demand for high-protein food such as meat, poultry, milk and other dairy products is increasing at an unprecedented level (WHO, 2015). In addition to the dietary demand, recreational activities such as horse riding, racing and other horse-associated activities are growing mainly in the developed world. For example, the number of horse riders in Europe is growing by about 5 % per year, and horse farms today occupy about 4 % of the continent's total agricultural land (European Horse Network, 2015). In contrast, total arable land around the world has been decreasing by about 1.5 % over the past 40 years (from 1970 to 2009) and still almost a billion people suffer from food insecurity (FAO, 2014, 2015). To cope with urbanisation, food security, the demand for high-protein food and recreational activities *versus* the limited availability of land, agricultural practices have been intensified (producing more per area per year with all necessary inputs) including livestock production (Bruinsma, 2003; Bouwman *et al.*, 2013; Herreroa & Thornton, 2013). Increased livestock farming demands more fodder and space, which is made possible through intensive management of the grazing systems by supplying concentrated feed to animals, applying fertiliser/manure to the field for more forage production, and increasing animal density per arable land. Such activities cause nutrient build-up in grazing systems (Hooda *et al.*, 1999, 2000; Hubbard *et al.*, 2004; Bouwman *et al.*, 2013).

Phosphorus (P), the "light bearer" of Greek mythology (Φωσφόρος), is one of the most important nutritional elements for all living beings. It is an essential component of adenosine triphosphate (ATP), phospholipids, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) which supplies energy for most biochemical reactions, forms important parts of cell membranes, maintains genetic codes, and guides protein synthesis, respectively

(Brady and Weil, 2012). Soils and P mineral deposits (used as P fertilisers) are the major sources of P in terrestrial ecosystems, while P sources in aquatic systems include both dissolved and particle-bound P in water and sediment. Apart from any internal loadings (mainly from the sediments), elevated P concentrations in fresh water bodies and in coastal waters primarily come from terrestrial sources. Atmospheric deposition of P is common in both systems and may also contribute significantly. Plants and microorganisms fulfil their P requirements directly from soils, while animals are primarily dependent on plants. Plants usually take up inorganic P from the soil solution, and soluble inorganic P in unfertilised soils is often very low, less than one per cent of total P (Pierzynski *et al.*, 2005). Moreover, soluble inorganic P is highly susceptible to forming compounds and complexes with metals, minerals, soil particles and organic matter (Brady and Weil, 2012). Therefore, usage of chemical fertilisers and manures is common to ensure sufficient P supply for optimum plant growth (Steegen *et al.*, 2001). However, continuous high inputs of P to arable land from any source may lead to an excessive accumulation of P (Nash and Halliwell, 1999; Hooda *et al.*, 2000; Ulén *et al.*, 2007). Beside its fertiliser value, P is one of the key elements affecting fresh water eutrophication, causing algal bloom, water quality deterioration, oxygen-free zones and loss of aquatic organisms including fish (Schindler, 1977). A rise in soil P levels increases the risk of P losses to water bodies *via* surface runoff and subsurface leaching. The latter may take place through fast macropore flow and a slower matrix flow.

2 A brief overview of phosphorus in animal grazing systems

2.1 Sources and distributions

In grazing systems, the sources of P include P-bearing soil minerals (primary sources), soil organic matter, mineral fertilisers, manure, fodder waste and atmospheric deposition. Of all these, soil P is quantitatively the main source of P. Total P contents in the top 15 cm soil range from 200 to 2000 kg P ha^{-1} (Brady and Weil, 2012) of which 40 - 70 % has been estimated to be inorganic P and 30 - 60 % organic P (Condron *et al*., 2005). However, the concentration of P in the soil solution is low, varying between tens of grams to a kilogram per hectare, depending on adsorption-desorption and precipitation-dissolution processes, and is regulated mainly by, soil pH, available cations and buffering capacity (Nash and Halliwell, 1999). Soils high in calcium, magnesium, iron and/or aluminium precipitate P from the soil solution making it unavailable for plant uptake or runoff losses in dissolved forms (Dougherty *et al*., 2004).

As in other agricultural areas, the application of fertilisers to grazing pastures is a common practice to increase forage production (Bruinsma, 2003; Bouwman *et al*., 2013). Dissolution of chemical fertiliser yields inorganic phosphate ions into the soil solution and thus acts as a readily available source of P. For example, water-soluble P (WSP) in single super phosphate is about 10 % and about 20 % in triple super phosphate (Hedley and McLaughlin, 2005). Inorganic fertilisers dissolve or mobilise more rapidly than manure/slurries. However, plants barely utilise more than 20 % of the added P during a single growing season (Roy *et al*., 2006) and a major fraction of the remaining P is adsorbed to soil particles. Therefore, regular application of P fertilisers from any source can lead to a steady increase in soil P levels (Hooda *et al*., 2000).

In grazed land, P is returned to soil as animal manure on a regular basis through dung and urine (Nash *et al.*, 2000). Livestock urine contains a very small amount of P (Braithwaite, 1976) and dung is the main source of P in animal manure (Morse *et al.*, 1992). Total P inputs to grazed fields depend on the quality of fodder eaten by the animals in the stables and/or in outdoor feeding areas, how much time the animals spend on the grazing fields and animal density. For example, total P concentrations in manure from free-range grazing cattle are almost half (0.48 % of dry matter) of those fed a forage diet supplemented with grains (0.80 % of dry matter) (Ewusi-Mensah, *et al.*, 2015). Phosphorus deposition in intensively managed horse-grazed fields (paddocks) where additional fodder is supplied ranges from 38 to 108 kg P ha^{-1} yr^{-1} depending on animal density which ranges from 5.3 to 14.5 livestock unit (LSU) ha^{-1} (1 horse = 0.8 LSU) (European Commission, 2013a; Parvage *et al.*, 2013). Animal manures have N:P ratios of about 3-5:1 (Hubbard *et al.*, 2004) while common forage crops uptake N to P at a ratio of about 8:1 (Caselles *et al.*, 2002; Zhang *et al.*, 2009). This indicates that nutrients in manure are in unbalance relative to the crops' need. Excess P added with the manure may contribute to soil P build-up and possible subsequent losses. Figure 1 represents a simplified depiction of P dynamics in a grazing system.

Animals in intensively managed systems are given fodder and concentrated feed regularly during outdoor stay on the grassland or in paddocks. Average P content in common pasture plants is about 0.35 % of dry biomass (Nash and Halliwell, 1999) and concentrated feed can have an even higher content. Fodder waste left on the soil can contribute to a significant P increase in the feeding zone. However, there is lack of knowledge about the size of this P pool (P input *via* fodder waste). Atmospheric deposition (dry deposition and rainfall) of P amounts to about 0.5 kg P ha^{-1} yr^{-1} (Anderson and Downing, 2006).

2.2 Pathways and forms of P losses from grazing systems

With regard to the final P load to streams and lakes from grazed land, transport pathways play a crucial role. Both wind and water can transport significant amounts of P from grazed fields to streams, lakes and seas. However, wind transports mainly particle-bound P (both mineral and organic) and is dominant in arid to semi-arid regions where fields have no/limited vegetative cover and soil particles are often more loose. In other parts of the world, water transport of P is the main pathway for losses, and the forms of losses include soluble inorganic P, organic P and particulate P with eroding soil and organic matter particles (Nash and Halliwell, 1999; Hooda *et al.*, 2000; Haygarth and Sharply, 2000; Bilotta *et al.*, 2007). The loss of P from soils is primarily determined by

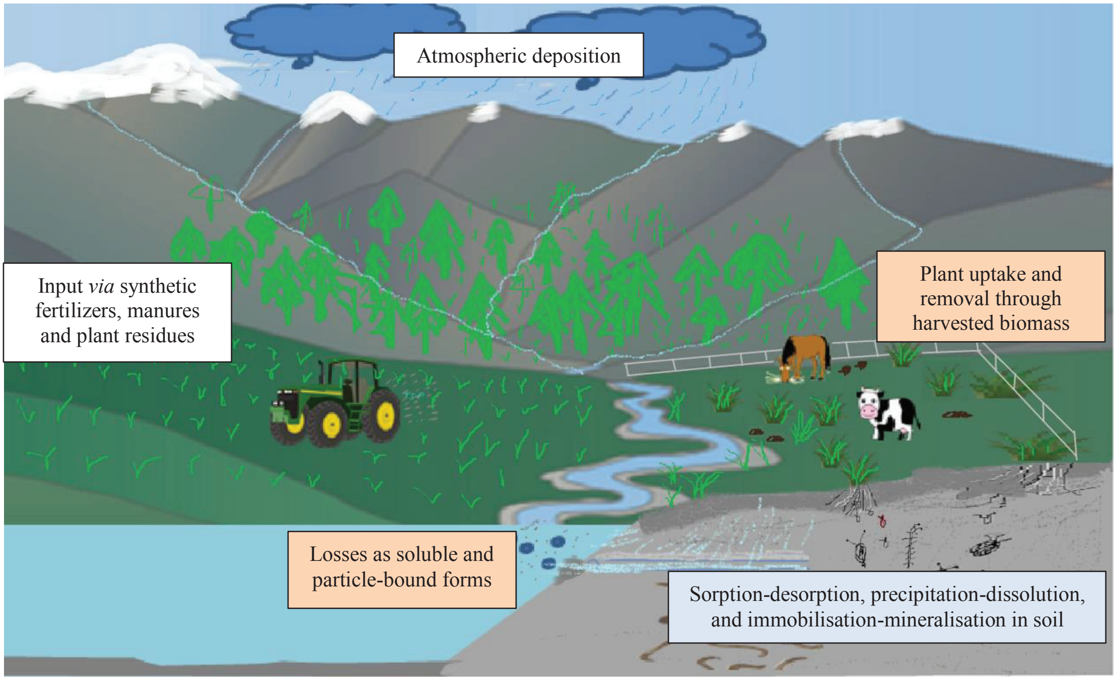

Figure 1. A simplified graphic representation of phosphorus (P) dynamics in a grazing system.

the solubility of P and the detachability of P-containing sediments from aggregates to the soil solution (McDowell *et al*., 2001). The topography of the landscape and soil's water permeability influences water and P movement from the soil surface and throughout the soil profile, and affects the final P load from grazed fields, paddocks and catchments to water bodies. Generally, soils with high relief are more susceptible to surface runoff, causing high loads of particulate P. In grazed land with a slope, faecal P is often lost through runoff, of which one-third could be as water soluble P and the rest as particulate P (Ebeling *et al*., 2002; Monaghan *et al*., 2002; Mundy *et al*., 2003; McDowell, 2006). However, the proportion of dissolved P and particulate P in runoff water varies depending on hydrological conditions, the nature of the animal manure (*e.g.* time of deposition and types of livestock), the dominant clay type of the soil and the soil textural class (Jordan and Smith, 1985; Hooda *et al*., 1999; Simard *et al*., 2000; Uusitalo *et al*., 2001; McDowell, 2006). Runoff losses are expected to be highest where there is a combination of intensive precipitation, clayey-type soil and grazing animals excreting just before raining events.

In contrast, water movements in grasslands on flatter landscapes are characterised by leaching through soil profiles as matrix flow, macropore flow and/or interflow. In Sweden and other countries with a high water surplus in winter, arable land used for grazing is usually drained and the drainage water carries both soluble and particulate-P. The main source, main transport pathway and the proportion of soluble and particulate-P vary widely from study to study. For example, Dougherty *et al*. (2008) showed that leaching losses of P from a dairy pasture had occurred mainly as water soluble P (around 90 %) and only 10 % as particulate P. Heathwaite *et al*. (1997) found that 50 % of organic P losses were through subsurface drainage and at least 33 % through surface runoff. Streams may also receive P directly from animals drinking from the stream and dropping urine and dung as they drink. McDowell (2006) reported a significant amount of P in stream sediments originated directly from the excretion of animals.

3 Problem identification and understanding the causes (Papers I, II & III)

3.1 Background

Excessive loads of P have caused eutrophication in many fresh and marine water bodies around the globe, with different agricultural sources identified as major contributors to P loads. In the northern hemisphere, the Baltic Sea is one of the most eutrophied water bodies (Swedish Environmental Protection Agency, 2013), with agriculture alone contributing over 60 – 70 % of diffuse and about 50 % of total anthropogenic water-borne loads of P (HELCOM, 2013a). As a result, the reduction of P losses from arable land and improved management of animal manures have been prioritised greatly by the countries surrounding the Baltic Sea.

Of the countries adjacent to the Baltic Sea, Sweden has the longest coastline (> 13,500 km) and contributes 13 % of total water-borne P loads (third largest contributor) to the Baltic Sea (HELCOM, 2011). Due to these high loads, Sweden has initiated different measures to reduce P loads from agricultural soils and succeeded in decreasing yearly loads by about 5 % during the period 1995 to 2005, but no significant improvement thereafter (Blombäck *et al.*, 2011). Therefore, further improvements are required, which means more appropriate countermeasures and the identification of all possible sources for losses not included in the current assessment. Horse keeping could be a potential source of P leakage to waters that have so far not been included (no specific guidelines) in the Swedish national nutrient reduction plans, in the Baltic Sea Action Plan (HELCOM, 2013b) and/or in the European Union Water Framework Directive (European Commission, 2013b).

The numbers of horses in many European countries are substantial and comparable with other large farm animals. For example, there are 1 million horses in Great Britain, 0.6 million in Spain, 0.4 million in Sweden, and 0.3 million in Belgium (European Pari Mutuel Association, 2009), equivalent to about 56 %, 72 %, 105 % and 60 % respectively of the total number of dairy cows (DairyCo, 2013). Although horse farms are often not considered as agricultural activities, they utilise more than six million hectares of permanent grassland, which is equivalent to *ca.* 4 % of the total agricultural land in the EU (European Horse Network, 2015). Some of these six million hectares are intensively managed as paddocks for outdoor keeping, feeding and grazing, often located close to stables.

Horse keeping is an important part of Swedish history and culture. There were about 700,000 horses in Sweden in the 1920s, a number that decreased sharply due to mechanisation of agriculture to about 70,000 in the 1970s (Kolstrup *et al*., 2013). However, Swedes' attraction for horses has grown again in the past 15 to 20 years. According to the Swedish Board of Agriculture (2013), the numbers of most farm animals (*e.g.* cattle, pigs, dairy cows) have decreased over the past two decades, while the number of horses has increased by more than 300 %, from 88,600 horses in 2000 to 362,700 in 2010, and the numbers are still rising. Today, horses occupy around 300,000 ha of Swedish land, which comprises about 10 % of the total agricultural land in the country, including 17,509 farms with an area of ≥ 5 ha (Swedish Board of Agriculture, 2013). Horse farms in other Nordic countries also occupy a larger fraction of the total agricultural area, for example, 6 % in Norway and 5 % in Finland (European Pari Mutuel Association, 2009).

In addition to horse stables, horses in Sweden are often kept outdoors within comparatively small, fenced-off paddock areas near stables. Unlike other farm animals, horse densities in paddocks are based on recommendations rather than regulations, and high animal densities may exist. In addition to high animal density, paddocks are used as daily outdoor feeding places and for exercise activities, even during snow-covered winter months. Fodder remnants and excreta deposited in paddocks may not be removed, which can result in a nutrient build-up in paddock soils. In addition, horse farms in Sweden are established near towns and cities, where vulnerable water bodies used for drinking water extraction can be affected. However, information on P dynamics and the P-related environmental impact of horse keeping is still scarce and this sector has so far not been included in environmental planning. Previous studies in Finland on paddock soils reported a higher nutrient build up and losses from these systems (Airaksinen *et al*., 2007; Närvänen *et al*., 2008). Therefore, horse grazing in Swedish paddocks combined with outdoor feeding may cause a higher risk of P build up in soil and subsequent high losses, which needs to be confirmed with proper investigations. An understanding of P dynamics (*i.e.* input, build-up/reserves and output/losses) in horse paddocks will help to find out whether these areas contribute substantial P losses in relation to other sources. In addition, if horse keeping has a potential impact on total land-based P losses, there will be a need to find potential mitigation options, including proper management of the paddocks and handling of horse manure.

3.2 Aims

To be able to answer the key question as to whether horse keeping can have a significant impact on P leaching, three types of investigations were performed. The first type of investigation included a pilot study on P concentrations in soil and drainage water of a paddock soil *versus* an adjacent arable soil used for cropping (Paper I). The major aims of this investigation were: (i) to determine whether paddocks have the potential for higher P losses than adjacent arable land, and (ii) to know which P form(s) dominate in paddock leaching as compared to the arable field. In the second type of investigation, a survey was conducted on existing horse farms with regard to management strategies and the nutrient status in paddock soils (Paper II). The specific objectives of this investigation were: (iii) to receive information about how paddocks were managed with regard to animal density, manure removal and years of operation, (iv) to identify nutrient-enriched zones in the paddocks, and (v) to categorise paddock soils with respect to their environmental risk, using the threshold soil concentration for P set by the Swedish Environmental Protection Agency (Swedish EPA, 2012). Finally, in the third investigation, paddock soils were studied with respect to nutrient status and nutrient leaching potential using a rain simulator in the laboratory (Paper III). The objectives of this leaching study were: (vi) to reconfirm the potential of high P losses previously forecasted by measuring soil P content only, and (vii) to compare losses with those from nearby unfertilised reference soils and from common agricultural fields in Sweden.

3.3 Sampling, preparation and chemical assay

During the investigations composite soil samples, soil monoliths and drainage water/leachate were collected. Composite samples were a mixture of five to eight subsamples taken with augers, after which the samples were dried and milled to less than 2 mm for chemical analysis. Soil monoliths were collected in plastic cylinders (20 cm long, 18.8 cm diameter) at points close to the spots used for composite soil sampling. Soil columns were kept in a cold room at 5 ^{o}C until the rain simulation began. The indoor rain simulation station had a sprinkler system with hydraulic atomising fine spray nozzles to create artificial rain. The nozzles had a capacity of 7 L h^{-1}, with a drop diameter of 0.07 - 0.10 mm. The sprinkler system was positioned 80 cm above the soil columns. More details of the rain simulator can be found in Liu *et al.* (2012a). Before rain simulation, the bottom of each soil column was carefully prepared by removing excess soil with a sharp knife and loose soil particles with a vacuum cleaner. The bottom was then wrapped with a polyamide cloth filter (50 µm) and the column placed on a perforated metal plate inside a steel base tray. The tray base was connected to a flexible plastic pipe, which drained leachate from the tray into a glass jar. To prevent any water entry to the tray from outside, the gap between the tray and the column wall was sealed with a plastic canvas cap and duct tape. Tap water containing 0.004 mg total P L^{-1} and 1.07 mg total N L^{-1} (pH 8.3) was used as rainwater. Prior to the leaching study, soil columns were kept in the rain chamber for a week to reach equilibrium at room temperature (22 ^{o}C).

Soil samples were analysed for water-soluble P (WSP) where the extraction was according to Self-Davis *et al.* (2000), applying a ratio of 1:3 for soil to water and determined colorimetrically (Murphy and Riley, 1962) using a Shimadzu UV-1201 spectrophotometer. Plant-available P, aluminium (Al) and iron (Fe) were extracted with 0.5 M ammonium acetate lactate (AL) solution at pH 3.75 (Egnér *et al.*, 1960) and analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) Optima 5300. The degree of P saturation (DPS) percentage was calculated as the ratio of the elements on a molar basis in the AL extract using the equation: DPS % = [P-AL ÷ (Fe-AL + Al-AL)] x 100

After acid digestion in 7 M HNO_3, the concentration of total P was determined by ICP-AES (SIS, 1997). Organic P was taken as the difference in inorganic P between combusted soil (ignition at 550 ^{o}C for 1 h) and a fresh sample, both shaken with 0.1 M H_2SO_4 for 16.5 h (Saunders and Williams, 1955). Concentrations of P in the extracted solutions were measured by ICP-AES (SIS, 1997). Concentrations of total organic carbon (TOC) and total N were determined after combustion of 1 g air-dry soil at 1250 ^{o}C for 5 minutes, using a LECO CN2000 analyser (LECO Corporation, 2003). Soil pH was determined in deionized water using a glass electrode pH meter and a soil-to-water ratio of 1:5.

Concentrations of P in water samples were measured in accordance with the European Standard EN 1189 (European Committee for Standardisation, 1996). For total P (TP) analysis, unfiltered samples were digested with a mixture of potassium peroxodisulphate ($K_2S_2O_8$) and sulphuric acid (H_2SO_4) for 30 minutes at 120 ^{o}C. After cooling at room temperature, the digested water samples were analysed for P in a flow injection analyser (FIA). Concentration of TP was also analysed in filtered samples and particulate P (PP) was calculated as the difference in TP between filtered and unfiltered samples. Dissolved reactive P (DRP) was determined by FIA using undigested but filtered samples (0.2-µm membrane filter paper). Dissolved organic P (DOP) was estimated by subtracting DRP and PP from TP in unfiltered samples.

3.4 Investigations

3.4.1 Pilot study

The investigation was carried out in an agricultural area located 30 km south of Stockholm (Fig. 2). The soil at the site was heavy clay and was classified as a Eutric Cambisol (Ulén and Persson, 1999). The slope of the study area was approximately 5 %. The paddock area comprised a total subsurface drained area of 7.2 ha arable land having a central collecting drain pipe, and included 2.77 ha horse paddocks used for grazing, outdoor feeding and outdoor keeping, even during snow-covered winter months.

The horse paddock had an animal density of 3.75 LSU ha^{-1} and received 14 kg P ha^{-1} yr^{-1} through direct manure excretion. An adjacent agricultural field (4.43 ha) with a similar soil type and drainage discharge was used for comparison of drainage P data and soil P status. The arable field was continuously cropped and both mineral fertiliser and manure were applied to the arable field at a rate of 13 kg P ha^{-1} yr^{-1}.

To compare P leaching losses between paddock soil and agricultural soil, drainage water was collected manually every second week over a period of eight years (2002 - 2010) from the drainage culverts of both the paddock catchment and the arable field. Leachate samples were analysed for DRP and TP. The results of drainage water analysis revealed that losses of both DRP and TP were higher from the paddock area than from the arable field (Fig. 3). Mean

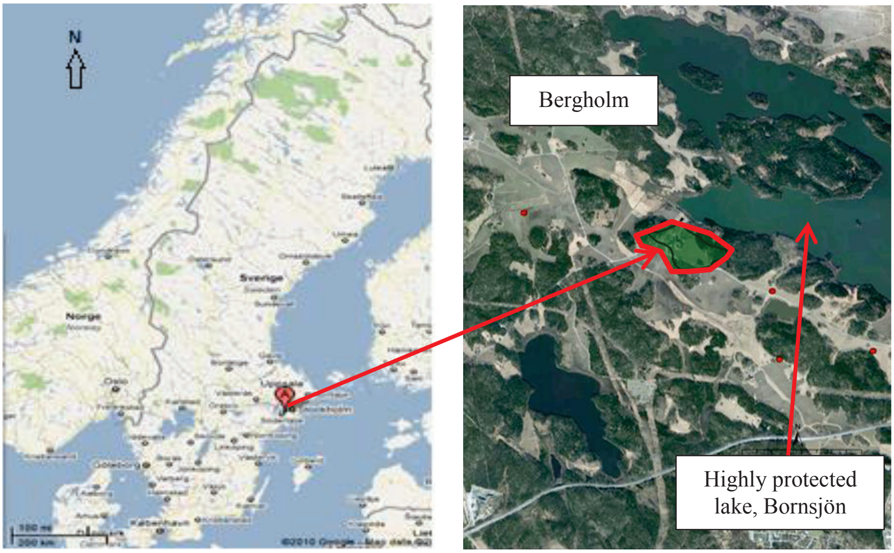

Figure 2. Location of the study site in Bergholm, Stockholm (geographic coordinates, 59°14'2.47"N, 17°42'44.82"E; published with permission of the Swedish Land Surveyor Gävle 1 2010/0050).

concentration of DRP in drainage water from the paddock catchment was about 13 times higher (0.27 *vs.* 0.02 mg L^{-1}) and TP was three times higher (0.33 *vs.* 0.10 mg L^{-1}) than from the arable field. Peak values exceeding 1 mg L^{-1} DRP and/or 1.5 mg L^{-1} TP were measured on some occasions in spring and autumn in the leachate of the paddock catchment, but no such peaks were detected from the arable field.

To complement the drainage data, topsoil (0 - 10 cm) samples were analysed from both land uses for WSP, P-AL, total P and DPS % (Table 1). The results showed a significantly ($p < 0.05$) higher concentration of P-AL (150 *vs.* 90 mg P kg^{-1} soil) and DPS % (7 *vs.* 5) in the paddock soil than the arable soil. However, there were no significant differences in the soil concentrations of WSP and total P, the main P constituents used for the assessment of P losses and soil P reserves respectively. Higher P contents in the topsoil were correlated to higher P losses (Sharpley *et al*., 1986; Börling *et al*., 2004). Also, soils with a high DPS % showed low affinity for P added (Ulén, 2006) and thus released more P to the soil solution, causing higher P losses (Sharpley, 1995; Beauchemin and Simard, 1999).

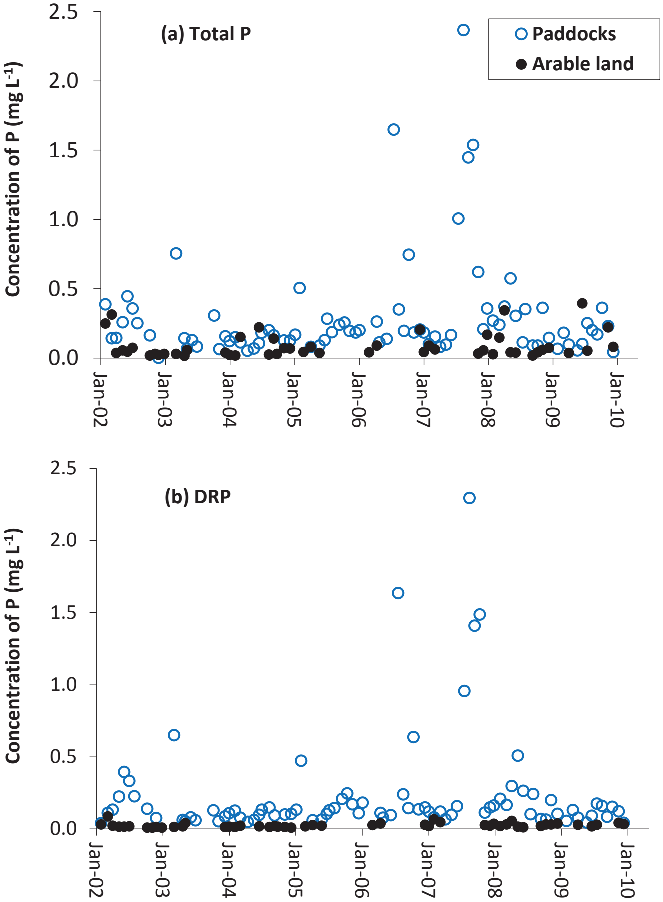

Figure 3. Concentrations of (a) total phosphorus (P) and (b) dissolved reactive P (DRP) in drainage water from two different types of land use systems.

Table 1. *Soil phosphorus (P) content in horse paddocks and an adjacent arable field (arithmetic mean ± standard deviations); DPS, degree of P saturation*

	Water soluble P	Plant available P	Total P	pH	DPS
Land use	(mg kg^{-1})				(%)
Paddocks (n = 15)	0.43 ± 0.4	14.9 ± 12.3*	117.3 ± 25.4	6.1 ± 0.3	7.4 ± 4.7*
Arable land (n = 5)	0.37 ± 0.3	8.7 ± 4.1	106.7 ± 9.2	6.3 ± 0.1	4.9 ± 1.6

* $p < 0.05$

In summary, results of the soil and drainage water analysis indicated a P build-up in paddocks and high P losses mainly as DRP from this system. This led to detailed investigations of P dynamics in paddocks, in which sampling strategies were revised due to observed distinct places (places with or without bowls/feeding boxes with fodder waste around them, places with dung piles, and snow-covered white zones), which were almost undetectable during summer with high grasses in the field (Fig. 4).

3.4.2 Survey of horse paddocks

In the survey study, the aim was to establish whether previous observations about different zones inside the paddocks were common phenomena in paddocks and whether P status in those areas differed. Further emphasis was given to revealing management aspects of paddocks such as horse density, type of fodder used for outdoor feeding, handling of excreted manure and fodder waste, *etc*.

Figure 4. Views of the horse paddocks investigated; manure excretion areas and feeding areas were more visible in winter, when paddocks were covered with snow, than in summer (photo: Pia Kynkäänniemi).

Seven horse farms were chosen that had been established for at least ten years in the Uppsala region. The farms represented different animal densities, soil textures (clay content from 1.8 to 45.6 %) and paddock age (Table 2). The survey was conducted in the spring, a few weeks after snowmelt, when excretion and feeding places were still visible within each paddock.

The size of the paddocks varied greatly among the farms, ranging from 1023 m^2 to 6781 m^2, and with horse density ranging from 14.5 to 5.3 (mean 8.6) LSU ha^{-1}. The duration of grazing and/or outdoor keeping of horses was dependent on the season: usually seven hours during October-April and around 18 hours in the period from May to September. Due to differing durations of the outdoor stay, horse density was recalculated to obtain a more correct assessment and to relate manure input to the actual time of the outdoor stay. The year-round density ranged from 7.4 to 2.6 (mean 4.1) LSU ha^{-1}. Concerning fodder, horses kept in paddocks were supplied with hay, oats and/or granules (blended commercially-available horse feed). Hay was put on the bare soil and residues remained on the soil. Oats and granules were placed in a feeding bowl. There was no dung removal on five of the seven farms, and only one farm cleaned the paddock every year and another farm every second year.

With regard to the characterisation of different zones inside the paddock, a similar pattern was found at the seven farms as follows: feeding area, grazing/outdoor exercise area and excretion area (Fig. 5). The feeding and excretion areas within the paddocks were relatively small, amounting to only 3-5 % of the total area, which were sampled and measured along with the remaining area used for grazing. Per horse, the feeding area ranged from 18 to 55 m^2 (mean 33 m^2), the excretion area from 24 to 72 m^2 (mean 51 m^2), and the grazing area from 509 to 1394 m^2 (mean 979 m^2).

Table 2. *General information and management aspects of the paddocks on the seven farms included in the survey study*

Farm (code), soil texture, and clay content (%)	Paddock age (years)	Horse density (livestock units ha^{-1})	Feed supply to the paddock	Dung removal from the paddock	Fresh manure load ($Mg\ ha^{-1}\ yr^{-1}$)	Load of total P ($kg\ ha^{-1}\ yr^{-1}$)
SJE, sand, 1.8	12	14.5	Hay & granules	Every 2nd year	77	108
UKB, loamy sand, 9.2	18	12.7	Hay & oats	None	61	85
ERS, sandy clay loam, 27.6	27	7.8	Hay & oats	None	38	52
FJD, clay loam, 36.8	20	7.7	Hay & oats	Every year	35	49
UKH, sandy loam, 17.9	18	5.9	Hay & oats	None	32	45
SVS, sandy loam, 19.7	47	5.3	Hay & granules	None	31	43
UPS, clay, 45.6	23	5.9	Hay	None	27	38
Mean	**23**	**8.6**	-	-	**43**	**60**

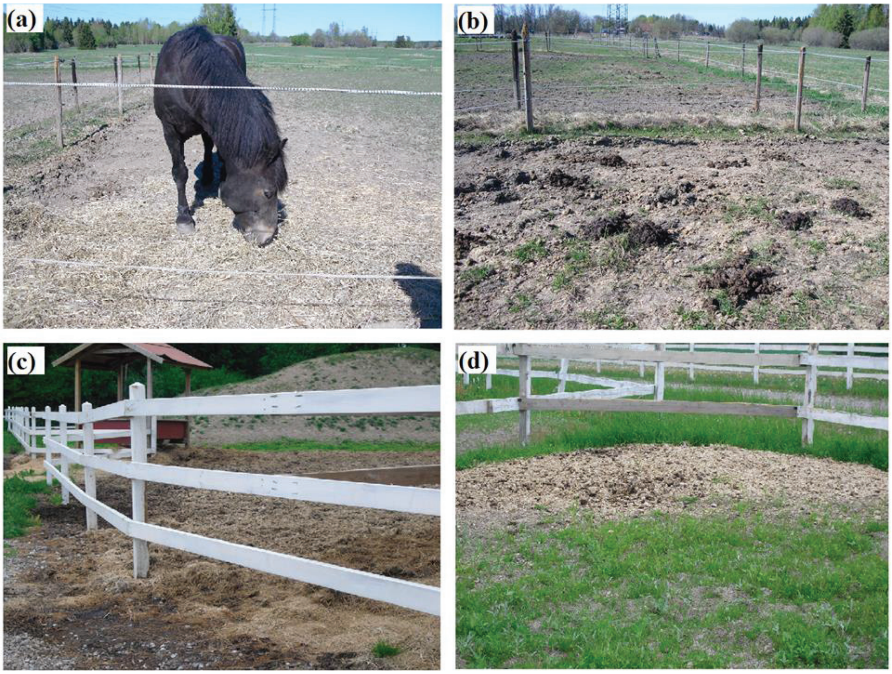

Figure 5. Examples of observed feeding (a, c) and excretion (b, d) areas within a paddock from two of the paddocks investigated.

To determine the nutrient status of the feeding, grazing and excretion areas, topsoil (0 - 20 cm) samples were collected and analysed for WSP, P-AL, total P, DPS % *etc.* Samples from undisturbed and non-grazed natural grassland adjacent to the paddocks were used as reference soil. Results from the soil analysis showed that mean concentrations of WSP, P-AL and total P in the paddocks were highest in excretion areas (11, 256 and 1034 mg P kg^{-1} soil respectively) followed by feeding areas (9, 222 and 973 mg P kg^{-1} soil respectively), and grazing areas (4, 106 and 774 mg P kg^{-1} soil respectively) (Table 3). The reference areas had the lowest concentrations (1.8, 39 and 642 mg P kg^{-1} soil respectively). Other soil properties, *i.e.* DPS %, organic C and total N, were also highest in the excretion and feeding area. The same trend was found on all seven farms investigated (see Paper II).

The high concentration of P in paddock soil can be explained by the high load, especially *via* excreta. Estimates based on year-round horse density showed that annual input of P in the paddock through fresh manure was equivalent to 38 - 108 kg of total P (mean 60 kg), of which 11 - 30 kg was expected to be as phosphate P (mean 17 kg) per hectare (Table 2).

Table 3. *Generalized soil data of the feeding, grazing, excretion, and reference areas of the seven farms studied (arithmetic mean ± SD); water soluble P (WSP), ammonium acetate lactate extractable P (P-AL), degree of P saturation (DPS), carbon (C) and nitrogen (N). Variances in soil parameters were determined separately. Means with different letters are significantly different ($p < 0.05$). Letters refer only to data within each column*

Land use	WSP	P-AL	Total-P	pH	DPS	Organic-C	Total-N
		(mg kg^{-1})				(%)	
Feeding (n= 28)	9.0 ± 6.9 a	222 ± 152 a	973 ± 397 ab	6.6 ± 0.3 a	44 ± 24 ab	3.3 ± 1.0 a	0.28 ± 0.09 ab
Grazing (n= 28)	4.0 ± 2.0 b	106 ± 67 b	774 ± 251 bc	6.4 ± 0.6 ab	28 ± 14 bc	2.5 ± 1.2 b	0.22 ± 0.11 b
Excretion (n= 26)	11.0 ± 9.8 a[‡]	256 ± 162 a	1034 ± 320 a	6.5 ± 0.2 a	66 ± 81 a	3.8 ± 1.2 a	0.30 ± 0.09 a
Reference (n= 28)	1.8 ± 1.4 b	39 ± 28 b	642 ± 94 c	6.1 ± 0.6 b	11 ± 9 c	2.5 ± 0.7 b	0.22 ± 0.07 b

[‡] Two samples had unusually high WSP concentrations and had a considerable influence on the overall results, and were excluded

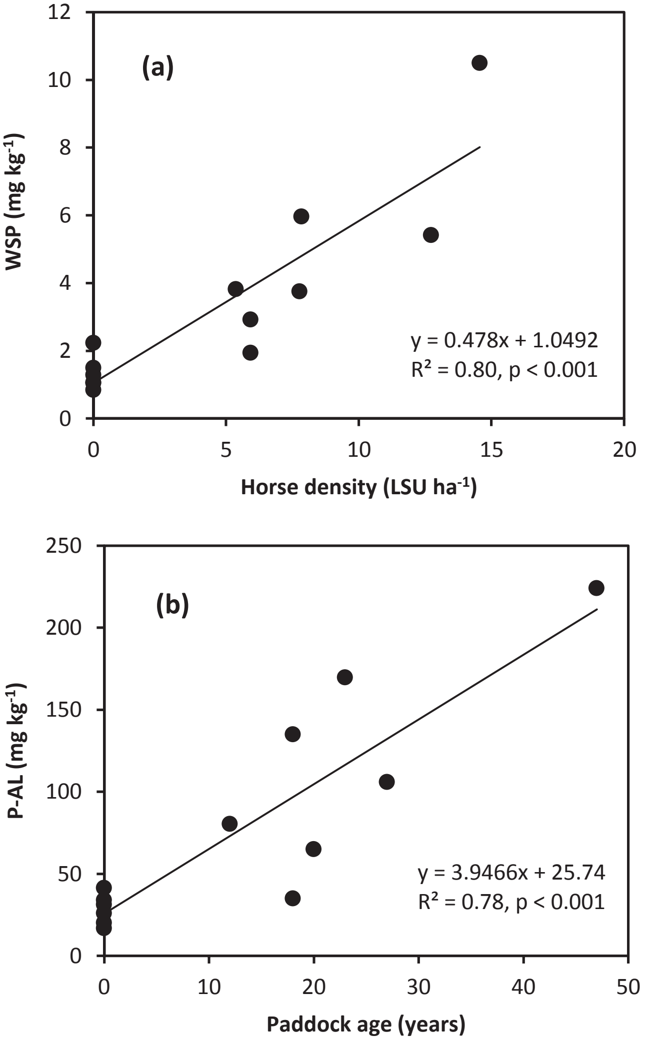

Figure 6. Concentrations of soil P fractions in relation to paddock management (horse density and paddock age): (a) water-soluble P (WSP) and (b) plant-available P (P-AL). Data from the reference areas were included and plotted as zero horse density and zero paddock age.

Accumulations of P in the different paddocks were influenced by horse density and paddock age and total P inputs to the paddock soils were estimated to be 805 - 2010 kg total P and 226 - 565 kg phosphate P per hectare over 12 - 47 years of paddock management. A strong correlation between WSP and horse density (R^2 = 0.80***[1], n = 13) and P-AL and paddock age (R^2 = 0.78***, n = 13) was found (Fig. 6), showing the importance of management on P build-up in paddock soils.

The results obtained can be compared to P management in agricultural soils, which is strictly regulated. Input of P through manure to Swedish arable soil is restricted to 22 kg P ha^{-1} yr^{-1} or 110 kg P ha^{-1} in a five-year cycle (Eskilsson, 2013). However, average P input to paddock soils was almost three times higher (60 kg P ha^{-1} yr^{-1}) than P addition with manure to agricultural soils, and horse density (8.7 LSUs ha^{-1}) was also far higher than the recommended value of 2.4 LSUs ha^{-1}. Therefore, it can be concluded that the high horse density was the primary reason for high concentrations of P in paddock soils. Deposition of manure and fodder P over many years explained the enrichment in the feeding and excretion areas. Previous studies have also reported nutrient enrichment in grazed paddocks as a result of high animal density. For example, Mathews *et al.* (1994) found high concentrations of soil N and P in feeding areas within two years due to feed entering the paddock. Singer *et al.* (2001) measured the soil P status in horse pastures with different animal densities and found correlations between horse density and concentrations of P in soil. Airaksinen *et al.* (2007) observed a significant increase in soil P concentration within a year at a density of 37.5 LSUs ha^{-1} and also found significantly higher runoff losses of P and N from the paddock after one year of horse grazing. Roquette *et al.* (1973) found that the concentration of plant-available P in grazed soil doubled within two years at a stocking density of 3.1 LSUs ha^{-1}. On the other hand, no or low external input resulted in a relatively nutrient poor system in reference areas.

High concentrations of P-AL in soil indicate the soil's capacity to supply P in the soil solution over longer periods and hence P losses from the soil systems. The Swedish EPA (2012) has proposed a scale for potential P losses based on soil P-AL data, where soils with P-AL concentrations below 80 mg P kg^{-1} are considered to have a low risk of extensive P leaching, soils with 80 - 160 mg P kg^{-1} a medium risk, and soils above 160 mg P kg^{-1} a high risk of extensive leaching. According to this scale, both feeding and excretion areas are high-risk areas for P leaching and grazing areas pose a moderate risk. Using the observed mean horse density (8.6 LSUs ha^{-1}), it can be estimated that around 34,000 ha of the total of 300,000 ha horse land in Sweden are used as horse paddocks. Of these 34,000 ha paddock areas, about 2,700 ha are feeding and excretion areas, which are high-risk areas for elevated P leaching, and 31,300 ha are grazed lands, which are moderate risk areas.

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[1] * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The survey clearly indicated that P concentrations in paddock soils were higher than in nearby unmanaged reference soils. High horse density and long-term use of land as paddocks were the most likely causes of nutrient build-up in these soils. Horse feeding and excretion areas inside the paddocks had the highest concentrations of P and were at high risk of significant P leaching losses based on the Swedish EPA's guidelines. However, to corroborate the high P leaching hypothesis, especially from the nutrient-rich feeding and excretion areas, further experiments were carried out using topsoil columns from those areas. Isolated soils columns were studied under laboratory conditions exposing them to simulated rainfall and measuring the P-leaching potential from different parts of the paddock (Paper III).

3.4.3 Leaching study

For the leaching study, two farms from the survey study were chosen that have contrasting soil textures (coded UPS: 46 % clay and 30 % sand; coded UKB: 9 % clay and 84 % sand, see Table 2) and representative animal density, paddock age and soil P contents. Undisturbed topsoil columns were collected at points close to the spots used for composite soil sampling for the survey study (Fig. 7). Four replicates of soil columns were collected from feeding, grazing and excretion areas of the paddocks and from the reference areas. Soil columns were exposed to four rain simulations (equivalent to 80 % of total soil volume), each with 40 mm rain during a three hour event. There was a 72-h interval between two simulations.

Figure 7. Sampling of the soil monolith (left) and the rain simulation chamber (right) used to investigate nutrient leaching from those soil columns (photo: Nargish Parvin).

Leachates were collected in glass jars. The volume of water leached per column was measured 48 h after each simulation and a set of subsamples was taken for chemical analysis and storage. Leachate samples were analysed for DRP, PP, DOP and TP.

Analysis of the leachate water from the clay topsoil showed that mean concentrations of TP, DRP and PP were significantly higher ($p < 0.05$) from the excretion area than from the grazing and reference areas (Fig. 8). Higher concentrations of all P forms were also found in the leachate from the feeding area, but the data were not significantly different from those of other areas. Net losses of P (expressed as mm of leachate) from the clay soil columns were in the ranges 1.3 – 8.6 g TP, 0.5 – 3.9 g DRP, 0.5 – 4.0 g PP and 0.1 – 0.7 g DOP ha^{-1} mm^{-1}. The highest P losses were measured from the excretion area, with DRP (46 %) and PP (47 %) being the main forms of P in the leachate. Total losses of P from the whole paddock area (weighted mean) were twice as high (2.7 g TP ha^{-1} mm^{-1}) as those from the reference area (1.3 TP g ha^{-1} mm^{-1}) and DRP was the dominant form (66 %).

Similar to the clay soil columns, concentrations of TP, DRP and TOP in the leachate from sandy soil were significantly higher ($p < 0.05$) from the excretion area than those from other areas. The concentration of TP in leachate from the excretion area was about four times greater than in leachate from the reference area, while DRP and TOP were about eight and twelve times greater respectively (Fig. 8). However, between the feeding, grazing and reference areas no significant difference was found concerning different P forms.

Net losses of P were greater than those from the clay soil and were in the ranges 4.0 – 26.7 g TP, 1.6 – 19.0 g DRP, 1.8 – 4.0 g PP and 0.4 – 4.7 g DOP ha^{-1} mm^{-1}. The highest losses were measured from the excretion area (26.7 g TP ha^{-1} mm^{-1}), of which 71 % occurred as DRP.

Unless nutrients are removed with harvested crops, high nutrient inputs to fields over long periods can exceed the soil's nutrient retention capacity and cause subsequent losses (Sharpley, 1995; Parvage *et al.*, 2011). The paddock soils studied received large amounts of nutrients over many years, mainly on excretion and feeding areas, which resulted in a higher nutrient build-up and higher losses from these two areas than from the reference soils.

When losses were recalculated using the mean leachate volume from Swedish arable fields of 300 mm, total P losses from paddocks would, on average, amount to 1.1 kg TP ha^{-1} yr^{-1} (mean data for the clay and sand paddock). The largest impact comes from the excretion area in the sand paddock (7.4 kg TP ha^{-1} yr^{-1}). For comparison, losses from Swedish agricultural top soils range from 0.2 to 0.9 kg TP ha^{-1} yr^{-1} found in similar leaching studies (Liu *et al*., 2012a, 2012b; Ulén *et al*., 2013) but also in long-term monitoring studies of drained plots representing agricultural lands with both clay soils and sandy soils (0.2 to 0.5 kg TP ha^{-1} yr^{-1}) (Aronsson and Stenberg, 2010; Aronsson *et al*., 2011; Neumann *et al*., 2011; Torstensson *et al*., 2006).

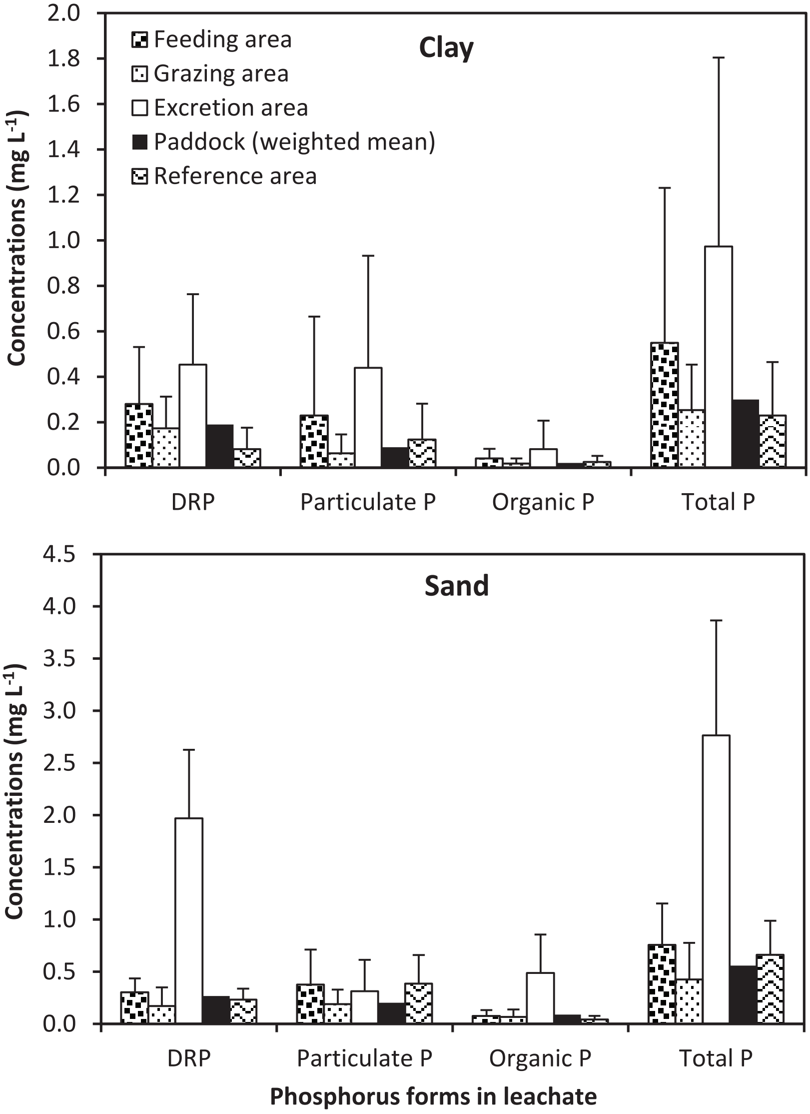

Figure 8. Phosphorus (P) concentrations in leachate from the clay and sand paddock in the form of dissolved reactive P (DRP), particulate P, organic P, and total P. Error bars denote standard deviation. Variations in concentrations of a particular form of P between different types of land use were determined separately. Means with different letters are significantly ($p < 0.05$) different.

Lower leaching losses are expected from arable than paddock soils because, as mentioned in the survey study, the P input to Swedish agricultural fields through manures is limited (22 kg P ha^{-1} y^{-1}) (Eskilsson, 2013) and so far no limit has been set for paddock soils. The paddock soils received about 60 kg P and 252 kg N ha^{-1} y^{-1} through manure excretion (Parvage *et al.*, 2013). Moreover, parts of added P and N to agricultural soils are removed through harvested crops, whereas grasses grazed in paddocks plus portions of the fodder given to animals are returned to the paddock through dung and urine. Thus, a continuous influx of nutrients to paddocks can potentially lead to a large P pool in soil. As soils with high P contents may also release more P to drainage water (Beauchemin and Simard, 1999; Ulén, 2006), as was confirmed in this study, there is a considerable environmental risk associated with horse paddocks.

4 Mitigation measures against phosphorus losses from paddocks (Paper IV)

4.1 Background

Previous studies have shown that P losses from paddock soils can be substantial and can pose a threat to water bodies (Paper I, II and III or Parvage *et al.,* 2011, 2013, 2015). The critical question is how to reduce leaching losses from horse paddocks. Efficient countermeasures that can reduce leaching by 50 % would reduce loads by about 20 tonnes P from the estimated 34,000 ha paddock soils per year. This is equivalent to about 4 % of the annual Swedish P load reduction target to the Baltic Sea by 2021 (HELCOM, 2013c).

Within the paddocks, feeding and excretion areas were found to be highly enriched with nutrients releasing significant amounts of P and other nutrients in leachate (Papers II & III). The challenge is how to avoid a nutrient build-up in paddock soils and how to reduce leaching losses from enriched paddocks. Provision of a feed trough and use of a plastic sheet on the ground in the feeding area may reduce fodder waste deposition. Accumulation of dung and urine on soil surfaces can be lowered by reducing animal density. Regular removal of manure from the paddock area is an efficient measure to reduce both surface and leaching losses of nutrients, as shown from cattle farms keeping animals under outdoor conditions (Salomon *et al*., 2008). However, regular removal of dung from paddock areas is a laborious measure and therefore only a few horse farms scrape away the dung, mainly to avoid re-contamination of horses with parasites. Another option for reducing nutrient translocation from dung and urine into the soil is to minimise the water influx into the soil. Available organic residues, *e.g.* wheat straw, wood shavings/wood chips and peat are often used as bedding material inside the stable to absorb urine and to reduce ammonia volatilisation (Andersson, 1996; Airaksinen *et* *al*., 2001; Misselbrook and Powell, 2005). Such organic bedding materials might also be useful for application outside in paddocks on dropping areas to reduce nutrient leaching thanks to their high water-holding capacity. In addition to water flows being reduced, these materials may also adsorb nutrients and immobilise nutrients during decomposition.

4.2 Aims

In this part of the thesis, the feasibility of outdoor use of bedding materials to reduce P build-up and losses was examined. The main aims were: (viii) to study the potential water retention and P-binding capacity of wheat straw, wood chips and peat, and (ix) to examine their potential use in excretion areas of paddocks to reduce P leaching losses.

4.3 Potential use of bedding materials in paddocks

To examine the feasibility of bedding materials to reduce water and P-leaching losses during outdoor use, three commonly used materials – peat (sphagnum peat from forest catchment), wood chips (from pine trees) and wheat straw - were tested. The experiment involved adding a layer of bedding materials to soil columns, putting fresh dung on the top of the bedding materials, applying artificial rain and measuring the leachate volume and P concentration in the leachates.

A total of 15 topsoil monoliths used for this study were collected from the grazing area of a sandy horse paddock. The fresh dung used for this experiment had a total P of 1218 mg P kg^{-1} DM, of which 86 % was soluble P and 57 % was DRP. Bedding materials were characterised for bulk density, dry matter content, water-holding capacity (WHC), content of WSP, and their capacity to bind inorganic P. Results showed that dry bulk density was highest for wood chips (82 kg m^{-3}), and wet bulk density and WHC were highest for peat (643 kg m^{-3} and 8.8 - 10.7 litre kg^{-1} DM respectively). The content of WSP was highest in wheat straw, 6.2 mg kg^{-1} DM. The maximum P-retention capacity of ground (< 2 mm) peat, wood chips and wheat straw was almost similar, at about 5 mg P g^{-1} DM. The background release of P from these materials was significant, 1.3 mg, 1.5 mg, and 10.6 mg g^{-1} DM respectively. The data indicate that peat and wood chips can only retain a small amount of P added and wheat straw may act as a net source instead, which did not meet the study objective.

The treatments included five groups (each with three replicates): (i) soil only (control), (ii) soil with fresh dung (750 g) on top (SD), (iii) soil with a 5 cm layer of peat and fresh dung on top (SPD), (iv) soil with a 5 cm layer of wood chips and fresh dung on top (SWCD), and (v) soil with a 5 cm layer of wheat straw and fresh dung on top (SWSD). Soil columns were exposed to six consecutive rain simulations at 24 h intervals, each with 20 mm rain (worst case in Sweden) and an intensity of 2 mm h^{-1} (Swedish average). The first rain simulation was performed without any material on top of the soils. The water volume leached per column was measured 24 h after each rain simulation. Leachates after each rainfall simulation were sampled for chemical analysis of TP, DRP, PP, DOP and TOC.

Results showed that bedding materials decreased leaching losses of water by almost half when applying consecutive rainfalls of about 20 mm per day. However, applying more rain than 20 mm within 48 h resulted in fewer differences compared to the control, as the retention capacity of the bedding materials had been reached (Fig. 9).

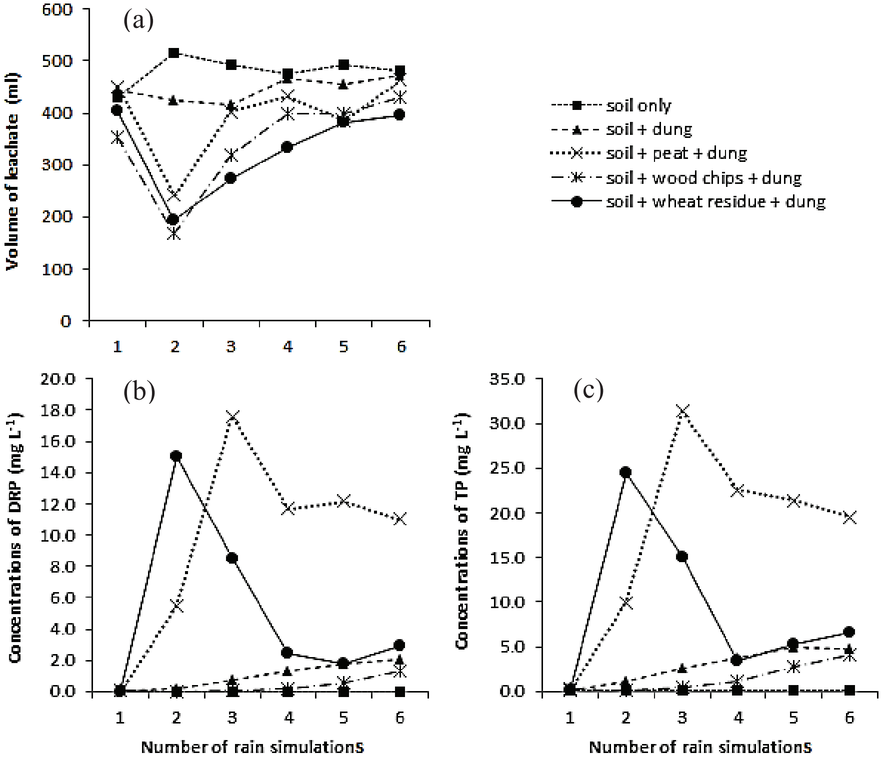

Figure 9. Water retention of three bedding materials applied as a layer on top of soils where after manure was applied (a) and leaching of phosphorus (P) as dissolved reactive P (DRP) (b) and total P (TP) (c) as affected by the treatments and numbers of rainfall simulations.

The addition of dung on soil increased P concentrations and total leaching loads upon the second simulation, while the addition of a layer of wood chips in-between dung and soil decreased leachate P concentration by almost half and total P load by two-thirds. Surprisingly, other bedding materials did not decrease, but rather increased P concentrations in the leachate considerably. Adding a layer of peat or wheat residue in between the soil and dung (SPD and SWSD treatments) increased total P loads from 0.11 kg P ha^{-1} to 15.2 and 12.5 kg P ha^{-1}, respectively (Table 4).

The decrease in P leachate by wood chips can partly be explained by their potential capacity to bind P. However, the mechanisms for high P loads from straw and peat-treated soils could not be elaborated. Wheat straw had a concentration of 6.17 mg WSP kg^{-1} DM and a dry bulk density of 41 kg m^{-3}. The addition of a 5 cm layer of straw over a hectare of land corresponded to an addition of 126 g WSP ha^{-1}, which is about 60 times lower than the measured P losses (7.68 kg DRP ha^{-1}). In addition, peat contained negligible amounts of WSP (below the detection limit).

These results indicated that wood chips could be a useful material for reducing P leaching from dropping areas in outdoor paddocks. Even though peat may have a high WHC and a proven capacity to reduce N losses in other studies (Andersson, 1996; Misselbrook and Powell, 2005), peat was found not to be a feasible material for reducing P leaching in outdoor paddocks. In contrast, wood chips with a lower water-holding capacity were an effective material and reduced P leakage by almost two-thirds.

Table 4. *Treatment effects on drainage volume and phosphorus (P) loads to drainage water; data in the parentheses show percentage of nutrient retained from the dung (positive values) or contributed by the bedding material (negative value) to the total losses; SD, soil and dung; SPD, soil-peat-dung; SWCD, soil-wood chips-dung; SWSD, soil-wheat straw-dung; DRP, dissolved reactive P; DOP, dissolved organic P*

	Treatments				
Forms of phosphorus	Control	SD	SPD	SWCD	SWSD
Total leachate (mm)	104	96	85	75	71
DRP (kg ha^{-1})	0.03	2.17	8.28 (-287)	0.40 (81)	7.68 (-259)
Particulate-P (kg ha^{-1})	0.05	1.54	2.42 (-62)	0.47 (69)	2.43 (-63)
DOP (kg ha^{-1})	0.02	1.25	4.45 (-263)	0.62 (49)	2.42 (-97)
Total-P (kg ha^{-1})	0.11	4.96	15.2 (-212)	1.49 (69)	12.5 (-158)

5 Composted horse manures as environmentally friendly phosphorus (P) fertilisers (Paper V)

5.1 Background

A central aspect of horse keeping is to take care of manure in a way that allows nutrients to be recycled to arable land. Due to a rapid increase in the number of horses in Sweden, manure production from horse stables reaches about 2 million tonnes (or Mg) wet weight yr^{-1} excluding bedding materials. This quantity of horse manure is a large resource and should be utilised primarily as a fertiliser and soil conditioner on agricultural soils. The total number of horses is more than dairy cows and about one quarter of the total number of cattle in Sweden (Swedish Board of Agriculture, 2014), which further demonstrates the extent and importance of proper manure handling from horse farms.

Field application of manure has been practised since the prehistoric era (Olson, 1987). Apart from improving soil fertility, regular manure loading to soils can also cause significant losses of nutrients, including P, to water and impair water quality (Hooda *et al*., 2000; Torstensson *et al*., 2006; Brock *et al*., 2007; Parvage *et al*., 2011, 2015). In Sweden, both mineral and organic soils receive animal manure on a regular basis, and the closest distance between the farmhouse/manure storage and arable field is often considered for ease of handling and distribution. The fertility status in organic soils is often high and its extent is considerable, at about 7.2 % of total Swedish agricultural land (Berglund and Berglund, 2010). Therefore, in order to improve the soil fertility status and minimise leaching losses (surface runoff rarely occurs in Sweden), the amount of horse manure applied to soil needs to be adjusted to the soil types and particular consideration should be given to organic soils.

5.2 Aims

This study dealt with the proper use of horse manure and bedding materials in agricultural fields (Paper V). The specific objective was: (x) to test the effect of application rate of composted horse manure in different types of soil and investigate P retention and loss through leaching.

5.3 Use of horse manure compost

Use of horse manure on agricultural fields should be as environmentally friendly as possible. In this study, P retention and the leaching potential of composted horse manure was investigated through the application of two loads (18 Mg ha^{-1} and 36 Mg ha^{-1}) on three dominant agricultural soil types: a loamy sand (Nåntuna), a loam (Wiad) and an organic soil (Hidinge peat). Twelve undisturbed topsoil columns (0 - 20 cm) from each soil were amended with horse manure compost, and P retention in soil and leaching of P were measured. Composted horse manure was collected from a commercial producer, being a mixture of horse dung including minor portions of fodder waste (mainly hay) and bedding materials (mainly wood chips). The material was composted for ten days in a metallic chamber with a continuous airflow. Thereafter, the premature compost was stockpiled outdoors on a concrete floor for about three to four months, from which the material was collected for this study. The compost had a pH of 7.9; C/N ratio of 51, total P of 1.76 g P kg^{-1} DM, of which 39 % was water soluble and 26 % phosphate P. Compost loads (18 and 36 Mg ha^{-1}) applied to the soils were according to Swedish rules of manure P application, half (11 kg P ha^{-1} yr^{-1}) and maximum amount (22 kg P ha^{-1} yr^{-1}) (see Paper II or Eskilsson, 2013).

The top 5 cm soil layer of each column was prepared with a hand shovel and composted horse manure were incorporated with great care and left for two days to reach equilibrium before commencing the leaching study. Non-amended soils were used as controls. Each treatment had four replications. Soil columns were exposed to simulated rainfall with an intensity of 8 mm h^{-1}. In total, three pore volumes were leached on three leaching events at intervals of 24 h between events. Although total porosity of sand, clay and organic soil differs, for simplicity the solid-to-void ratio was assumed to be equal. A 100 mm rain application was regarded as one pore volume for all 20 cm soil columns.

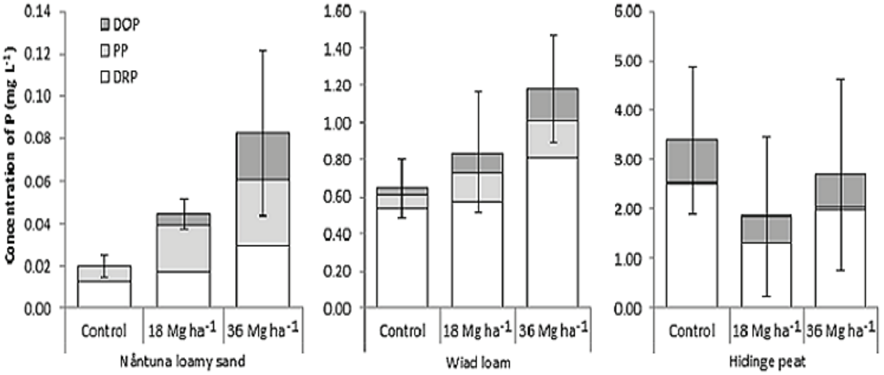

Figure 10. Mean concentrations of phosphorus (P) in leachates from columns of three agricultural topsoils (0 – 20 cm) amended with composted horse manure; DRP, dissolved reactive P; PP, particulate P; DOP, dissolved organic P. Error bars denote standard deviations of the means.

Leachate volume per column was measured 24 h after each simulation and a set of subsamples (500 ml for each) was stored at 4 ^{o}C. Nutrient release for each column was obtained by measuring nutrient concentrations in a flow-normalised composite sample of three leaching events. A total of 12 composite samples for each soil type were analysed for DRP, TP, PP and DOP. Results showed that background concentrations of DRP in the leachate from the loamy sand were very low (mean 0.01 mg P L^{-1}) as compared to the loam (0.54 mg P L^{-1}) and the organic soil (2.52 mg P L^{-1}). The organic soil also had the highest concentrations of PP, DOP and TP, followed by loam and the loamy sand.

Compost addition of 18 Mg ha^{-1} did not cause any significant change in leachate concentrations of P in the Nåntuna loamy sand. However, increasing the load to 36 Mg compost ha^{-1} resulted in a significant increase of TP ($p = 0.009$), from 0.02 mg P L^{-1} in the control to 0.08 mg P L^{-1} (Fig. 10). None of the compost loads had a significant effect on P concentrations in the Wiad loam. Surprisingly, the Hidinge peat treated with compost had lower P concentrations in the leachate than the control.

Estimates of total P losses based on leachate data (see Table 4) showed that compost-amended Nåntuna loamy sand (22 kg P, 36 Mg compost ha^{-1}) lost 0.25 kg TP ha^{-1}, which is 4.3 times higher than the control. This increment was equivalent to 0.9 % of the total amount of P added through composted horse manure. On the other hand, background losses of P from Wiad loam (1.6 kg TP ha^{-1}) and Hidinge peat (8.0 kg TP ha^{-1}) were much higher than the maximum amount leached from Nåntuna loamy sand with the highest load of compost. Wiad loam lost 9.2 % of the P added at a rate of 36 Mg compost ha^{-1}, while

Hidinge peat retained the P added with both compost loads. In addition, compost amendments to Hidinge peat reduced P leaching losses by up to 45 % compared to the amount lost from the control lysimeters (Table 5).

Table 5. *Leachate volume (mean ± standard deviation) and total phosphorus (P) losses in drainage after 300 mm of rain from three agricultural top soil columns (0 – 20 cm) amended with composted horse manure. Figures in parentheses show the percentage change compared to the control. A negative value indicates retention*

	Nåntuna loamy sand			Wiad loam			Hidinge peat		
Analysis	Control	18 Mg ha^{-1}	36 Mg ha^{-1}	Control	18 Mg ha^{-1}	36 Mg ha^{-1}	Control	18 Mg ha^{-1}	36 Mg ha^{-1}
Leachate (mm)	286 ± 28	264 ± 13	311 ± 34	257 ± 54	279 ± 43	307 ± 24	241 ± 10	307 ± 78	280 ± 69
Total P (kg ha^{-1})	0.05	0.12 (151)	0.25 (438)	1.59	2.25 (41)	3.58 (125)	8.03	4.45 (-45)	6.72 (-16)

The results showed that the nutrient retention and leaching potential of soils differed greatly. Due to a higher background nutrient content, the organic soil leached more P than the two mineral soils. Although the addition of compost at a high rate increased nutrient leaching significantly in the mineral soils, the retention of nutrients was far greater than the losses. The apparent retention of added-P *via* compost in organic soil was 100 %, which might be due to adsorption on soil P binding sites, precipitation with available cations (e.g. Fe, Al and Ca) (Bloom, 1981; Borggaard et al., 1990; Lookman et al., 1996; Börling et al., 2001), and a rapid increase in microbial growth, requires further investigation. The study indicates that the soil's background information is of crucial importance when assessing nutrient retention or leaching risks through manure.

6 Conclusions

The studies described above clearly show that paddock soils had higher P contents and a higher P leaching potential than agricultural soils. Within paddocks, feeding and excretion areas may act as hotspots for P losses. Thus, horse paddocks can be a potential source of water pollution. Proper management of fodder waste and excreted manure within paddocks can reduce P build-up in soil and thereby minimise losses. Use of wood chips in excretion or feeding areas may be an effective method for reducing P leakage. Use of composted horse manure on agricultural fields at recommended rates increased P-leaching losses from mineral soils, but may still be an important step in reducing P leakage from horse keeping. Also, whether organic soils can be amended with horse manure compost without any surplus P into drainage requires further investigation.

7 Messages for society

It is expected that proper handling of manure and mitigation measures will decrease the P load from horse-keeping systems to water bodies. Besides mitigation measures, horse paddocks need to be included in Swedish mitigation plans to reduce nutrient losses. The data measured indicate that a better protection of water bodies and a significant reduction of P to the Baltic Sea by 2021 would be possible if horse paddocks were included as a potential P source and if regulations concerning paddock management could be deployed. Introducing legislation for the management of paddocks will help making paddocks more environmentally friendly and is a measure to avoid nutrient enrichment of water bodies. Regulations on animal density and farm establishment are part of the Helsinki Convention (HELCOM, 2014) and the Swedish Board of Agriculture (2014). According to these regulations, animal density is controlled to keep manure production in balance with the arable land available for spreading and crop requirements for P and N. The legislation is applied for all types of farm animals, *e.g.* cattle, dairy cow, sheep, pig and poultry except horses. New rules/regulations to control animal density on horse farms as well may be a useful step towards minimising leaching losses. In summary, legislation concerning animal density, improved paddock management and manure handling is required. The following paddock management aspects should be considered for legislation:

(i) reducing animal density to the recommended density of 2.4 LSU or 3 horses ha^{-1}
(ii) removing manure from paddocks on a regular basis, perhaps weekly or monthly and recycling the manure in available arable fields
(iii) covering the soil within paddock feeding areas or providing a feed trough to avoid fodder losses to soil

(iv) restricting drainage constructions near and/or inside paddocks

(v) establishing paddocks at a safe distance from drainage ditches and water bodies, and

(vi) converting paddock areas to other land uses after 10 - 20 years.

Some of these regulations have already been introduced in Finland in 2003 (Uusi-Kämppä *et al.*, 2012) but other countries adjacent to the Baltic Sea, including Sweden, should follow to reach a common goal of reducing nutrient load to the Baltic Sea.

8 Limitations and future concerns

Even though the data about P-leaching potential from horse paddocks leave little doubt, the inclusion of more sites across the country, including field observations, would strengthen these conclusions. In addition, the study sites chosen were relatively large and belonged to commercial farms, while many horse owners in the country may have fewer horses per paddock and may take better care of the fodder waste and manure.

Regarding outdoor use of bedding materials, the study described was conducted in a controlled environment receiving more rainfall at a time than average and the testing duration was relatively short, only two weeks. Water and P retention in the bedding materials may deviate in real conditions of fluctuating moisture and temperature, trampling by horses, and longer time of exposure. In the final study of P retention and leaching potential from agricultural soils receiving composted horse manure, the study was also in a controlled environment and for a shorter period, which may have allowed only the chemical and/or physicochemical processes (*i.e.* adsorption-desorption and precipitation-dissolution) of P movement in the soil. However, complex physicochemical and biological processes occur simultaneously under field conditions. The effect of environmental factors on microbial diversity and activity also play a crucial role, which is ignored in laboratory conditions. Moreover, except for the pilot study, leachates were collected from topsoil columns. Unless the subsoils are well structured or have continuous pores and water movements are dominated by macropore flows, the final P load to drainage water depends on the subsoil's P-retention capacity (Djodjic *et al*., 2004; Andersson *et al*., 2013). Subsoil can act either as a source or a sink. Therefore, the results from these studies can only be seen as strong indications. Complementary field studies (together with questions to understand the processes) in future may improve current understanding and contribute significantly to resolving P leakage and eutrophication problems in the Baltic Sea or in other water bodies.

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