Phosphorus and faecal bacteria in runoff from horse paddocks and their mitigation by the addition of P-sorbing materials

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The growing popularity of horse keeping is accompanied by an increase of phosphorus (P) and faecal micro-organisms from outdoor paddocks. We used an indoor rainfall simulation to monitor concentrations of dissolved reactive P (DRP) and faecal coliforms in runoff and percolation water from different paddock footings. Drainage water was also monitored from two paddocks constructed of woodchips. Sand retained more DRP (p<0.0001) and coliforms from percolation water than woodchips. Some of the footings were amended with P-sorbing materials, such as [$Ca(OH)_2$], [$Fe_2(SO_4)_3$], or Fe-gypsum, to retain DRP. High DRP concentrations (17–18 mg l^{-1}) were observed in runoff from a woodchip footing amended earlier with $Ca(OH)_2$ and in sand footing amended with $CaCO_3$. However, application of Fe-gypsum to woodchips decreased the DRP load in percolation water by 83% compared to the footing without Fe-gypsum. Fe compounds were better than Ca compounds. The decrease in coliforms was usually small due to the modest pH changes in the water.

Key words: equine area, faecal indicator bacteria, footing materials, runoff, water quality

Introduction

Despite the growth of the horse industry, with new stables being established even near population centres, few studies have focused on the effects of horse paddocks on water quality (Airaksinen et al. 2007, Sullivan 2010). Among the total 75500 horses in Finland, roughly 13000 are kept around the cities of Helsinki (Uusimaa) and Turku (Southwest Finland) (Suomen Hippos Oy et al. 2012). Sand, topsoil (often clay), or woodchips are commonly used as footing materials, with the percolation capacity of water being generally highest for woodchips and lowest for clay. The paddock conditions also affect horse welfare. Poorly managed paddocks or mud and manure can soften the hoof, facilitating microbe invasion (Stephenson et al. 2003).

In Finland and Sweden, horses are usually kept in small, fenced-off areas near the stables (Pikkarainen 2005, Parvage et al. 2011). According to Pikkarainen (2005), two horses are kept together for an average of 7 hours daily in a paddock with an average size of 1100 m^2 (year around horse density of 5.3 ha^{-1}). Finland is estimated to have up to 35000 paddocks with a total area of 3800 ha. One horse produces 10 kg of phosphorus (P) and 61 kg of nitrogen (N) annually in dung and urine (Jouni Nousiainen, personal communication, MTT Jokioinen, 19 April 2011). If the horse density is 5.3 ha^{-1}, the annual input of P and N may be more than 50 and 300 kg ha^{-1}, respectively, to the paddock area with little or no vegetation. In comparison, the maximum annual amounts of fertilizer P and N allowed in Finland for grassed fields are 70 and 250 kg ha^{-1}, respectively.

In Finland and Sweden, high concentrations of dissolved reactive P (DRP, 1.0 to 15 mg l^{-1}) and total P (TP, 1.5 to 18.8 mg l^{-1}) have been measured in the drainage and surface runoff from horse paddocks (Airaksinen et al. 2007, Närvänen et al. 2008, Parvage et al. 2011). Moderate and high concentrations (5.5 to 70.8 mg l^{-1}) of acid ammonium acetate extractable P (P_{Ac}) have also been observed in the soil floors of paddocks (Airaksinen et al. 2007, Närvänen et al. 2008). In many studies, the DRP concentrations in surface runoff have increased linearly with the soil test values for P in the surface soil layer (Sharpley et al. 1977, Jansson et al. 2000, Närvänen et al. 2008). Thus, horse paddocks probably cause local nutrient and microbe loss to watercourses, resulting in water eutrophication, algae blooming (Correll 1998), and hygiene problems (Sinton et al. 1998).

In earlier studies, artificial wetlands and the addition of P-sorbing materials to runoff water were tested as methods for purifying paddock runoff (Närvänen et al. 2008, Kynkääniemi et al. 2010). In a study by Närvänen et al. (2008), the DRP and TP in the runoff was reduced 95% and 81%, respectively, after the addition of 160 kg ferric sulphate per year into the runoff water from a 0.5 ha paddock with seven young stallions. We studied the addition of Ca or Fe-containing amendments, such as $Fe_2(SO_4)_3$, $Ca(OH)_2$, or Fe-gypsum, to the surface layer of paddock footings

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because several studies had shown the potential of P-sorbing materials to reduce the solubility of P in soils (Agyin-Birikorang et al. 2007) and DRP losses in field runoff (Penn and Bryant 2006). Different kinds of materials have been studied for their P retention properties (O'Connor et al. 2005), but those containing Ca, Al, or Fe in soluble or solid oxide forms have been the most promising.

The purpose of this paper is 1) to discuss P losses and the numbers of coliform bacteria in runoff from horse paddocks, 2) to demonstrate how different paddock footing materials (sand, clay soil, woodchips, and crushed stone) affect P concentrations in paddock runoff, and 3) to estimate the potential of different amounts of P-sorbing materials in footings to reduce the transport of DRP, TP, and faecal coliforms in runoff and percolation water. Whether sand, due to its smaller pore size, is better at removing DRP and coliforms compared to woodchips was evaluated, as well as whether runoff and percolation waters are acid or alkaline enough to remove coliforms after the addition of $Fe_2(SO_4)_3$ or $Ca(OH)_2$.

Material and methods

Field monitoring of the mitigation of P in drainage water was performed by adding P-sorbing compounds containing Fe or Ca to the woodchips used as a footing material in horse paddocks. Grab samples of drainage flow were collected from the paddocks for laboratory analyses (Fig. 1). A rainfall simulation technique (Uusitalo and Aura 2005) was utilized to investigate P loss and the hygienic quality of runoff and percolation water from different footing materials in rainfall study 1 and 2, respectively (Fig. 1). Samples from paddock footings or footings constructed with sand or woodchips were amended with materials containing Fe or Ca. The samples were placed under a rainfall simulator, and the runoff or percolation water was collected for laboratory analysis. Coliform bacteria (faecal coliforms, *Escherichia coli*), faecal streptococcus, and sulfite-reducing clostridia were used as indicators of water quality to determine the presence of pathogens.

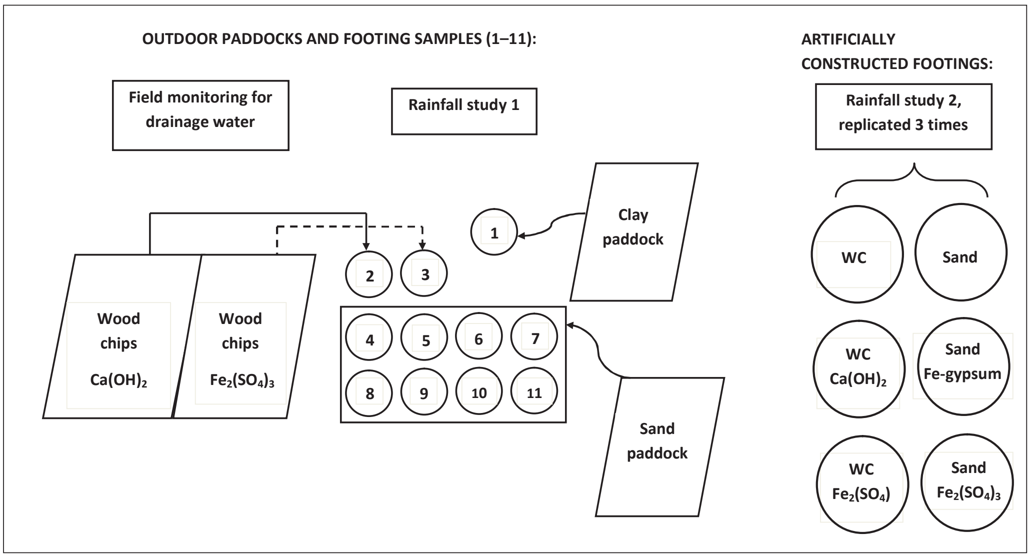


Fig.1. Paddock footings in the three experiments.

Field monitoring of drainage water

The addition of P-sorbing materials to reduce nutrient concentrations in the drainage water from two paddocks (17 Icelandic horses ha^{-1}) was studied in south-western Finland in 2005–2008 (Table 1). Slaked lime [$Ca(OH)_2$, 0.84 tn ha^{-1}] or granulated ferric sulphate [$Fe_2(SO_4)_3$, trade name Ferrix-3, 0.84 tn ha^{-1}] was added to the surface layer of two paddocks (1900 m^2 each) covered with a 20-cm layer of woodchips only, or with a 15-cm layer of sand and a 10-cm layer of woodchips (Fig. 2). Slaked lime was added to the middle layer of woodchips, whereas ferric sulphate was added to the surface of the woodchip layer. The paddocks were established on clay soil. A total of 12 grab samples were taken from the drainage flow two to four times per year for water analysis. Sampling was performed on a day with high rainfall (>10 mm) or one of the subsequent days.

Table 1. Characteristics of footing materials and amendments, their application rates, and the amounts of Ca and Fe added.

Footing material/ Amendment	Application rate	Ca applied	Fe applied
		tn ha^{-1}	
Field monitoring (drainage water)			
$Ca(OH)_2$ (slaked lime)	0.84	0.45	0
$Fe_2(SO_4)_3$ (Ferix-3), Kemira Oyj	0.84	0	0.16
Rainfall study 1 (surface runoff)			
$Ca(OH)_2$	2.7	1.5	0
	5.4	2.9	0
	10.7	5.8	0
$Fe_2(SO_4)_3$ (PIX-115) + $CaCO_3$	2.0+6.7	2.3	0.24
	4.1+8.9	3.6	0.48
	6.2+13.3	5.3	0.71
$CaCO_3$	4.4	1.8	0
Rainfall study 2 (percolation water)			
Aspen woodchips (moisture 26%)	830	n.a.	n.a.
Sand[(1)] (moisture 4%)	2100	n.a.	n.a.
Quartz sand (0.5–1.6 mm)	830	n.a.	n.a.
$Ca(OH)_2$	5.6	3.0	0
Fe-gypsum[(2)] (Fe_2O_3 ~ 14%, $CaSO_4x2H_2O$ ~ 70%, $CaCO_3$ ~ 10%, TiO_2 ~ 5%; moisture 15%)	5.6	0.82	0.66
$Fe_2(SO_4)_3$ (Ferix-3)	1.1	0	0.22

[(1)] Particle size distribution: 4.2% (6–8 mm), 4.3 (4–6 mm), 7.9% (2–4 mm), 15.9% (1–2 mm) and 67.7% (<1 mm)
[(2)] Pori plant of Sachtleben Pigments Oy
n.a. not available

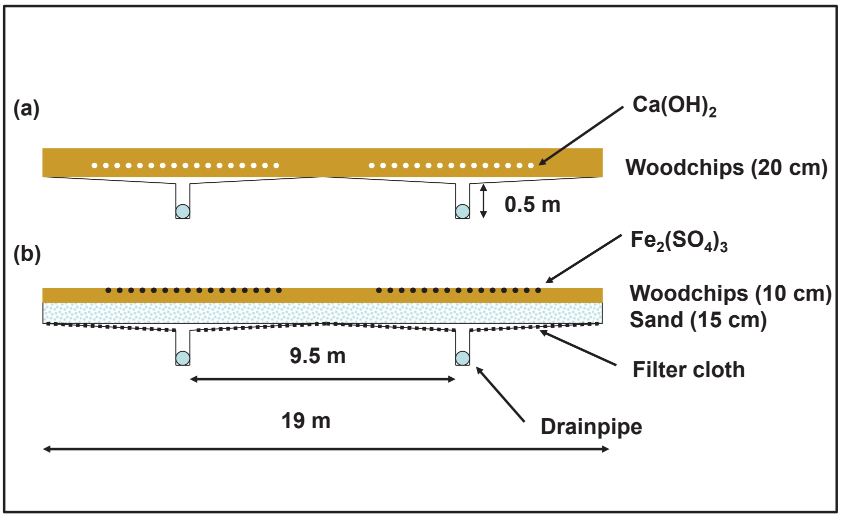


Fig. 2. Cross-sections of two paddocks constructed using woodchips and amended with (a) $Ca(OH)_2$ (slaked lime) or (b) $Fe_2(SO_4)_3$ (Ferix-3) during the field monitoring study.

Rainfall study 1 and surface runoff

In the first rainfall simulation (surface runoff study), samples of footing materials (sand, clay soil, and woodchips) were carefully taken by spade from four outdoor paddocks and put into metal bowls (diameter 24 cm, height 6 cm) in August 2006 (Fig. 1). Two of the paddocks were constructed out of woodchips and amended with slaked lime [Ca(OH)2] or ferric sulphate [Fe(SO4)3] as described above (Fig. 2). The bowls with samples were stored in plastic bags for a couple of days. Before the rainfall simulation, 2.7, 5.4, or 10.7 tn ha-1 of Ca(OH)2 was added to the surface of sand samples to test the potential to decrease P runoff, with one replicate serving as an untreated control (Table 1). Three other sand samples were treated with 2.0, 4.1, or 6.2 tn ha-1 of liquid ferric sulphate (Fe2(SO4)3 trade name PIX-115) while saturating the samples with water. Chalk powder (CaCO3) was added (6.7, 8.9, or 13.3 tn ha-1) to the PIX-115-treated sand 30 min after starting the rainfall simulation. The results from the addition of Fe2(SO4)3 and CaCO3 are from the water samples taken after the addition of CaCO3. Nothing was added to the clay footing samples. The paddock management is presented in Table 2.

Before the rainfall simulation, the footing samples were fully saturated with 700 to 1400 ml of deionised water and set at a 4% incline under a stationary drip-type rainfall simulator. The samples were kept in rain (deionised water; 21 mm h^{-1}) for 90 min and three bottles (500 ml each) of surface runoff water collected for analysis. The measured P concentrations were corrected for dilution during the rainfall simulation, similar to the study by Uusi-Kämppä et al. (2012). The hygiene indicators, however, were not corrected due to the logarithmic growth of micro-organisms.

Table 2. Footing materials with amendments, paddock sizes, and horse density in rainfall study 1. Woodchip paddocks were amended 1 year before sampling, whereas sand paddocks were amended just before the rainfall simulation.

No.	Footing materials	Size m^2	Horses ha^{-1}
1	Clay	800	20
2	Woodchips (WC) + 0.84 tn ha^{-1} $Ca(OH)_2$	1900	17
3	Woodchips (WC) + 0.84 tn ha^{-1} $Fe_2(SO_4)_3$ (Ferix-3)	1900	17
4	Sand (control)	520	20
5	Sand + 2.7 tn ha^{-1} $Ca(OH)_2$	520	20
6	Sand + 5.3 tn ha^{-1} $Ca(OH)_2$	520	20
7	Sand + 10.7 tn ha^{-1} $Ca(OH)_2$	520	20
8	Sand + 2.0 tn ha^{-1} $Fe_2(SO_4)_3$ (PIX-115) + 6.7 tn ha^{-1} $CaCO_3$	520	20
9	Sand + 4.1 tn ha^{-1} $Fe_2(SO_4)_3$ (PIX-115) + 8.9 tn ha^{-1} $CaCO_3$	520	20
10	Sand + 6.2 tn ha^{-1} $Fe_2(SO_4)_3$ (PIX-115) + 13.3 tn ha^{-1} $CaCO_3$	520	20
11	Sand + 4.4 tn ha^{-1} $CaCO_3$	520	20

Rainfall study 2 and percolation water

Paddock footings (6 treatments × 3 replicates) were artificially constructed in PVC cylinders (diameter 15 cm, height 25 cm) with a tight net at the bottom to allow water flow for percolation water analysis. A 15-cm layer of footing material, such as sand (particle size 0–8 mm) originating from a local gravel pit or aspen woodchips (10–20 mm), was added to a 5-cm layer of quartz sand (particle size 3–5 mm) in the cylinders. Dried and powdered Fe-rich gypsum residue (5.6 tn ha^{-1}) from TiO_2 production, powdered $Ca(OH)_2$ (5.6 tn ha^{-1}), or granulated ferric sulphate [$Fe_2(SO_4)_3$, trade name Ferix-3, 1.1 tn ha^{-1}] was applied to the surface layer to reduce P loss in percolation water (Table 1). More details about the materials and their chemical properties were presented by Uusi-Kämppä et al. (2012).

The PVC cylinders were placed on a collar (volume 240 ml, height 12 mm) filled with quartz sand (diameter 3–5 mm) and saturated from the bottom upwards with deionised water. The next day, the water was allowed to flow out for one hour to the bottom level of the sample and the percolation water collected for chemical and hygienic analyses (0-sample). Finally, 9.9 or 8.3 g (dry matter) of horse dung (TP concentration 1.75 and 1.55 mg g^{-1}) was spread on the surface of the footing material, equal to 10 or 7 kg ha^{-1} of TP, corresponding to the annual input of TP into a paddock area with a horse density of 1 horse ha^{-1}. The results for hygienic indicators in dung are presented in Table 3.

The cylinders were placed under the rainfall simulator and percolation water collected for analysis. The duration of the rain event (10 mm h^{-1}) was 6 h and 5 h on the first and second simulation day, respectively. The volume and mass of the percolation water were recorded. On the first day, approximately 1200 ml of percolation water was obtained as six separate 200 ml subsamples. The first three water samples were for chemical analysis, and the last three samples were pooled and then divided for chemical and hygienic analyses. The next day, 1000 ml of percolation water was collected for chemical analysis. During the rainfall simulation, the temperatures of the laboratory air and deionised water were 20–21 °C and 15.4 °C, respectively. In all studies, the concentrations of DRP and TP and the levels of faecal bacteria in the deionised water used in the rainfall simulations were below the detection limit of the methods used.

Water analysis

For DRP analysis, water samples were filtered (0.2 µm, Whatman, Maidstone, UK) on the day of collection. For TP analysis, unfiltered subsamples were digested with peroxide sulfate in an autoclave (Turtola 1996). Concentrations of DRP and TP were measured using a FIAstar autoanalyzer according to Finnish standards SFS 3025 (1986) and SFS 3026 (1986), respectively, which are based on the molybdate blue method and use of ascorbic acid as the reducing agent (Murphy and Riley 1962). The concentration of particulate P (PP) was estimated by calculating the difference between TP and DRP.

Water quality indicators were enumerated by a membrane filtration method. Water samples were filtered through a Millipore filter (diameter 47 mm) with a pore size of 0.45 µm (for sulfite-reducing clostridia 0.22 µm). Faecal coliforms and *E. coli*/coliforms were cultivated on mFC agar (Difco) (SFS 4088 1988) and Harlequin *E. coli*/coliform medium (LabM), respectively. The plates were incubated for 24 h at 44.5 °C (mFC) and 37 °C (Harlequin) before enumeration. On the Harlequin medium, blue-green colonies were counted as presumptive *E. coli,* and all rose-pink colonies were counted as presumptive coliforms (LabM). Faecal streptococcus and sulfite-reducing clostridia were incubated on KF-streptococcus medium (44 h, 44.5 °C) (SFS 3014 1984) or the Oxoid Anaerobic Jar (44 h, 37 °C) (SFS-EN 26461-2 1993), respectively. Bacteria counts were expressed as the geometric means of the colony forming units (cfu) per 100 ml of water.

Statistical analysis

In the field monitoring of drainage water and rainfall study 1 of surface runoff, statistical analysis was not possible due to the small number of samples. In rainfall study 2 of percolation water, the statistical analysis was based on the experimental design, a balanced incomplete block design comprising six treatments (n=3) and five blocks. The date of the rainfall was the block factor. Four treatments were included in every block, except the last block, which had only two. All of the treatments could not be placed under the same rainfall, which is the reason why the incomplete block design was used.

Every treatment had a few observations in every block. In the analysis, these observations were summarized and the weighted means calculated from the concentrations. The model on which the analysis was based is as follows:

$$y_{ij} = \mu+block_i+tre_j+\varepsilon_{ij}$$

where µ is the overall mean, $block_i$ and ε_{ij} are the random effects of the *i*th block (*i* = 1, 2,…, 5) and the residual effect tre_j represents the fixed effects of the *j*th treatment (*j* = 1, 2,…, 6). All of the random effects were assumed to be mutually independent. The statistical model was fitted using the restricted maximum likelihood (REML) estimation method and SAS/MIXED software (version 9.2).

The distributions of all variables were skewed. Logarithmic transformations were used to normalize the data distribution before statistical analysis. All of the estimates were transformed back to the original scale, except for the standard errors.

Results and discussion

Field monitoring of drainage water

In the drainage water from paddocks constructed using woodchips and amended with $Ca(OH)_2$ or $Fe(SO_4)_3$, the concentrations of DRP and TP were small (≤0.01 and ≤0.51 mg l^{-1}, respectively) at the beginning of the study but increased during the 3 years of observation (Fig. 3). The observed DRP and TP values were often lower for woodchips amended with $Fe_2(SO_4)_3$ than those amended with $Ca(OH)_2$. Other studies have reported that Fe-containing materials on the soil surface provided better results than Ca-containing materials (Uusi-Kämppä et al. 2012), whereas Ca-based materials typically work under very alkaline (pH 9–12) conditions (Berné and Richard 1991, Diaz et al. 1994). The other reason for a smaller DRP concentration from the $Fe_2(SO_4)_3$-amended paddock was that 15-cm sand layer under the woodchips, which was not present in the $Ca(OH)_2$-amended paddock (Fig. 2).

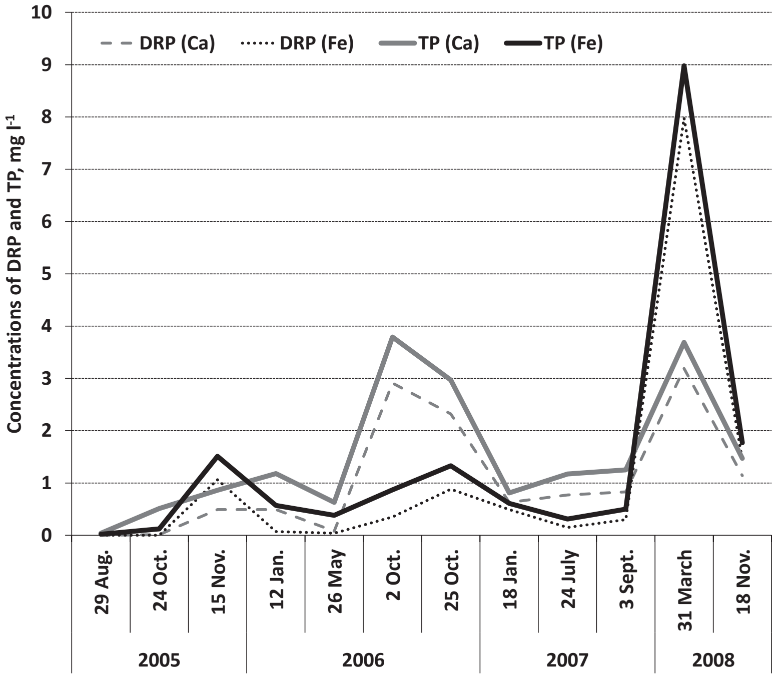


Fig. 3. Concentrations of dissolved reactive phosphorus (DRP) and total phosphorus (TP) in drainage water from the paddock constructed out of woodchips and amended with $Ca(OH)_2$ (slaked lime) or $Fe_2(SO_4)_3$ (Ferix-3) during the field monitoring study.

High DRP concentrations (up to 3 mg l^{-1}) were measured in the drainage water from $Ca(OH)_2$-amended woodchips in October 2006 and March 2008. These values are 2–6-fold higher than the values reported by Jansson et al. (2000) for open ditches adjacent to stable areas. The paddock drainage flow in the present study was not diluted with other runoff water originating from areas outside the paddocks. In Sweden, Parvage et al. (2011) measured 13-fold and 3-fold higher mean concentrations of DRP and TP, respectively, in drainage water from a grazed horse paddock (3.75 livestock units ha^{-1}) compared to the water from the adjacent arable land. Peak values were also observed in paddock flow, occasionally exceeding 1.5 mg l^{-1} TP and 1 mg l^{-1} DRP in the spring and autumn, but no peaks were observed in the drainage water from arable land.

A high DRP concentration of 8 mg l^{-1} was measured in the drainage water from the $Fe_2(SO_4)_3$-amended paddock in March 2008 (Fig. 3). An equally high DRP concentration was measured earlier in percolation water from a forested feedlot for cattle where no P-sorbing materials were used (Uusi-Kämppä 2002). The effectiveness of $Fe_2(SO_4)_3$ in retaining P probably decreased or was depleted after 2 years. The PP concentrations were low (< 1 mg l^{-1}), probably due to the ability of the underlying clay soil to prevent particles from entering the drainage water.

The pH level was slightly higher in the drainage flow from woodchips amended with $Ca(OH)_2$ (mean 7.0) compared to $Fe_2(SO_4)_3$ (mean 6.8), which is an acidic product (pH <2). In this preliminary study, comparison of the two P-sorbing materials was difficult due to the absence of a calibration period and presence of a sand layer in the footing amended with $Fe_2(SO_4)_3$ (Fig. 2).

Rainfall study 1 and surface runoff

Extremely high DRP concentrations (45 mg l^{-1}) were measured in runoff when crushed stone was used as the footing material and the dung was not removed immediately from the paddock area (data not shown). Very high DRP concentrations (6–18 mg l^{-1}) were also obtained from sand footings without any P-sorbing material (Fig. 4) compared to the corresponding DRP value of 2.2 mg l^{-1} for clay footing. Similar DRP concentrations (up to 15.0 mg l^{-1}) were measured in the surface runoff from paddocks in the study by Airaksinen et al. (2007). In our study, most of the P was in the form of DRP in the runoff from footings, similar to the studies by Airaksinen et al. (2007) and Närvänen et al. (2008).

In Finland, Jansson et al. (2000) observed 3- to 4-fold higher concentrations of DRP (0.55 mg l^{-1}) and TP (1.28 mg l^{-1}) in ditch water adjacent to horse areas compared to the ditches of agricultural fields. However, in the field study by Turtola and Kemppainen (1998), the DRP concentration in runoff peaked at 25 mg l^{-1} after applying cattle slurry to snow-covered soil. Runoff and DRP concentrations were high in both the water-saturated samples of the present study and the frozen field in Turtola and Kemppainen's (1998) study due to the limited percolation of water into the ground. In the rainfall simulations, the concentrations in runoff may have been higher than in nature due to the rather high rainfall intensity (21 mm h^{-1}). Thus, the experiment demonstrates the worst situations during snow melting, when the soil is frozen and runoff at its highest.

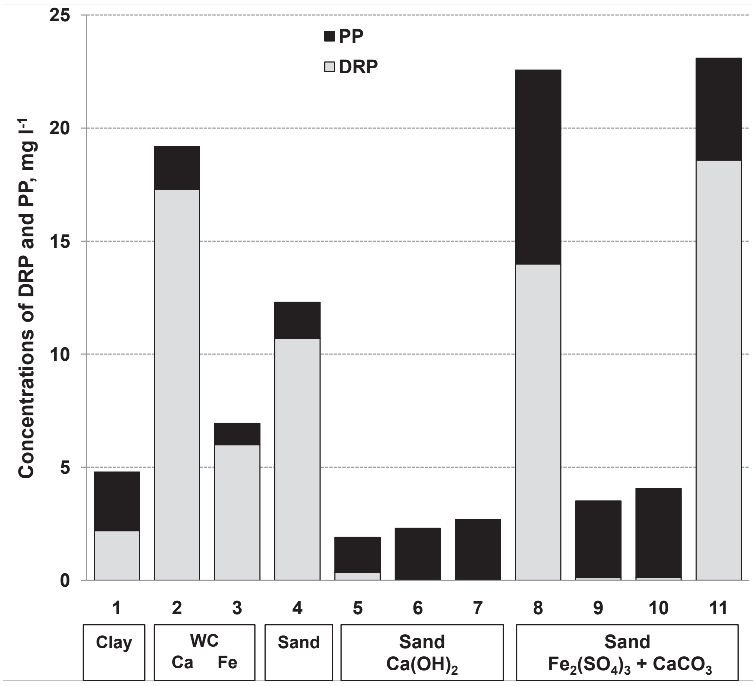


Fig. 4. Concentrations of dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) in surface runoff from footings constructed of clay, woodchips, and sand with P-sorbing materials during rainfall study 1. The application rates are presented in Table 2.

Performance of P-sorbing materials

The concentrations of DRP and TP in the runoff were lower for woodchips amended with $Fe_2(SO_4)_3$ (0.84 tn ha^{-1}) than for woodchips amended with the same amount of $Ca(OH)_2$ (Fig. 4). Lower concentrations of DRP and TP were also measured in the drainage flow after $Fe_2(SO_4)_3$ application compared to $Ca(OH)_2$ application at the same site in 2006 and 2007. The DRP and TP concentrations were lower overall in the drainage flow than in the surface runoff, probably due to the adsorption of DRP on the sand layer, the P-sorbing materials applied to the woodchips, and the sieving effect of the clay soil. In the top layer sampled for the simulation, the amount of $Ca(OH)_2$ that was applied may have been lower than in the deeper layer, resulting in less efficient retention of DRP from the runoff compared to the runoff from the $Fe_2(SO_4)_3$-amended woodchips. This observation was due to the application of Ca-containing materials to a depth of 10 cm to protect the horses from eating the chemical compound. In contrast, granular Fe-containing materials were applied on the surface of the woodchip material, from where it was thought to penetrate into deeper layers over time.

The addition of 2.5 tn ha^{-1} $Ca(OH)_2$ to the sand surface in the laboratory decreased the DRP and TP concentrations by 97% and 85%, respectively, compared to the sand without amendments (Fig. 4). The added amounts of $Fe_2(SO_4)_3$ (2 tn ha^{-1}) and $CaCO_3$ (6.7 tn ha^{-1}) were not effective at decreasing the concentrations. When the amount of applied Fe was doubled, the decrease in DRP and TP was 99% and 71%, respectively. On the other hand, the use of $CaCO_3$ alone had no effect on the values (Fig. 4).

Rainfall study 2 and percolation water

Phosphorus loss

The general trend was that percolation water from a sand footing had 100%, 89%, and 97% lower concentrations of DRP, PP, and TP compared to a footing made of woodchips (p <0.0001, Table 3). No addition of Fe or Ca was needed as the sand itself was very effective at decreasing the DRP, PP, and TP concentrations in the percolation water. The sand used probably included Fe, resulting in the retained DRP being liberated from the horse dung during the rainfall simulations.

One reason for the high P concentrations in the footings constructed using aspen woodchips was the liberation of DRP into the percolation water from the footing material itself (0.47–0.94 mg l^{-1}) before dung application. High TP concentrations in effluents from hardwood (up to 40 mg l^{-1}) were initially observed by Chardon et al. (2011) when nitrate was removed from the drainage water using woodchips. In our study, the high DRP concentration from woodchips was significantly decreased (over 76%) by the addition of $Ca(OH)_2$ or Fe-gypsum to the footing material (Table 3). However, $Ca(OH)_2$ was not as effective as Fe-gypsum in reducing the TP concentration (46%, p=0.012 and 67%, p <0.001, respectively). The DRP concentrations in the water from woodchips amended with Ca- and Fe-based materials were the same as in the field monitoring study (see Fig. 3).

Altogether, four single samples (woodchips, woodchips with $Ca(OH)_2$, woodchips with Fe-gypsum, and sand) were amended with horse dung (30 g, containing 17 mg TP) and irrigated (10 mm h^{-1}, 3 h) a third time. The resulting DRP concentrations in the percolation water were 11.30, 8.68, 5.80, and 0.04 mg l^{-1}, respectively. This experiment showed that the effect of P-sorbing materials may decrease over time and that P loss can increase again in paddock runoff. However, the DRP concentration from the sand footing was still low. The footing was loaded according to a horse density of 1 horse ha^{-1}, whereas the typical density in Finnish paddocks is up to 5.3 horses ha^{-1} (Pikkarainen 2005). In practise, the paddocks are loaded for several years, whereas in our study the annual load of a single horse was given once. Thus, paddocks may be more heavily loaded than in this study.

The highest DRP content (2.7 mg, equivalent to 1.5 kg ha^{-1}) was from the paddock footing constructed out of woodchips, partly due to the rather high DRP content (~1.0 mg in 0-sample) of the woodchip material itself. Overall, up to one-fifth of the TP input leached through the footing constructed of woodchips without any P-sorbing material. The addition of $Ca(OH)_2$ and Fe-gypsum decreased the DRP load by 75% and 83%, respectively (Table 3). The TP content (3.6 mg) was decreased by 68% by the addition of Fe-gypsum (Table 3), whereas the addition of $Ca(OH)_2$ did not decrease the load significantly.

The DRP load into the percolation water from the sand footing was negligible (<0.001 mg, Table 3). However, the water volume was 25% less from the sand footings than footings constructed out of woodchips due to high permeability of the woodchip material. The average percolation flow was 90 mm and up to 120 mm for sand and woodchips, respectively, when total precipitation was approximately 110 mm. Although the sand footing efficiently retained DRP, its infiltration capacity may decrease over time, increasing the risk of surface runoff. The TP content of 0.1 mg in the percolation water from the sand footing was decreased by 78% and 60% by applying Fe-gypsum and $Fe_2(SO_4)_3$, respectively. In particular, the 10-cm sand layer below the layer of woodchips in the monitoring study might also be a significant reason for the lower P concentration in the drainage water from the $Fe_2(SO_4)_3$-amended paddock compared to the $Ca(OH)_2$-amended paddock.

Table 3. Estimates of the phosphorus concentrations (mg l^{-1}) and contents in percolation water (µg) and *p*-values for sand and woodchips (WC) with P-sorbing materials (sand mix, WC mix) in rainfall study 2.

	Treatments (n=3)						Differences of means (*p*-values)						
Response	WC	WC+ $Ca(OH)_2$	WC+Fe-gypsum	Sand	Sand+Fe-gypsum	Sand+ $Fe_2(SO_4)_3$	WC vs. sands	WC vs. WC mix	WC vs. WC+ $Ca(OH)_2$	WC vs. WC+Fe-gypsum	Sand vs. Sand mix	Sand vs. Sand+Fe-gypsum	Sand vs. Sand+ $Fe_2(SO_4)_3$
DRP, mg l^{-1}	1.32	0.31	0.27	0.00	0.00	0.00	<0.0001	<0.0001	<0.001	<0.001	0.927	0.921	0.951
TP, mg l^{-1}	1.89	1.03	0.62	0.06	0.02	0.03	<0.0001	0.001	0.012	<0.001	0.580	0.579	0.676
PP, mg l^{-1}	0.57	0.72	0.35	0.06	0.01	0.02	<0.0001	0.517	0.188	0.028	0.293	0.297	0.418
DRP, µg	2739	673	456	0.7	0.5	0.4	<0.0001	0.025	0.076	0.030	0.671	0.748	0.676
TP, µg	3565	2383	1133	96.8	21.7	38.5	<0.0001	0.044	0.323	0.017	0.007	0.004	0.052
PP, µg	1072	1683	669	99.0	20.5	37.3	<0.0001	0.974	0.220	0.210	0.003	0.002	0.026

DRP=dissolved reactive phosphorus, TP=total phosphorus, PP=particulate phosphorus.

Levels of bacteria in faeces and water

In addition to P, the levels of faecal bacteria were studied in faeces sampled from the horse's rectum, dung on the surface of the paddock footings, and water samples. The number of presumptive *E. coli* in fresh faeces collected directly from 10 horses in the Ypäjä area was between 6.6×10^4 and 4.6×10^7 g^{-1} (dry weight). Similarly, in dry manure collected from a paddock for the rainfall simulations, the geometric means for the number of presumptive *E. coli* were 7.0×10^4 and 1.7×10^4 cfu g^{-1} for the first and second dung samples, respectively (Table 4). Weaver et al. (2005) counted *E. coli* and faecal streptococcus in fresh manure from horses in a pasture and reported similar numbers as we found in the dung used in the rainfall simulation.

Table 4. The mean numbers of presumptive *E.coli*, other coliforms, *Faecal coliforms, Faecal streptococcus,* and sulfite-reducing clostridia in the dung of rainfall study 2.

Dung sample	*E.coli*	Other coliforms	*Faecal coliforms*	*Faecal streptococcus*	Sulfite-reducing clostridia
	cfu g^{-1} (dry matter)				
1	7.0×10^4	1.6×10^5	9.4×10^4	1.5×10^7	1.6×10^3
2	1.7×10^4	6.2×10^4	2.4×10^4	2.1×10^7	2.7×10^2

Field monitoring of drainage water

In the drainage water from the paddock footing made of woodchips, the levels of indicator bacteria decreased over time (Table 5), whereas the concentrations of P fractions increased (Fig. 3). The levels of faecal coliforms [2.4×10^2–6.7×10^5 cfu (100 ml)$^{-1}$] were of a similar order of magnitude as those measured for forested feedlots for suckler cows in eastern Finland (Uusi-Kämppä et al. 2001). In the present study, the number of presumptive *E. coli* and faecal streptococcus was less in runoff from the paddock where $Fe_2(SO_4)_3$ was used compared to the paddock amended with $Ca(OH)_2$. The sand layer in the Fe-amended footing may also have decreased bacterial levels in the water. In all three studies, the levels of sulfite-reducing clostridia were below the detection limit of the method used.

Table 5. Presumptive *E. coli*, other coliforms, faecal coliforms, and faecal streptococcus in drainage water from the paddock constructed out of woodchips and amended with $Ca(OH)_2$ or $Fe_2(SO_4)_3$ (Ferix-3) in the field monitoring study.

Time period	*E. coli*		Other coliforms		*Faecal coliforms*		*Faecal streptococcus*	
	cfu (100 ml)$^{-1}$							
	$Ca(OH)_2$	$Fe_2(SO_4)_3$	$Ca(OH)_2$	$Fe_2(SO_4)_3$	$Ca(OH)_2$	$Fe_2(SO_4)_3$	$Ca(OH)_2$	$Fe_2(SO_4)_3$
Nov. 2005	n.a.	n.a.	n.a.	n.a.	$4.1\text{x}10^5$	$6.7\text{x}10^5$	$1.5\text{x}10^5$	$1.0\text{x}10^5$
Oct. 2006	$2.7\text{x}10^4$	$5.8\text{x}10^3$	$4.9\text{x}10^4$	$3.5\text{x}10^4$	n.a.	n.a.	$3.0\text{x}10^4$	$1.7\text{x}10^4$
Sept. 2007	$3.5\text{x}10^4$	$4.5\text{x}10^2$	$6.2\text{x}10^4$	$1.8\text{x}10^4$	n.a.	n.a.	$3.5\text{x}10^4$	$4.5\text{x}10^2$
Nov. 2008	$3.0\text{x}10^1$	$1.5\text{x}10^1$	$4.7\text{x}10^2$	$1.5\text{x}10^3$	$2.4\text{x}10^2$	$1.5\text{x}10^3$	$1.5\text{x}10^3$	$5.3\text{x}10^2$

n.a. = not available

Rainfall study 1 and surface runoff

High numbers of presumptive *E. coli* [1.7×10^4–5.5×10^5 cfu (100 ml)$^{-1}$] were measured in the runoff from all footing materials collected from the horse paddocks (Fig. 5). The numbers of presumptive *E. coli* were also high in the runoff from sand footing, but the addition of 10 tn ha^{-1} of $Ca(OH)_2$ to the sand reduced the numbers to below the detection limit. The pH value of the runoff increased up to 11.7–12.5, killing micro-organisms. Swedish experiments showed that $Ca(OH)_2$ is effective in inactivating *Salmonella typhimurium* if a sufficient increase in pH is achieved (pH>11) and maintained for several days (Nyberg et al. 2011).

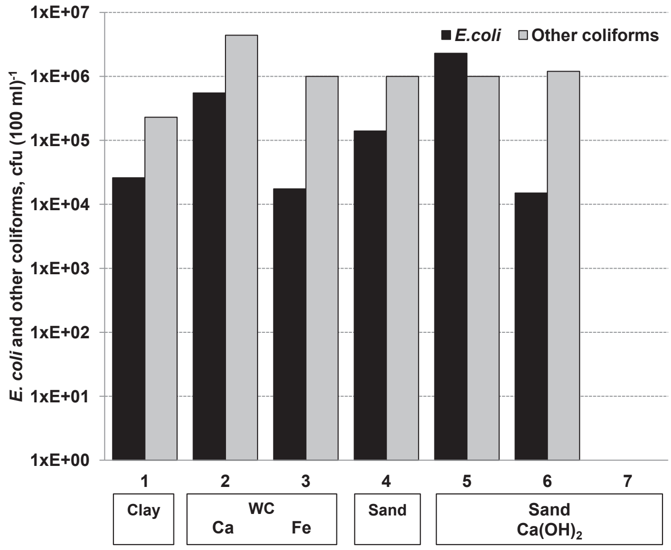
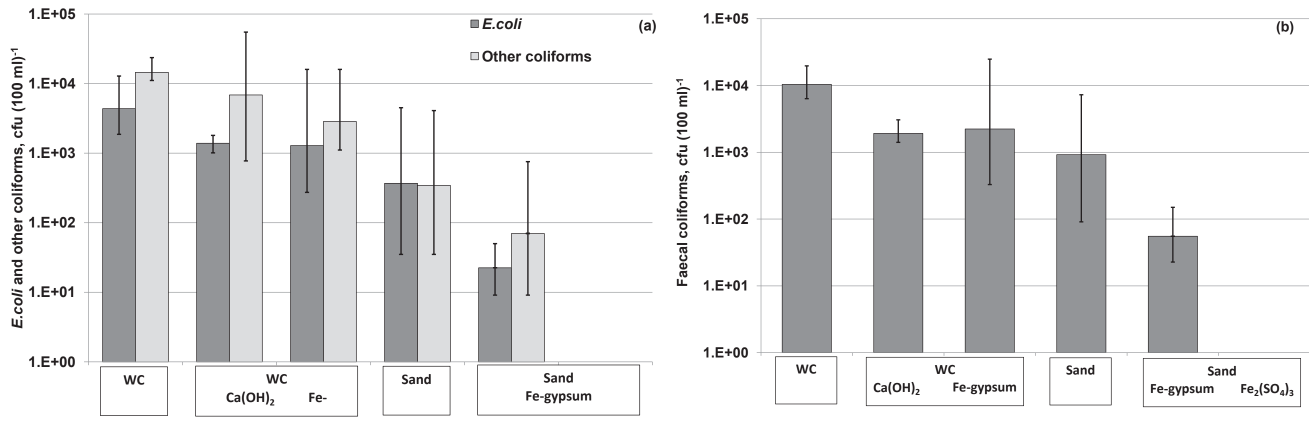


Fig. 5. Numbers of presumptive *E. coli* and other coliforms in surface runoff from footings constructed of clay, woodchips, and sand with P-sorbing materials during rainfall study 1. The application rates are presented in Table 2. Note that the number of bacteria is below the detection limit in the case of sand amended with 10 tn ha^{-1} $Ca(OH)_2$.

Rainfall study 2 and percolation water

Fewer faecal coliforms were present in the percolation water from the sand footing than from the footing constructed out of woodchips due to the better retention capacity of the sand (Fig. 6). The pore space in the sand footing was smaller than in the footing constructed of woodchips; therefore, the sand probably prevented the transport of microbes into the percolation water better than the woodchips. The levels of faecal coliforms and *E. coli* in the water were reduced by the application of Fe-gypsum to the sand footing. The addition of $Fe_2(SO_4)_3$ to the sand completely removed coliforms and faecal streptococcus from the water due to the decrease in pH (pH 4.8–5.1). Although the addition of $Ca(OH)_2$ and Fe-gypsum decreased the numbers of faecal coliforms, rather high levels [3.3×10^2 to 2.5×10^4 cfu (100 ml)$^{-1}$] were measured in the percolation water from footings constructed out of woodchips. The reason for the poor reduction of *E. coli*, faecal coliforms, and faecal streptococcus by $Ca(OH)_2$ was that the amount applied was not sufficient to increase the pH above 11; the pH remained between 7.6 and 9.0 (data not shown). The Fe-gypsum had no effect on the pH



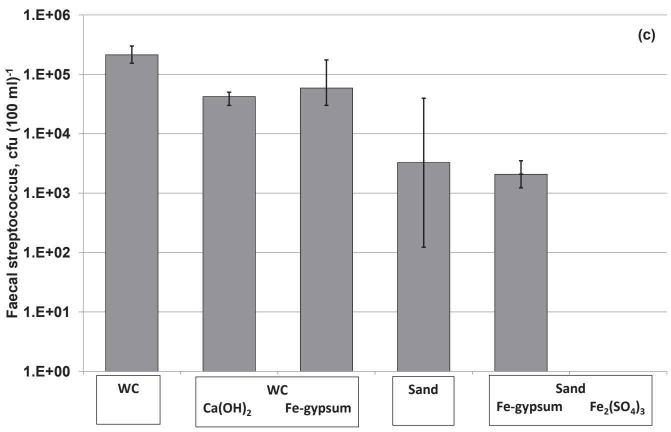


Fig. 6. Numbers of presumptive *E. coli*, other coliforms (a), faecal coliforms (b), and faecal streptococcus (c) in percolation water from footings constructed of woodchips (WC) or sand and amended with Ca- or Fe-containing materials during rainfall study 2. Data are the geometric mean of three replicates. Error bars indicate maximum and minimum values. Note that the number of bacteria is below the detection limit in the case of sand amended with $Fe_2(SO_4)_3$.

Conclusions

High concentrations of DRP and TP, as well as high levels of indicator bacteria, were observed in drainage water and runoff from horse paddocks. According to the current guidelines, horse paddocks must be established in a way that eliminates the risk for groundwater pollution and minimizes the risk of surface water pollution (Finnish Ministry of the Environment 2003). The distance from a paddock to a main ditch should be at least 20 m, and to a brook or watershed at least 100 m. Droppings must be removed from the surface of a paddock frequently (Finnish Ministry of the Environment 2003). Not all Finnish paddocks are managed according to these guidelines: some are situated too near to waters, some have no drainage system, some were improperly established, and in some droppings are not removed regularly. However, our results show that a very high risk exists for the loss of both P and faecal micro-organisms into runoff from the paddocks to water, but the risk can be reduced by choosing good footing materials and adding P-sorbing material.

In the present study, sand footing retained DRP, TP, and faecal coliforms better than woodchips. The DRP and TP concentrations and number of bacteria were lower in the percolation water than in the surface runoff water, as the footing materials retained P and filtered out coliforms. In practice, the surface should have a good infiltration capacity, and the drainage system should function well to prevent surface runoff from the paddocks. The paddocks must be built in a way that the soil is first drained, and then the footing material added (Jansson and Särkijärvi 2010).

Application of Fe-containing materials to the footing decreased DRP concentrations, as well as the number of faecal coliforms, in the percolation water. However, P-sorbing materials may not work efficiently in winter when the paddock surface is frozen. More information is needed about the best amendments and suitable amounts for different conditions. Problems were not detected in the mouths of horses, though 0.84 tn ha^{-1} of slaked lime or $Fe_2(SO_4)_3$ was added to footings constructed out of woodchips. Because the higher rate of P-sorbing materials (as applied in the rainfall simulation studies) was not tested in a real paddock, we cannot guarantee a lack of health risks to horses. In light of the results obtained in the present study, further studies are required to test P-sorbing materials, including the effects of the materials on horse health.

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