Can Organic Materials Reduce Excess Nutrient Leaching from Manure-Rich Paddock Soils?

Mohammed Masud Parvage,* Barbro Ulén, and Holger Kirchmann

Abstract

Horse paddocks have been identified as a significant contributor of animal waste nutrients to natural waters; thus, modified paddock management is needed. Because chemical amendments pose a health risk to horses, an alternative for reducing nutrient translocation from manure is to add available organic residues to the soil. To examine the feasibility of outdoor use of organic materials to reduce nutrient losses from paddock soils, three commonly available organic materials (peat, wheat straw, and wood chips) were tested for their nutrient retention capacities in batch experiments followed by leaching experiments in an in-house lysimeter station using artificial rainfall. Results showed that the ground peat and wood chips retained some phosphorus (P), whereas grounded wheat straw released P to the solution. In leaching experiments, peat reduced nitrogen (N) losses by 40% but increased P and carbon (C) losses severalfold. Wheat straw was ineffective in reducing P, N, or C losses and in some cases increased the losses. Wood chips effectively reduced P and C losses, by 70 and 40%, respectively, but not N losses. It was concluded that, among the three organic materials, only the wood chips can be used outdoors to reduce nutrient losses from paddock soils.

Core Ideas

• Paddock soils are “hot spots” for nutrient losses that need to be managed.
• The capacity of organic materials to reduce nutrient loss from soil is not widely known.
• Peat reduced N losses, and wood chips reduced both P and C losses.
• Wheat straw increased nutrient leaching losses.

Horse keeping is an emerging animal sector in Sweden. Management of horse farms differs in some aspects from that of other animal farming systems. For example, animal density on Swedish farms is limited by the arable land available for manure spreading, which must not exceed 22 kg phosphorus (P) ha⁻¹ yr⁻¹ (Swedish Board of Agriculture, 2015). In contrast, horse paddocks in Sweden receive almost threefold higher P loads (60 kg P ha⁻¹ yr⁻¹) directly from manure because horse density is much higher (8.6 livestock units ha⁻¹, where 1 horse = 0.8 livestock unit) (European Commission, 2013) on these farms (Parvage et al., 2013). Furthermore, storage and recycling of horse manure is not strictly controlled. Within horse paddocks, feeding and defecation areas have been found to be highly enriched with nutrients, releasing significant amounts of P, nitrogen (N), and carbon (C) into surface and drainage water (Airaksinen et al., 2007; Dahlin and Johanson, 2008; Parvage et al., 2015). High loading of nutrients into surface water is undesirable due to the detrimental effect on water quality and aquatic biodiversity. Thus, reducing nutrient losses from nutrient-enriched soil zones is a priority.

Vegetative filter strips and chemical amendments (ferric sulfate treatments) have been suggested as effective measures to minimize nutrient losses via surface runoff (Närvānen et al., 2008; Webber et al., 2009). Regarding leaching losses, the most important management action is to prevent accumulation of large amounts of manure on paddock surfaces and thus curb translocation into the soil. Accumulation of feces and urine on the soil surface can be decreased by reducing animal density. Moreover, regular removal of manure from soil has been demonstrated to effectively reduce both surface and leaching losses from outdoor cattle lots (Salomon et al., 2008). However, regular removal of manure from paddock areas is a laborious process. The few horse farms that regularly remove droppings from paddocks do so with the aim of reducing recontamination by parasites.

Nutrient entry into the soil from feces and urine will decrease if the amount of water entering the soil can be decreased. Commericially available organic materials, such as peat, cereal straw, and wood chips, are often used as bedding materials inside stables to absorb urine and reduce ammonia volatilization (Airaksinen et al., 2001; Andersson, 1996; Misselbrook...
and Powell, 2005). These materials might also be useful outdoors in reducing nutrient leaching on feeding and defecation areas in horse paddocks through their high water-holding capacity (WHC). In addition, P and N can be chemically bound to organic residues and become immobilized during decomposition of the organic amendments.

Horse paddocks have been identified as a significant source of P and N leaching to natural waters (Parvage et al., 2011, 2015); therefore, new methods of paddock management are needed to reduce these nutrient losses. The aim of this study was to examine the feasibility of using peat, wheat straw, and wood chips as amendments on defecation areas in outdoor horse paddocks to reduce the loss of nutrients through leaching. The hypothesis was that application of these organic materials reduces nutrient losses by reducing water flow through soil and increasing the binding of P and N in the material. These effects were expected to be most pronounced for peat, which has a greater WHC and more exchange sites for binding than wheat straw and wood chips.

### Materials and methods

#### Analysis of Organic Amendments and Manure

The organic amendments used were sphagnum peat, wheat straw, and wood chips from pine trees. These materials (non-grounded) were analyzed for dry matter (DM), bulk density, WHC, and dissolved (in water) reactive P (DRP). Dry matter was measured after drying the samples at 105°C overnight, and bulk density was determined by measuring the weight of dry straw in a volume of 1 L. For WHC measurement, 1 L of bedding material was immersed in 6 L water in a 20-L bucket until the material reached saturation (around 24 h). The water content in saturated samples (three replicates) was then measured for WHC after 24 and 96 h of drainage. Dissolved reactive P was measured using a 1:30 (w/w) organic material/water ratio (1:60 for wheat straw). Suspensions were shaken for 24 h, centrifuged at 3000 rpm (2091 g-equivalence), and filtered with 0.45-µm filter paper, and the concentration of DRP was determined colorimetrically (Murphy and Riley, 1962) using a Shimadzu UV-1201 spectrophotometer.

The P sorption capacity (PSC) of dried and milled (<2 mm) material was determined by shaking the materials for 24 h with phosphate solution (prepared from KH₂PO₄) at increasing concentrations (0–100 ppm P at an organic material/P solution ratio of 1:25) and measuring the remaining P in solution. The procedures used for analyzing P in solution were the same as those used for DRP measurement. The PSC in the materials was estimated as follows:

\[
PSC = \text{amount of P added} - (\text{amount of P left in solution} + \text{DRP content of the material})
\]

Fresh horse manure (about 5 kg) from horses fed on hay and water was collected and analyzed for moisture and nutrient content. Water-soluble nutrients in the fresh manure were determined after water extraction (deionized water, 1:3 w/w). In brief, 100 g of thoroughly mixed fresh sample was transferred to a 1000-mL plastic bottle. Then, 300 mL of deionized water was added. The sample was shaken vigorously by hand for 5 min and centrifuged at 3000 rpm for 20 min. Any floating or large particles in the supernatant were filtered out using a polyamide cloth filter (50 µm), and an aliquot of the supernatant was carefully transferred to a glass bottle. The aliquot was filtered through a 0.20-µm membrane filter before determination of water-soluble nutrients.

#### Leaching Experiment

Soil monoliths were collected from the grazing area of horse paddock UKB (code name). Details about the management practices, soil texture, and chemical properties were described in Parvage et al. (2013). In brief, the soil is a loamy sand, and the site has been used as a horse paddock for the last 18 yr. The soil is slightly acidic (pH 6.3), with nutrient concentrations of 5.2 mg DRP kg⁻¹, 829 mg total P (TP) kg⁻¹. P saturation percentage 24%, total organic C 2.2%, and total N (TN) 0.21%.

Fifteen undisturbed soil columns were collected from the top-soil (0–20 cm) in plastic cylinders (20 cm long, 18.8 cm diameter) in April 2011 and kept in a cold room at 5°C until the start of the experiment. To measure leaching losses of the nutrients under rainfall conditions in the experiment, the columns were moved to an indoor rain simulation station, where a sprinkler system with hydraulic atomizing nozzles created artificial rain. The nozzles had a delivering capacity of 7 L h⁻¹, with droplet diameter ranging from 0.07 to 0.10 mm. The sprinkler system was positioned 80 cm above the soil columns. The base of each soil column was carefully prepared by removing excess soil with a sharp knife and loose soil particles with a vacuum cleaner. The base was then wrapped with a polyamide cloth filter (50 µm). The column was placed on a perforated metal plate lying inside a steel base tray. The tray base from each column was connected to a flexible plastic pipe, which drained leachate from the tray into a glass jar. To prevent any rainwater from entering the tray from outside, the gap between the tray and the column wall was sealed with a plastic canvas cap and duct tape. Before the leaching experiments were performed, the soil columns were kept in the rain chamber for a week to equilibrate to room temperature (22°C). Three days (72 h) before the experiment began, the soil columns were washed. Moisture content in the columns was equalized by applying 30 mm simulated rain with an intensity of 2 mm h⁻¹, and any drainage water was discarded. Tap water containing 0.004 mg TP L⁻¹, 1.066 mg TN L⁻¹ (pH 8.3) was used as the source of the simulated rain water.

Five treatments with three replicates were applied to the soil columns: (i) soil only (control), (ii) soil with fresh manure only (750 g, half of a manure patch) on top (manure-only treatment), (iii) soil with a 5-cm layer of peat topped with fresh manure (peat treatment), (iv) soil with a 5-cm layer of wheat straw topped with fresh manure (wheat straw treatment), and (v) soil with a 5-cm layer of wood chips topped with fresh manure (wood chip treatment). The organic amendments were air dried and applied on the basis of depth rather than soil weight.

Soil columns were exposed to six rain simulation events, each supplying 20 mm rain at 24-h intervals (Sweden’s heaviest rainfall) at an intensity of 2 mm h⁻¹ (Swedish average). The first rain simulation was performed without any organic material and/or manure on top of the columns, giving background leachate data for all columns. Leachate was collected in glass jars, and the volume leached per column was measured 24 h after each rain simulation. Glass jars with leachate were shaken thoroughly to homogenize the contents, and a set of water samples was taken.
for chemical analysis and storage. To avoid cross contamination, collection jars were washed twice (once after each sampling event) and reused.

**Analysis of Leachate**

A total of 90 leachate samples (15 columns × 6 rain simulations) were analyzed for P, N, and C concentrations. The concentration of P was measured in accordance with European Standard EN 1189 (European Committee for Standardisation, 1996). The concentration of TP was analyzed in unfiltered samples after digestion with a mixture of potassium peroxodisulfate (K₂S₂O₈) and sulfuric acid (H₂SO₄) for 30 min at 120°C. After cooling to room temperature, the digested samples were analyzed for P in a flow injection analyzer. Dissolved reactive P was determined by flow injection analyzer using undigested but filtered samples (0.2-μm membrane filter paper). Concentration of TP was also analyzed in filtered samples, and particulate P (PP) was calculated as the difference in TP between filtered and unfiltered samples. Dissolved organic P (DOP) was estimated by subtracting DRP and PP from TP in unfiltered samples. Concentrations of total organic C (TOC) and TN were measured in unfiltered samples using a Shimadzu TOC-VCPH analyzer after combusting the samples at 720°C.

**Statistical Analysis**

Sample mean and standard deviation were calculated in Excel 2010, statistical analyses with the software MINITAB 16, and P sorption data with Sigma plot 11. Amounts of P, N, and TOC leached per treatment were calculated using mean concentration and mean leachate volume of the previous five rain simulation events. The paired t test was performed to test for differences between treatments. Phosphorus sorption maxima were obtained by plotting data with piecewise nonlinear regression.

**Results**

**Characterizations of Horse Manure**

The mean size and weight of individual manure heaps were 722 ± 109 cm² and 1537 ± 275 g, respectively. The manure had a soil moisture content of 69 ± 1% and a pH of 7.1. Mean concentrations of total nutrient in the manure, determined from dried and milled (<2 mm) samples, were as follows: 370 g organic C kg⁻¹ DM, 8.9 g TN kg⁻¹ DM, and 1218 mg TP kg⁻¹ DM. Of the TP in the manure, 1043 mg (86%) was water-soluble P, and 689 mg wood chips.

**Characterizations of Organic Amendments**

Measured characteristics of the organic amendments are shown in Table 2. Dry bulk density was highest for wood chips (82 kg m⁻³) and lowest for wheat straw (41 kg m⁻³), whereas wet bulk density was highest for peat (643 kg m⁻³). Because the bulk density of the amendments varied, the addition of a 5-cm layer of organic material on top of the soil column in an 18.8-cm-diameter cylinder represents 94 g peat, 57 g wheat straw, and 114 g wood chips.

Water-holding capacity was highest for peat (10.7 L kg⁻¹ DM for 24 h and 8.8 L kg⁻¹ DM for 96 h drainage) and lowest for wood chips (2.6 and 1.9 L kg⁻¹ DM, respectively). This indicates that peat has the potential to retain more water and potentially reduce water losses to a greater extent than wood chips. The potential for water retention of wheat straw was somewhat higher (nonsignificant) than that of wood chips but was significantly lower than that of peat. Calculations based on the WHC data showed that a 5-cm layer of (air-dried) peat, wheat straw, and wood chips could retain 36.2, 6.5, and 10.7 mm rain water, respectively.

Peat and wood chips were fairly acidic (pH 4.9 and 4.8, respectively), whereas wheat straw was slightly alkaline (pH 7.9). Wheat straw released the highest amount of DRP (6.2 mg P g⁻¹ DM), followed by wood chips (3.5 mg P g⁻¹), but there was no detectable DRP release from peat. The maximum P retention capacity for peat, wheat straw, and wood chips was similar (about 5 mg P g⁻¹ DM), whereas the net binding varied from (+) 4.30 mg P g⁻¹ DM for peat to (−) 4.25 and (±) 2.25 mg P g⁻¹ for wheat straw and wood chips, respectively (Fig. 1), where the plus sign represents more bindings than releases and the minus sign represents more releases than bindings. This finding indicates that peat and wood chips can retain only a small portion of the TP load. Wheat straw, on the other hand, may act as a net source, contrary to the study objective of reducing nutrient leaching losses by using these materials. However, there was a sorption breakpoint in all materials, and at a certain P concentration in solution P sorption capacity declined. This critical solution P concentration was 75 mg P L⁻¹ for peat, 54 mg P L⁻¹ for wheat straw, and 56 mg P L⁻¹ for wood chips. The reason for this breakpoint is not fully understood because the pH of the added solution was acidic (5.5) from the start of the experiment and dropped by only about 0.6 to 0.7 pH units during measurements. As a result, the study did not examine whether there was a shift in ionic strength causing anionic repulsion between the added phosphate ions and organic acid anions (e.g., carboxylate and phenolate).

**Effect of Organic Amendments on Water Discharge and Leachate Concentrations**

Leachate volume from untreated soil columns ranged between 350 and 450 mL after the first rainfall simulation event.

### Table 1. Chemical composition of fresh horse manure.

<table>
<thead>
<tr>
<th>Analysist</th>
<th>Fresh horse manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture, %</td>
<td>69</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>7.1</td>
</tr>
<tr>
<td>EC, mS m⁻¹‡</td>
<td>117</td>
</tr>
<tr>
<td>DRP, mg kg⁻¹ DM†</td>
<td>689 (57)§</td>
</tr>
<tr>
<td>Total P, mg kg⁻¹ DM†</td>
<td>1043 (86)</td>
</tr>
<tr>
<td>Total N, mg kg⁻¹ DM†</td>
<td>380 (43)</td>
</tr>
<tr>
<td>TOC, g kg⁻¹ DM†</td>
<td>5.4 (1.5)</td>
</tr>
<tr>
<td>DM, %</td>
<td>31</td>
</tr>
<tr>
<td>Total C (% of DM)</td>
<td>37</td>
</tr>
<tr>
<td>Total N (% of DM)</td>
<td>0.89</td>
</tr>
<tr>
<td>Total P (mg kg⁻¹ DM)</td>
<td>1218</td>
</tr>
<tr>
<td>C/N (in DM)</td>
<td>42</td>
</tr>
<tr>
<td>C/P (in DM)</td>
<td>303</td>
</tr>
<tr>
<td>N/P (in DM)</td>
<td>7.3</td>
</tr>
</tbody>
</table>

*† DM, dry matter; DRP, dissolved reactive P; EC, electrical conductivity; TOC, total organic C. Subscript letter w indicates measured in water extract.

‡ Extracted in 1:3 manure/water ratio.

§ Values in parentheses represent percentage of the total.
Variations were statistically nonsignificant, probably due to heterogeneity in soil affecting water flow pathways.

The effect of the amendments was measured from the second rain simulation event onward. Leachate volume from the control soil increased to 520 mL after the second simulation event, whereas leachate from manure + organic amendment treatments decreased to about half the initial volume (from 450 to 240 mL for peat, from 400 to 190 mL for wheat straw, and from 350 to 170 mL for wood chips). No change occurred for the manure-only treatment (Fig. 2a). Reduced leaching of water from the wheat straw and wood chip treatments can be explained by the WHC of those two materials. The peat achieved only about half of its leaching reduction capacity, probably due to hydrophobicity of the dry peat. Thereafter, the differences in leaching volumes between treatments decreased with each rain simulation event, and after the fourth simulation event there were no significant differences ($p = 0.340–0.481$) between treatments.

The concentration of P in leachate from the control soil was barely affected by the number of rainfall simulations, remaining at around 0.02 to 0.05 mg DRP L$^{-1}$ and 0.07 to 0.15 mg TP L$^{-1}$. In the manure-only column, simulated rainfall did not increase the leachate concentration of DRP and DOP initially, but it increased the leachate concentration of PP during the second simulation event (from 0.1 to 0.8 mg PP L$^{-1}$). During the last two rain simulation events, DRP and DOP were the main forms of P losses from the manure-only soil (Fig. 2). Concerning the organic amendments, addition of wood chips on top of the soil decreased the P concentration in leachate by almost half compared with the manure-only treatment. In contrast, both the peat and wheat straw treatments caused P concentration to peak in the leachate after the second rain simulation event. Phosphorus concentrations in the peat treatment were the highest after the third rain simulation event (18 mg DRP L$^{-1}$; 31 mg TP L$^{-1}$). Thereafter, P concentrations dropped again but remained higher than in the other treatments. The main form of P losses from the different treatments was DRP, not PP.

Total N concentrations in leachate from the manure-only column increased in the second rain simulation event, whereas the concentrations in leachate from soils with organic amendments and manure decreased. No changes occurred over time in the control treatment. The peat treatment effectively reduced the concentration of TN by almost half over the first three rain simulation events. After the fourth event, the concentrations of TN dropped in all treatments (40–110 mg TN L$^{-1}$) compared with after the first event (220–500 mg TN L$^{-1}$). This significant decrease in N leaching may be explained by N immobilization within the amendments.

![Fig. 1. Phosphorus sorption isotherms for organic materials (peat, wheat straw, and wood chips). Data were plotted with piece-wise nonlinear regression using Sigma Plot 11. The minus sign in the y-axis represents more release of P than bindings.](image-url)
Fig. 2. Parameters measured in leachate. (a) Volume of leachate. (b) pH. (c) Concentration of dissolved reactive phosphorus (DRP). (d) Particulate P (PP). (e) Dissolved organic P (DOP). (f) Total P (TP). (g) Total organic C (TOC). (h) Total N (TN).
Concentrations of leached organic C were highest in the peat treatment (350 mg TOC L⁻¹) during the third rain simulation event, followed by the wheat straw treatment. Concentrations of TOC in leachate from the wood chip–treated columns were similar to those in the leachate from the manure-only columns but were significantly lower than in the leachate from the other organic amendment treatments. A notable finding was that TOC concentrations in the wood chip treatment did not increase until the fourth rain simulation event.

**Effect of Organic Amendments on Total Losses of P, N, and C from Manure-Treated Columns**

Total loads of P, N, and C from the soil columns were significantly affected by treatment (Table 3). The addition of manure increased the leachate loads about 85-fold for DRP and DOP, 34-fold for PP, and 59-fold for TP compared with the control soil. Adding peat or wheat straw with manure increased TP loads 34-fold for PP, and 59-fold for TP compared with the control. Losses of TOC increased 8 to 10-fold from the control soil treated with manure and peat, which reduced losses by 40% compared with the control. Losses of TOC increased ninefold through manure addition compared with soil only. Furthermore, loads of TOC increased about 10- to 12-fold from the peat or straw treatments but decreased significantly from the wood chip treatment (Table 3).

**Discussion**

Higher P leaching from soils after manure incorporation is common because animal manures (beef cattle, dairy cow, pig) have high concentrations of soluble P, ranging from 16 to 70% of TP (Barnett, 1994; Hubbard et al., 2004; Kleinman et al., 2005). The horse manure used in this study had a very high content of water–soluble P, amounting to 86% of TP. Therefore, high loads of P in leachate were expected. Some of the soluble P in manure may be retained in soil, and part may be lost through surface runoff and/or drainage water. In studies by Svanbäck et al. (2013), Liu et al. (2012), and Kleinman et al. (2009), high P leaching losses from soil after applications of cattle and pig manure were observed. Airaksinen et al. (2007), Närvänen et al. (2008), and Uusi-Kämppä et al. (2012) found high P losses from horse-grazed fields, derived from manure.

Due to their high water-retention capacity, the organic amendments tested here decreased leachate volume until they became saturated with water (after the third rain simulation event) (Fig. 2). However, there was no decrease in P or C losses from the peat and straw treatments despite less water being leached; the concentrations increased during the second and third leaching events. This indicates that the effect of initially lower leaching volumes was counteracted by higher concentrations over time. In contrast, lower TP and C losses in the wood chip treatment were the result of reduced water losses, as shown by the fact that concentrations did not change over the second and third leaching events. Nonetheless, the concentrations of P and C increased in the fourth, fifth, and sixth rain simulation events, as shown by the high concentrations of P and C from the manure-only columns (12.5 kg P ha⁻¹ from the wheat straw treatment on an areal basis (Table 3)). The main form of P losses from the treatments had no effect on total losses of N, except for the soil treated with manure and peat, which reduced losses by 40% compared with the control. Losses of TOC increased ninefold through manure addition compared with soil only. Furthermore, loads of TOC increased about 10- to 12-fold from the peat or straw treatments but decreased significantly from the wood chip treatment (Table 3).

<table>
<thead>
<tr>
<th>Forms of P†</th>
<th>Control</th>
<th>Soil and manure</th>
<th>Soil, peat, and manure</th>
<th>Soil, wheat straw, and manure</th>
<th>Soil, wood chips, and manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRP, kg ha⁻¹</td>
<td>0.03</td>
<td>2.17</td>
<td>8.28 (0)‡</td>
<td>7.68 (0)</td>
<td>0.40 (82)</td>
</tr>
<tr>
<td>Particulate P, kg ha⁻¹</td>
<td>0.04</td>
<td>1.53</td>
<td>2.40 (0)</td>
<td>2.42 (0)</td>
<td>0.46 (70)</td>
</tr>
<tr>
<td>DOP, kg ha⁻¹</td>
<td>0.01</td>
<td>1.24</td>
<td>4.45 (0)</td>
<td>2.41 (0)</td>
<td>0.62 (50)</td>
</tr>
<tr>
<td>Total P, kg ha⁻¹</td>
<td>0.08</td>
<td>4.94</td>
<td>15.1 (0)</td>
<td>12.5 (0)</td>
<td>1.48 (70)</td>
</tr>
<tr>
<td>Total N, kg ha⁻¹</td>
<td>130</td>
<td>130</td>
<td>77.5 (40)</td>
<td>118 (9)</td>
<td>134 (0)</td>
</tr>
<tr>
<td>TOC, kg ha⁻¹</td>
<td>16.0</td>
<td>155</td>
<td>211 (0)</td>
<td>188 (0)</td>
<td>93.0 (40)</td>
</tr>
</tbody>
</table>

† DOP, dissolved organic P; DRP, dissolved reactive P; TOC, total organic C.
‡ Values in parentheses show percentage change caused by treatment (positive value indicates an increase; negative value indicates a decrease).
fifth, and sixth rain simulation events, when leachate volumes from the wood chip treatment were similar to those from the soil treated with manure only. This indicates that reduced water flow was not the main mechanism behind the reduction in P and C losses from the wood chip treatment. It can be speculated that before water saturation, the wood chip material acted as a filter material for dissolved and particulate P and C.

In contrast, the reason for the higher P and C concentrations in leachate from peat and wheat straw treatments is not clear and needs further investigation. For example, the concentration of DRP in the wheat straw material was 6.17 mg P kg⁻¹ DM, and the addition of a 5-cm layer (dry bulk density 41 g L⁻¹) corresponded to only 0.35 mg DRP column⁻¹. However, P losses from manure plus wheat straw treatments amounted to 21.3 mg, compared with 6.01 mg in the manure-only treatment. Thus, the losses of P were much higher than the amount of P added with the straw. In addition, the peat material contained almost no DRP (below detection limit), but the losses still increased on addition to manure (Table 3).

The pH of the organic materials and/or in the leachate might be expected to explain the high P losses from the peat and wheat straw treatments. However, the pH of peat was acidic and that of wheat straw was alkaline, and thus the same mechanism could not have regulated P release to the leachate. In addition, the leachate pH was slightly acidic in all treatments, ranging from 5.3 to 6.2 (Fig. 2), which did not explain reduced P in one treatment and increased P in the other.

Leachate from the peat and wheat straw columns contained more soluble C than that from the wood chip treatment (Table 3), which may have induced high P leaching from the peat and wheat straw columns through several mechanisms. First, soluble organic anions could have formed complexes with soil cations and positively charged mineral surfaces, reducing the number of phosphate-binding sites and causing higher P losses. Second, high concentrations of organic anions in solution could have induced anionic competition, replacing P from the exchange sites (Hutchison and Hesterberg, 2004). High losses of DRP from the peat and wheat straw treatments indicate that these mechanisms may have been in operation. Øgaard (1996), Kpomblekou and Tabatabai (2003), and Guan et al. (2006) also observed a reduction in P retention through organic manure and compounds present in manure. Øgaard (1996) observed significantly lower P retention in soil amended with fresh manure (containing more low-molecular-weight organic acids) than with composted manure. Kpomblekou and Tabatabai (2003) observed higher concentrations of P in soil solution after adding low-molecular-weight organic acids (oxalic, tartaric, citric acid). Guan et al. (2006) measured reduced P binding on aluminum hydroxide due to the presence of humic acids in the solution. Furthermore, part of the soluble inorganic P in the manure could have formed complexes with soluble organic matter in the bedding material and would thus be unavailable to soil P-binding sites and lost as DOP and PP. A significant correlation between TOC and DOP (R² = 0.69; p < 0.001) and PP (R² = 0.92; p < 0.001) losses from the soil columns is an indication that this may have occurred (Fig. 3). Moreover, soluble C could have a priming effect on soil organic matter decomposition and mobilize and/or mineralize part of soil organic P and N, affecting leaching losses. However, the present experiment ran for only 2 wk, and greater losses were observed on the third and fourth day (during the second and third leaching event). Thus, biological influences on P, N, and C leaching losses from the soils can be assumed to be less important.

Limitations of this study are that (i) it was conducted in-house in a controlled environment receiving standard rainfall at set intervals and (ii) the duration was only 2 wk. Further research under field conditions may demonstrate how higher WHC or the P-retention capacity of wood chips can help reduce P losses in real conditions with fluctuating moisture and temperature and trampling by horses and the duration of the reduction effect.

Conclusions

The results showed that (i) wood chips effectively reduced P and C leaching losses (by 70 and 40%, respectively) but did not reduce N-leaching losses, (ii) peat only reduced N losses by 40% and increased P and C losses severalfold, and (iii) wheat straw was ineffective in reducing P, N, or C and actually increased leaching losses. Overall, wood chips were better than other two materials in reducing P (and C) leakage. Peat and wheat straw seem to be ineffective at reducing nutrient losses; these materials could be mixed with manure to increase P solubility in arable fields, reducing fertilizer P inputs.
Acknowledgments

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References


