

Nutrient Leaching from Soil Amended with Manure and Compost from Cattle Fed Diets Containing Wheat Dried Distillers' Grains with Solubles

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Abstract Livestock manure and compost are commonly used to supply nutrients for crops and improve soil quality. However, excess application may increase the risk of nutrient loss and eutrophication. We investigated the potential leaching losses of nitrogen (N), phosphorus (P), and non-purgeable organic carbon (NPOC) over 105 days in the laboratory. Soils were amended with four treatments: (1) manure (BM) and (2) compost (BC) from cattle fed a typical finishing diet, (3) manure (DDGSM), and (4) compost (DDGSC) from cattle fed diets containing 60 % wheat dried distillers' grains with solubles (DDGS) replacing barley grain. A non-amended control soil was included for comparison. Leachate samples were collected 0, 7, 21, 42, 70, and 105 days after amendment application. Amendment application significantly increased leaching loss of total nitrogen (TN), NO_3^- -N, NH_4^+ -N, total phosphorus (TP), ortho-P (PO_4^{3-} -P), and NPOC from soils by 2.2 to 154.8 times compared with the control. Regardless of whether DDGS was included in cattle diet, cumulative leaching losses of TN, NO_3^- -N, TP, and PO_4^{3-} -P were significantly higher, while NH_4^+ -N and NPOC were lower from compost-amended soil than manure-amended soil.

The proportion of cumulative N leaching losses relative to the total N applied was greater with DDGSM and DDGSC than BM and BC, while a greater proportion of total P was leached from DDGSM and DDGSC than BM. Based on the results, more attention should be paid to the potential risk of soil nutrient leaching posed after applying manure and compost, and the higher risk of N and P leaching losses from soil amended with DDGS manure and compost than manure from beef cattle fed typical finishing diets.

Keywords Nitrogen · Phosphorus · NPOC · Manure · Compost · DDGS

1 Introduction

Globally, eutrophication is a major problem in many freshwater and marine aquatic ecosystems owing to many different sources losing nutrients to water bodies (Parvage et al. 2015a). Agriculture is a dominant contributor of non-point source nitrogen (N) and phosphorus (P) losses, which are of utmost environmental concern because they accelerate eutrophication (USEPA 1996). Nutrient leaching from soils to surface and groundwater are affected by many factors such as weather conditions, soil texture and chemical properties, farm management practices, and fertilization (Tong et al. 1997; González et al. 2009). Substantial fertilizer application to farmland has led to increasing N and P leaching into groundwater. Protecting water quality while maintaining economically viable production systems is a major challenge facing the

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agricultural industry (Elmi et al. 2005). A clear understanding of the potential leaching risk of organic amendments is needed so that management practices can be modified to protect water quality.

Animal manure not only supplies nutrients to agricultural soils but also improves soil physical and biological properties while replenishing soil organic matter (Brady and Weil 2012). However, over-application of animal manure can increase the risk of water contamination due to nutrient leaching (Masaka et al. 2013), especially N and P (González et al. 2009; Aronsson et al. 2014; Parvage et al. 2015b). Composting is an alternative approach for manure management, which can stabilize C and N while increasing P concentrations (Deluca and Deluca 1997; Larney et al. 2006). Composting beef cattle manure reduced the available N concentration by 60 % compared with fresh manure while increasing available P by 283 % (Larney et al. 2006). Basso and Ritchie (2005) reported that compost application decreased nitrate leaching by 43 % compared with manure-amended soils. Although it is expected that composting manure should reduce N leaching losses, it is uncertain how diet modification may impact N and P leaching from manure and composted manure-amended soils.

Bio-energy initiatives have increased ethanol production in North America in the last 10 years, which has increased the use of dried distillers' grains with solubles (DDGS) as a livestock feed (Berger and Good 2007). As the principal by-product of ethanol production, DDGS contains 20 to 35 % crude protein and has energy values on par with or greater than corn and is thus being used to replace a portion of the grain in high energy ruminant diets (Klopfenstein et al. 2008). The N and P content of DDGS is approximately three times that of unprocessed grain (Spiehs et al. 2002). Hao et al. (2009) observed increases in water-soluble NH_4^+ and PO_4^{3-} content and NH_4^+/TN ratio in manure as the level of wheat DDGS in cattle diets increased. Application of manure or compost, from cattle fed DDGS, to cropland soils can supply more nutrients for crop growth (Benke et al. 2010), but it may also lead to greater nutrient leaching losses. Numerous studies have investigated the effects of manure and compost on soil nutrient leaching. However, nutrient leaching from soils amended with manure and composted manure from cattle fed DDGS is poorly understood.

A better understanding of how diet manipulation and manure management practices can affect nutrient leaching from soil is required to develop environmentally sound livestock management strategies. In this study, we

assessed the impact of DDGS in cattle diets on nutrient leaching from manure- and compost-amended soils during a 105-day laboratory leaching experiment. The objective was to quantify N, P, and non-purgeable organic carbon (NPOC) leaching dynamics from soils amended with manure and composted manure from cattle fed contrasting diets to determine how diet type and manure management affect potential nutrient leaching losses.

2 Materials and Methods

2.1 Soil and Organic Amendments

Surface soil (0–15 cm) was collected near Lethbridge, Alberta, Canada (49°42'N, 112°47'W). The soil was a Dark Brown Chernozem (fine-loamy, mixed Typic Haploboroll) with 435 g kg⁻¹ sand, 271 g kg⁻¹ silt, and 294 g kg⁻¹ clay. The site was cropped to wheat in the preceding growing season. After removal of the crop residue, one composite sample (50 kg) of the top 15 cm of the soil was collected. Roots and crop residues were removed by hand and the soil was left to air dry at room temperature. The soil was then ground to pass through a 2-mm sieve, thoroughly mixed and stored at room temperature (22 ± 1.6 °C) until the start of the experiment.

Four types of organic amendments produced at Lethbridge Research and Development Centre were used for the study: manure (BM) and compost (BC) from cattle fed a typical finishing diet (DM basis) containing 85 % barley grain, 10 % barley silage, and 5 % supplement, and manure (DDGSM) and compost (DDGSC) from cattle fed a diet containing 60 % wheat DDGS, 25 % barley grain, 10 % barley silage, and 5 % supplement. Both BM and DDGSM manure were collected from cattle feedlot pen on the same day when open compost windrows were constructed. The BM and DDGSM manure were composted for 99 days (Hao et al. 2011) and BC and DDGSC composts were collected on day 99 when the composting process terminated. Both manure and compost samples were freeze-dried, ground to pass through a 2-mm sieve, and thoroughly mixed before use. The main properties of the soil and organic amendments used in this study are given in Table 1.

2.2 Physical and Chemical Analysis

Soil and amendment pH were measured in 1:2 soil to water and 1:10 amendment to water (mass to volume) suspension

Table 1 Main chemical properties of soil and organic amendments used and the amended soil after amendment application and prior to first leaching event (mean ±sd)

Property	Organic amendment				Non-amended and amended soil				
	BM ^a	BC ^a	DDGSM ^b	DDGSC ^b	CK ^c	BM	BC	DDGSM	DDGSC
pH	8.0±0.0 a	8.0±0.0 a	7.6±0.0 b	7.2±0.0 c	6.6±0.0 d	6.8±0.0 a	6.8±0.0 a	6.9±0.0 a	6.5±0.0 c
Organic C (g kg ⁻¹)	434±2 a	407±6 b	391±22.0 b	353±5 c	27.6±1.3 d	78.7±2.6 a	56.4±1.5 c	76.8±3.3 ab	73.2±2.2 b
Total N (g kg ⁻¹)	16.7±0.3 c	18.0±0.6 b	13.7±0.3 d	23.6±0.4 a	2.8±0.1 c	4.8±0.2 b	4.3±0.3 b	4.4±0.3 b	5.6±0.4 a
C/N ratio	26.0±0.6 b	22.7±1.1 c	28.6±1.7 a	15.0±0.2 d	9.9±0.3 c	16.5±0.2 a	13.3±0.8 b	17.5±0.6 a	13.0±0.5 b
Total P (g kg ⁻¹)	5.2±0.3 c	5.8±0.3 c	8.8±0.1 b	13.7±0.5 a	0.7±0.0 d	1.3±0.1 c	1.4±0.2 c	1.9±0.2 b	2.8±0.4 a
C/P ratio	83.6±4.3 a	70.4±4.5 b	44.6±2.9 c	25.7±1.2 d	38.4±1.9 b	58.9±2.4 a	40.1±4.4 b	41.1±3.8 b	26.1±3.1 c
Soil test P (mg kg ⁻¹)	3305±164 d	4540±65 c	7347±485 b	10652±369 a	11±1 e	366±30 d	550±21 c	756±54 b	1061±129 a
PO ₄ ³⁻ -P ^d (mg kg ⁻¹)	1287±33 c	1056±39 d	2574±35 a	2443±101 b	1.6±0.2 d	59.0±1.3 c	55.6±3.0 c	251±18 b	287±5 a
NH ₄ ⁺ -N (mg kg ⁻¹)	391±6 b	160±9 c	1305±28 a	375±15 b	4.1±0.2 d	50.0±2.8 b	25.9±0.8 c	213±18 a	51.8±7.6 b
NO ₃ ⁻ -N (mg kg ⁻¹)	232±5 c	545±14 b	114±2 d	2641±111 a	13.9±0.2 d	43.7±1.5 c	92.9±4.7 b	25.5±0.5 cd	390±24 a
Available N ^e (mg kg ⁻¹)	623±6 c	705±21 c	1419±27 b	3016±124 a	18.0±0.4 e	93.6±3.9 d	119±5 c	239±17 b	441±18 a

Different letters following the mean values within each row indicate significant differences among the four organic amendments or non-amended and amended soils at $P < 0.05$

^a BM and BC represents manure and compost from cattle fed a typical finishing diet, respectively

^b DDGSM and DDGSC represents manure and compost from cattle fed a diet with DDGS added, respectively

^c Non-amended soil

^d Water soluble PO₄³⁻-P

^e Sum of NH₄⁺-N and NO₃⁻-N

using an Accumet AB pH meter (Fisher Scientific, Hampton, NH). Soil particle size distribution was analyzed by the hydrometer method after pre-treatment to remove soluble salts, organic matter, and carbonates. Soil moisture content at water holding capacity (WHC) was determined according to Fierer and Schimel (2002). The organic C (OC) and total N (TN) contents were determined by dry combustion with a Carlo Erba CNS analyzer (Carlo Erba Instruments, Milan, Italy). The inorganic C was removed with 6 mol L⁻¹ HCl prior to soil organic C determination. Nitrate and ammonium (NO₃⁻-N and NH₄⁺-N) concentrations were determined with a model AA3 auto-analyzer (Bran+Luebbe, Norderstedt, Germany) following extraction of 5-g soil samples or 0.5-g organic amendment with 2 mol L⁻¹ KCl (25 mL). Total P (TP) concentration was determined by a discrete analyzer (Easy-Chem Pro, Systea Analytical Technologies, Anagni, Italy) following H₂SO₄ and H₂O₂ digestion (Parkinson and Allen 1975). The soil test P (STP) was extracted using 2.5-g soil or 0.25-g amendment and 25 mL of 0.5 mol L⁻¹ NaHCO₃ while water-soluble PO₄³⁻-P was determined using 10-g soil or 2-g amendment and 20-mL ultra-pure water. The P concentration in the extracted solutions was determined with a discrete analyzer (Easy-Chem Pro, Systea Analytical Technologies, Anagni, Italy).

2.3 Leaching Experiment

All treatments were replicated three times, including soil samples receiving no amendment which served as the control (CK). Fifteen plastic syringes (60 mL) were prepared for the leaching experiment, with 5-g sand first placed into each syringe. After homogeneously mixing 3.33 g of each amendment with 20 g of air-dried soil, the mixture was transferred into the syringe above the sand. The amendment to soil ratio (1/6) used in our study was similar to the values (1/4 to 1/7) reported by Duong et al. (2013), who applied three composts to soil at 23–27 g moist (17–20 g dry) compost to 115 g soil. Ultra-pure water was added with a pipette to adjust soil column moisture to 90 % WHC on day 0. The one-leaching

volume was calculated as the difference in the amount of water held by soil at full saturation (100 % porosity) and at WHC, which were 12.5 mL for the CK soil column and 22.8 mL for the amended soil. Soil columns were incubated at room temperature (22 °C) for 105 days. On days 0, 7, and 21, one-leaching volume of ultra-pure water was added to each soil column and the leachate was collected. Another leaching volume was added and the second volume of leachate was collected. On days 70 and 105, there was only one-leaching volume addition and leachate collection. Additionally, 0.01 mol L⁻¹ CaCl₂ solution was used instead of ultra-pure water on day 42, 70, and 105 leaching events due to the slow rate of water percolation through the soil column observed during the leaching event on day 21.

During each leaching event, the total volume of leachate collected was measured and a sample was analyzed for pH, TN, TP, NH₄⁺-N, NO₃⁻-N, PO₄³⁻-P, and NPOC. Leachate pH was measured with an Accumet AB pH meter. The NH₄⁺-N, NO₃⁻-N, and PO₄³⁻-P were analyzed as described above. The TN and TP contents were determined by semi-automated colorimetry and spectrophotometer after digesting the samples with K₂SO₄-H₂SO₄ solution (USEPA 1993). The leachate NPOC concentration was measured with a Dohrmann DC-90 (Rosemont Analytical Inc., Santa Clara, CA).

2.4 Calculation of Nutrient Leaching Losses and Statistical Analysis

Nutrient released from soil was calculated using nutrient concentration in leachate and leachate volume, the leaching loss of each nutrient during each leaching event was the mean of three replicates. Cumulative loss of each nutrient from soil was calculated as the sum of nutrient losses from all leaching events over the 105 days. Additionally, the proportion of cumulative total N, total P, and NPOC leaching losses relative to total N, P, and C applied by the compost or the manure were calculated as follows:

$$(\text{Cumulative Leached } N_{\text{amend}} - \text{Cumulative Leached } N_{\text{CK}}) / (\text{Applied N}) \times 100$$

$$(\text{Cumulative Leached } P_{\text{amend}} - \text{Cumulative Leached } P_{\text{CK}}) / (\text{Applied P}) \times 100$$

$$(\text{Cumulative Leached NPOC}_{\text{amend}} - \text{Cumulative Leached NPOC}_{\text{CK}}) / (\text{Applied C}) \times 100$$

where Cumulative Leached N_{amend} , Cumulative Leached P_{amend} , and Cumulative Leached $NPOC_{amend}$ are the total N, total P, and NPOC leached from the amended soil (mg), respectively; Cumulative Leached N_{CK} , Cumulative Leached P_{CK} , and Cumulative leached $NPOC_{CK}$ are the total N, total P, and NPOC leached in the control (mg), respectively; and Applied N, Applied P, and Applied C are the total N, P, and C applied by the compost or the manure (mg), respectively.

Two-way ANOVAs were used to analyze the effects of management approach, diet type, and their interactions on nutrient leaching. The two-way ANOVAs for four of six measured parameters showed strongly significant interactions between management approach and diet type; thus, we conducted a one-way ANOVA. Treatment means were separated using Duncan's multiple range test. All statistical analyses were performed using the software SPSS 20.0.

3 Results

3.1 Cumulative Leaching Volume and pH

The total leaching volumes collected over the six leaching events were 106 ± 1.8 , 203 ± 2.4 , 209 ± 2.3 , 205 ± 0.9 , and 208 ± 2.4 mL, representing 84.8, 89.0, 91.7, 89.9, and 91.2 % of leaching water applied to the soil column for CK, BM, BC, DDGSM, and DDGSC treatments, respectively (Table 2). The lower volumes of leaching water added to CK and leachate collected from CK reflect the smaller one-leaching volume than the amended treatments.

For the first three leaching events, the leachate pH values of amended treatments were lower than those of the CK, while there were no differences among all

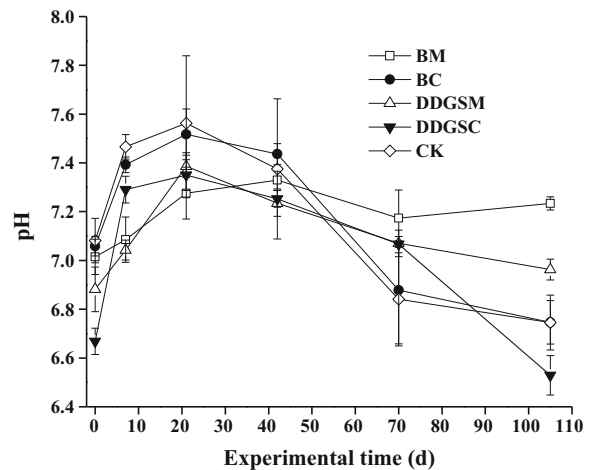


Fig. 1 Mean leachate pH during six leaching events over 105 days. Vertical error bars are the standard deviations of the mean ($n = 3$)

treatments for the rest of the leaching events (Fig. 1). The mean leachate pH initially increased, then peaked on day 21 for all treatments, except BM, which peaked on day 42, and gradually decreased thereafter.

3.2 Nitrogen Concentration in Leachate

During the six leaching events over the 105 days, the leachate TN and NO_3^- -N concentrations attained their highest values at the first leaching event and sharply decreased thereafter, remaining low for the rest of the leaching events (Fig. 2). The leachate NH_4^+ -N concentrations for BM and BC treatments initially increased, peaked at the second leaching event, and gradually decreased until the end. However, the temporal dynamics of leachate NH_4^+ -N concentrations for DDGSM and DDGSC treatments were similar to TN and NO_3^- -N. In

Table 2 Cumulative N, P, and NPOC leaching losses from six leaching events over 105 days (mean \pm sd)

Parameter	CK	BM	BC	DDGSM	DDGSC
Total N (mg)	0.5 \pm 0.1 d	3.5 \pm 0.1 c	3.9 \pm 0.2 c	5.6 \pm 0.2 b	11.2 \pm 0.6 a
NH_4^+ -N (mg)	0.01 \pm 0.0 d	0.5 \pm 0.1 c	0.4 \pm 0.1 c	1.8 \pm 0.1 a	1.0 \pm 0.1 b
NO_3^- -N (mg)	0.4 \pm 0.0 d	1.2 \pm 0.1 c	2.2 \pm 0.0 b	2.2 \pm 0.2 b	8.9 \pm 0.6 a
Total P (mg)	0.064 \pm 0.0 e	2.8 \pm 0.1 d	3.8 \pm 0.3 c	8.1 \pm 0.4 b	10.1 \pm 1.0 a
PO_4^{3-} -P (mg)	0.058 \pm 0.0 e	2.2 \pm 0.2 d	3.4 \pm 0.3 c	7.4 \pm 0.3 b	8.8 \pm 0.7 a
NPOC (mg)	1.8 \pm 0.1 c	24.6 \pm 2.0 a	17.3 \pm 0.7 b	24.3 \pm 0.9 a	22.9 \pm 0.8 a

Different letters following the mean values within each row indicate significant differences among the five treatments at $P < 0.05$

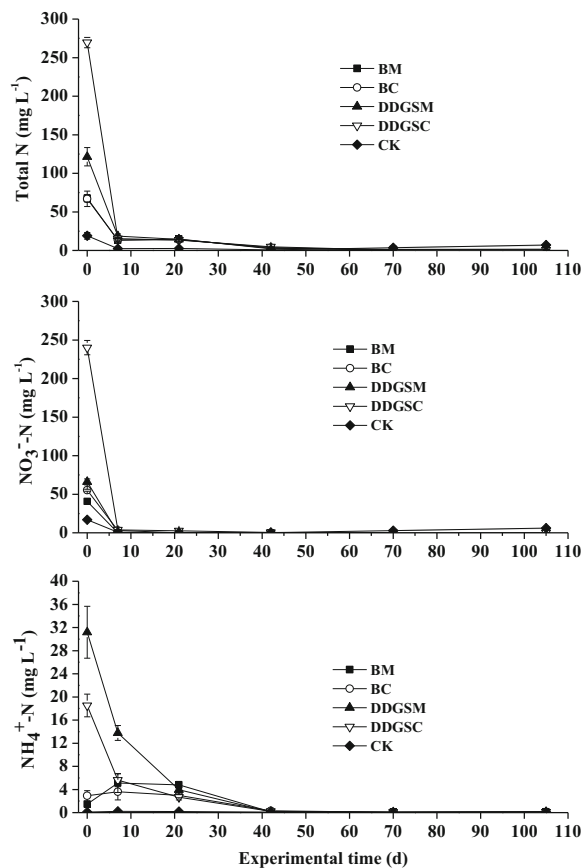


Fig. 2 Mean leachate total N, NO₃⁻-N, and NH₄⁺-N concentrations during six leaching events over 105 days. Vertical error bars are the standard deviations of the mean ($n = 3$)

general, application of organic amendments increased N leaching from soil.

The leachate TN and NH₄⁺-N concentrations for all amended treatments were significantly higher than the non-amended control during the first three leaching events, whereas no significant differences were detected during the later leaching events. In contrast, the NO₃⁻-N concentration was only significantly higher in the amended treatments than the control during the first leaching event. The leachate NO₃⁻-N concentration of the amended treatments in the first leaching event ranged from 40.6 to 240 mg L⁻¹, which were 2.4 to 14.2 times the values from the control (16.9 mg L⁻¹). In the first three leaching events, composted manure resulted in lower leachate NH₄⁺-N concentrations than the raw manure, especially for the first two leaching events for the composted manure with DDGS added to cattle diet. During the first two leaching events, regardless of whether manure or compost was applied, substituting

wheat DDGS for barley in the cattle diet significantly increased NH₄⁺-N concentration in the leachate. However, in the later leaching events, no diet type effect on the NH₄⁺-N concentration in leachate was observed regardless of whether manure or compost was applied.

3.3 Net Nitrogen Leaching Losses

The cumulative TN, NO₃⁻-N, and NH₄⁺-N leaching losses were affected by cattle diet type ($P < 0.001$) and manure management ($P < 0.001$) and their interaction ($P < 0.001$) (Table 4). The cumulative TN and NO₃⁻-N leaching losses were in the order of DDGSC > DDGSM > BC > BM > CK (Table 2), and the cumulative NH₄⁺-N leaching loss was in the order of DDGSM > DDGSC > BM > BC > CK. After the final leaching event on day 105, total N losses from amended soils ranged from 3.5 to 11.2 mg, NO₃⁻-N from 1.2 to 8.9 mg, and NH₄⁺-N from 0.4 to 1.8 mg, which were 5.6- to 20.2-, 2.2- to 22.4-, and 27.5- to 127-fold higher than the non-amended CK, respectively. The interactions were largely driven by the manure or compost containing DDGS. The DDGSC leached disproportionately greater total N and NO₃⁻-N compared with the BC treatment, while the DDGSM-treated soils leached disproportionately more NH₄⁺-N than the BM-treated soils.

Application of BC resulted in 1.1 and 1.8 times greater TN and NO₃⁻-N cumulative leaching losses than BM. The DDGSC treatment had 2.0 and 4.0 times the leaching losses of TN and NO₃⁻-N from the DDGSM treatment. No significant difference was detected between the NH₄⁺-N leaching losses of the BM and BC treatments, whereas application of DDGSC significantly decreased NH₄⁺-N leaching by 43.2 % compared with the DDGSM treatment. Furthermore, in comparison to manure or compost without DDGS, replacing barley with DDGS in the cattle diet significantly increased cumulative TN, NO₃⁻-N, and NH₄⁺-N losses.

Most leached N was present as NO₃⁻-N for the non-amended CK, as indicated by the 0.72 NO₃⁻-N/TN ratio. Application of organic amendments significantly decreased ($P < 0.05$) the NO₃⁻-N/TN ratio to 0.35, 0.40, and 0.57 for BM, DDGSM, and BC, respectively, but significantly increased ($P < 0.05$) it to 0.80 for DDGSC treatment. In contrast, the NH₄⁺-N/TN ratio in leachate significantly increased ($P < 0.05$) from 0.03 in CK to 0.09 to 0.32 in the amended treatments. There were significant positive correlations between TN and NO₃⁻-N cumulative leaching losses and the AN, TN,

and $\text{NH}_4^+\text{-N}$ content in non-amended and amended soil. The cumulative $\text{NH}_4^+\text{-N}$ losses were also positively correlated to the TN and AN content in the non-amended and amended soil (Table 5). The cumulative total N leaching loss from the amended soil accounted for 11.2 and 13.6 % of total N applied by DDGSM and DDGSC, which was significantly higher than the BM (5.3 %) and BC (5.6 %) (Table 3), with the diet type and management approach effects similar to that of the cumulative total N leaching loss.

3.4 Phosphorus Concentration in Leachate

Leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentrations in CK were all lower than 1 mg L^{-1} , and had no obvious fluctuation during six leaching events over the 105 days (Fig. 3). Organic amendments increased P leaching from soil, as indicated by the significantly higher ($P < 0.05$) leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentrations in amended treatments than the non-amended CK during the first four leaching events. The leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentrations in the amended treatments were 1.8- to 123- and 1.9- to 110-fold higher than the CK. However, leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentrations in the last two leaching events were lower than 0.6 mg L^{-1} and did not significantly differ among treatments. Over the 105 days, the leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentrations for BC, DDGSM, and DDGSC treatments peaked on day 0, and gradually decreased thereafter. The leachate $\text{PO}_4^{3-}\text{-P}$ concentration for the BM treatment peaked on the second leaching event on day 7, whereas TP concentration peaked in first leaching event on day 0 and decreased thereafter. In the first two leaching events, the manure management approach had a significant impact on P leaching when DDGS was added to the cattle diet, with the leachate TP and $\text{PO}_4^{3-}\text{-P}$ concentration in manure-amended soils consistently lower than compost-amended soil. The

Table 3 The proportion of cumulative total N, total P, and NPOC leaching losses to the total N, P, and C applied by manure and compost (mean \pm sd)

Parameter	BM	BC	DDGSM	DDGSC
Total N (%)	5.3 \pm 0.3 c	5.6 \pm 0.5 c	11.2 \pm 0.5 b	13.6 \pm 0.7 a
Total P (%)	15.7 \pm 0.9 c	19.4 \pm 1.7 b	27.5 \pm 1.3 a	21.8 \pm 2.2 b
NPOC (%)	1.6 \pm 0.1 a	1.2 \pm 0.1 b	1.7 \pm 0.2 a	1.8 \pm 0.1 a

Different letters following the mean values within each row indicate significant differences among the four amendment treatments at $P < 0.05$

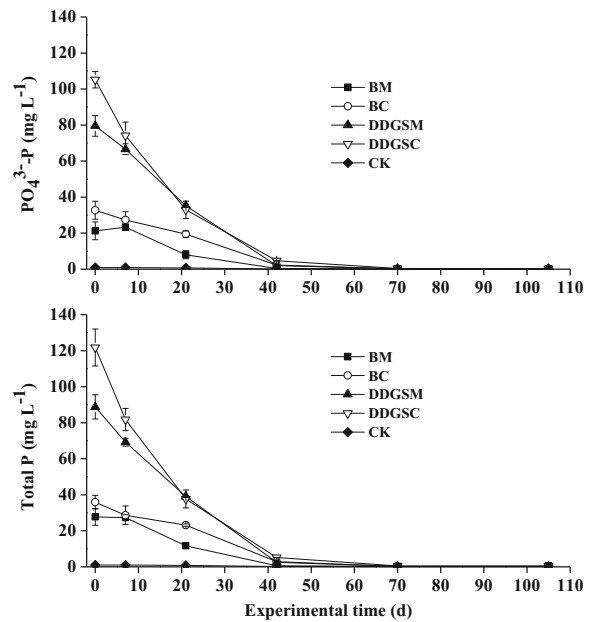


Fig. 3 Mean leachate total P and $\text{PO}_4^{3-}\text{-P}$ concentrations during six leaching events over 105 days. Vertical error bars are the standard deviations of the mean ($n = 3$)

impact was only significant in the first leaching event when the cattle were fed a typical finishing diet.

3.5 Net Phosphorus Leaching Losses

The cumulative TP and $\text{PO}_4^{3-}\text{-P}$ leaching losses were significantly affected by diet type and manure management approach, but not their interaction (Table 4). The cumulative leaching losses of TP and $\text{PO}_4^{3-}\text{-P}$ were ($P < 0.05$) in the order of DDGSC > DDGSM > BC > BM > CK (Table 2), which was similar to TN and $\text{NO}_3^-\text{-N}$. After the final leaching event, the total P losses from amended soils ranged from 2.8 to 10.1 mg and $\text{PO}_4^{3-}\text{-P}$ ranged from 2.2 to 8.8 mg, which were 42.1- to 155- and

Table 4 Analysis of variance (P values) of the effects of manure management approach (A), diet type (D), and their interactions ($A \times D$) on N, P, and NPOC leaching from soils

Parameter	A	D	$A \times D$
Total N	<0.001	<0.001	<0.001
$\text{NH}_4^+\text{-N}$	<0.001	<0.001	0.001
$\text{NO}_3^-\text{-N}$	<0.001	<0.001	<0.001
Total P	0.002	<0.001	0.185
$\text{PO}_4^{3-}\text{-P}$	0.001	<0.001	0.755
NPOC	<0.001	0.007	0.004

36.8- to 151-fold higher than the non-amended CK (Table 2).

Cumulative TP leaching losses from compost-amended soils (DDGSC, BC) were 1.2 and 1.4 times the TP losses from the manure-amended soils (DDGSM, BM). The cumulative PO_4^{3-} -P losses clearly depended on the management approach, with the total losses significantly greater from compost-amended than manure-amended soils. Diet type had a significant effect on P leaching loss; cumulative TP losses from DDGSM and DDGSC treatments were 2.9 and 3.4 times the BM and BC treatments, respectively. Cumulative PO_4^{3-} -P losses from DDGSM and DDGSC treatments were 2.9 and 2.6 times the BM and BC treatments, respectively. The cumulative leaching losses of PO_4^{3-} -P represented 78.8 to 91.9 % of TP. There were positive correlations (Table 5) between cumulative TP and PO_4^{3-} -P leaching losses and TP and PO_4^{3-} -P content in the non-amended and amended soil. The cumulative total P leaching loss from the amended soil accounted for 15.7, 19.4, 27.5, and 21.8 % of total P applied by BM, BC, DDGSM, and DDGSC, respectively (Table 3), indicating that including DDGS in the cattle diet instead of barley could promote P leaching.

3.6 Leachate Organic Carbon Concentration and Cumulative Leaching Losses

The leachate NPOC concentrations were highest in the first leaching event on day 0, then sharply decreased and reached their lowest values in the final leaching event on day 105 (Fig. 4). Application of organic amendments significantly increased leachate NPOC concentration compared with the non-amended CK. The largest

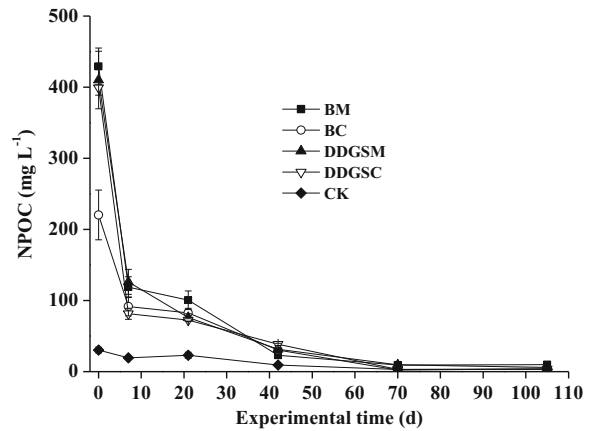


Fig. 4 Mean leachate NPOC concentration during six leaching events over 105 days. Vertical error bars are the standard deviations of the mean ($n = 3$)

increase occurred in the BM treatment on day 0, when the leachate NPOC concentration was 14.1 times the CK.

The cumulative NPOC leaching loss was affected by diet type ($P = 0.007$), manure management approach ($P < 0.001$), and their interaction ($P = 0.004$, Table 4). The cumulative NPOC leaching losses in amended treatments ranged from 17.3 to 24.6 mg, which corresponds to 9.9- to 14.1-fold the CK values. The cumulative NPOC leaching losses ($P < 0.05$) followed the order of $BM > DDGSM > DDGMC > BC > CK$. BM-amended soils had 42 % greater NPOC leaching losses than BC-amended soils, while DDGSM-amended soils had 6.1 % greater NPOC leaching losses than DDGSC-amended soils. The interaction between diet type and manure management was due to the significantly lower NPOC leaching losses from the BC-amended soils relative to the DDGSC-amended soils, whereas there was no significant difference between BM and DDGSM-

Table 5 Relations (Pearson correlation coefficients) of cumulative leaching losses of N, P, and NPOC to non-amended and amended soil properties ($n = 15$)

Leachate properties	Properties of non-amended soil and soil after amendment application prior to first leaching event								
	pH	OC	TN	NH_4^+ -N	NO_3^- -N	AN	TP	STP	PO_4^{3-} -P
TN	-0.40	0.63**	0.85**	0.27	0.89**	0.98**	0.95**	0.94**	0.89**
NH_4^+ -N	0.22	0.69**	0.49	0.93**	0.19	0.64**	0.61*	0.71**	0.86**
NO_3^- -N	-0.62*	0.41	0.75**	0.02	0.97**	0.94**	0.89**	0.85**	0.77**
TP	-0.18	0.68**	0.77**	0.57*	0.69**	0.95**	0.91**	0.97**	0.97**
PO_4^{3-} -P	-0.17	0.67**	0.74**	0.60*	0.67**	0.94**	0.90**	0.96**	0.98**
NPOC	0.39	0.98**	0.83**	0.56*	0.32	0.59*	0.64**	0.74**	0.64**

* Significant at $P < 0.05$; ** Significant at $P < 0.01$

amended soils. There were positive ($P < 0.05$) correlations between NPOC cumulative losses and the pH and OC content for the non-amended and amended soil (Table 5). The cumulative NPOC leaching loss from the amended soil only accounted for 1.2 % of total C applied by BC, which was significantly lower than from BM (1.6 %), DDGSM (1.7 %), and DDGSC (1.8 %) (Table 3). However, no significant differences were detected among BM, DDGSM and DDGSC.

4 Discussion

4.1 Leachate pH

The relatively lower leachate pH in the amended treatments than the non-amended CK for the first three leaching events can be partially attributed to nitrification of applied NH_4^+ . This was supported by the significant inverse correlation between leachate pH and NO_3^- -N concentration ($r = -0.38$, $P < 0.05$). Nitrification of NH_4^+ releases both NO_3^- and H^+ ions, leading to the observed decreased leachate pH and the inverse relation between leachate NO_3^- -N concentration and pH. In addition, the decomposition of manure and compost could release some dissolved organic acids (Hao et al. 2014), which could have also reduced the leachate pH for the first three leaching events.

4.2 Nitrogen Leaching

In the current study, the mean leachate TN and NO_3^- -N concentrations in the non-amended control in the first event were 19.0 and 16.9 mg L^{-1} , respectively, which were greater than the maximum permissible limit of 10 mg NO_3^- -N L^{-1} for safe drinking water (USEPA 1990) and the standard for NO_3^- in potable water (50 mg NO_3^- L^{-1}) of Europe (EEA 2000) and WHO (2004). Organic amendments increased NO_3^- -N and NH_4^+ -N concentrations in leachate, but more NO_3^- -N leached than NH_4^+ -N. Although the NH_4^+ -N content in BM and DDGSM was higher than NO_3^- -N (Table 1), the leachate NH_4^+ -N concentrations of these two treatments were lower than for NO_3^- -N. This is likely a reflection of the ammonia oxidation and nitrification reactions that occur when manure or compost containing NH_4^+ -N is applied to soil (Lang et al. 2016).

Application of BM and DDGSM increased NH_4^+ -N leaching loss by 25 and 76 % compared with BC- and

DDGSC-treated soils, respectively (Table 2). In this study, the cattle manure was left in the feedlot pens for an additional 45 days manure storage (between the end of the cattle feeding trial and the start of the composting experiment) during which time volatile loss of NH_3 was probably a major cause of N losses, consistent with the much lower water-extractable NH_4^+ and dissolved NH_3 at the start of composting than at the end of the feeding trial (Hao et al. 2009). On the other hand, BC and DDGSC increased TN and NO_3^- -N leaching losses by 12.1 to 297 % compared with BM and DDGSM. This was different from the results of Basso and Ritchie (2005), who reported that NO_3^- -N leaching loss from manure-amended soil was 1.7 times the compost-amended soil at the same N application rate. The significantly higher TN and NO_3^- -N content in compost-amended soil than the manure-amended soil contributed to the higher leaching losses. This is supported by the significant positive correlation between TN and NO_3^- -N contents in amended soil and the cumulative losses of TN and NO_3^- -N (Table 5). Similar to management approach, cattle diet type also affected N leaching. As reported by Canh et al. (1998), including DDGS in the cattle diet increased NH_4^+ -N content and the proportion of NH_4^+ -N to TN in the manure and compost, which corresponded to greater NH_4^+ -N leaching losses. The cumulative total N leached in the amended soil represented 5.3 to 13.6 % of total N in manure and compost added to soil (Table 3), close to the available N/TN values (3.7 to 12.8 %) in the four organic amendments we used. This was higher than the results of Parvage et al. (2015b), who reported 3.1 and 9.6 % of total N added with two levels of composted horse manure leached out of a loamy sand soil in Sweden. A higher proportion of N in applied DDGSM and DDGSC leached out of soil than from BM and BC, indicating that including DDGS in the cattle diet increased the risk of N leaching loss.

After the first three leaching events, the differences in leachate TN and NH_4^+ -N concentrations between the control treatment and those receiving organic amendments were generally small, whereas the NO_3^- -N concentration was only significantly higher in the amended treatments than the control during the first leaching event (Fig. 2). Organic amendments with a C/N ratio above 15 typically immobilize available N (Chadwick et al. 2000; Qian and Schoenau 2002; Webb et al. 2013), which may explain why there was limited leaching from the amended soils after day 21 as all amendments had C/N ratios between 15 and 29. Masaka et al. (2013) also

reported that application of cattle manure increased NO_3^- -N leaching loss from cultivated soil, and the lower quality manure with less N (C/N = 17.9) could reduce the risk of NO_3^- -N leaching compared with the higher N manure (C/N = 16.8).

4.3 Phosphorus Leaching

Our results indicate that the soil we used has the potential to lose significant concentrations of P to subsurface water. During the 105-day leaching, leachate PO_4^{3-} -P concentrations in the non-amended CK were higher than 0.05 mg L^{-1} , which is the maximum contaminant limit of PO_4^{3-} -P for surface water quality in the USA (USEPA 1992). Among all P fractions in soil, dissolved PO_4^{3-} has the greatest mobility (Lai 2014). In this study, PO_4^{3-} -P represented 78.8 to 91.9 % of cumulative TP leaching losses from the non-amended and amended soils, which was higher than the results reported by Liu et al. (2012) and Aronsson et al. (2014). This can be explained by the higher proportion of soluble PO_4^{3-} -P in the organic amendments applied in this study (Table 1).

The PO_4^{3-} supplied by manure and composted manure moved downward through the soil profile, thereby resulting in the increase of leachate PO_4^{3-} -P concentration (Fig. 3). Schelde et al. (2006) noted that leaching of P through the soil profile depends on the chemical (pH, organic matter, and P content) and physical soil properties (pore structure and bulk density), which influences the P species, solubility, and transport. The TP and PO_4^{3-} -P content of the four amendments we used were 7 to 19 and 647 to 1579 times the levels in the soil (Table 1), respectively, which was responsible for the significant difference in P concentration in leachates. On the other hand, a change in soil P sorption capacity after organic amendments are applied might play a crucial role determining the P leaching risk. Previous studies have shown that the sorption and transport characteristics of P in soil greatly affect P leaching (Liu et al. 2012; Andersson et al. 2013). A low P sorption capacity of soil can limit P retention in the soil matrix (Glæsner et al. 2011), and increase the risk of P leaching loss. In our study, application of organic amendments increased the organic matter content in soil because of the high organic C content in those amendments (Table 1). Soil organic matter could decrease phosphate adsorption by blocking the phosphate adsorption sites in soils (Moshi et al. 1974). For example, organic acids released by organic amendments compete with P for sorption sites, increasing the solubilization and

mobility of P compounds (Eghball et al. 1996). Although large P inputs can increase soil available P, they also increase the risk of P leaching losses in the long term. Balancing P input with harvested biomass P removal represents an effective management practice to maintain adequate soil P levels while limiting the risk of P loss.

Significant effects of management approach and diet type on P leaching from soil were observed (Table 4). Because compost had significantly higher TP content, it resulted in more TP leaching losses than manure (Table 2). Interestingly, even though the PO_4^{3-} -P content in compost with or without DDGS added to cattle diet was significantly lower than that of manure, compost still had increased PO_4^{3-} -P leaching losses. This might be related to the relatively lower C/P ratio of composted manures (Table 1), as organic materials with low C/P ratio release more soluble P through decomposition and mineralization processes (Gagnon and Simard 1999; Cooperband et al. 2002; Frossard et al. 2002). Nest et al. (2014) also reported that application of organic fertilizer with lower C/P resulted in more P leaching loss from a Belgian silt loam soil. Additionally, after 105 days leaching, 27.5 and 21.8 % of total P applied by DDGSM and DDGSC leached from soils, significantly higher than from BM and BC treatments (Table 3). This might be related to the higher STP/TP ratio in DDGSM and DDGSC (Table 1). Lower relative total P leaching losses were reported by Parvage et al. (2015b), who observed only 0.6 and 0.9 % of total P added with two levels of composted horse manure leached from a loamy sand soil in Sweden. The retention capacity of soil (Brady and Weil 2012) and available P content in organic amendments might explain the difference. Including DDGS in the cattle diet significantly increased TP and PO_4^{3-} -P leaching losses.

4.4 Organic Carbon Leaching

The mean leachate NPOC concentration in the control treatment ranged from 3.0 to 30.4 mg L^{-1} in the first three leaching events. Miller et al. (2013) reported a flow-weighted mean concentration for NPOC (18.9 mg L^{-1}) in effluent from non-amended soil in Alberta, which was within our range of values. The concentration and amount of NPOC leached from the soils were strongly affected by the application of organic amendments (Fig. 4, Table 2). Parvage et al. (2015b) also reported that applying composted horse manure significantly increased the leachate C concentration for

mineral soils. Kindler et al. (2011) noted that dissolved organic C (DOC) concentration and leaching loss depend to a large degree on sorption in subsoil. Because of their high organic C content, the organic amendments we used in this study significantly increased the soil organic C content (Table 1), which may coat soil particle surfaces and reduce the ability of soils to retain nutrient cations, thereby increasing leaching potential of DOC (Ashworth and Alloway 2004). Greater organic C in organic amendments corresponded to higher organic C losses during the 105-day leaching. This was supported by the significant positive correlation between cumulative NPOC leaching loss and soil organic C content (Table 5). However, only 1.2 to 1.8 % of total C applied by the manure and compost leached from soils (Table 3), indicating that a small proportion of applied C was susceptible to leaching. As DOC is one of the most active and mobile C pools (Jardine et al. 2006), it plays an important role in the cycling and distribution of nutrients and C both within and between ecosystems (Van Gaelen et al. 2014). Kindler et al. (2011) noted that C leaching from soils significantly affects estimates of the net ecosystem C balance of croplands. Furthermore, excess DOC leaching into water bodies may reduce drinking water quality because DOC reacts with chlorine to form disinfection by-products (Liang and Singer 2003). Further study is required to improve understanding of how DOC leaching from agricultural soils impacts water quality.

Application of manure and compost could improve soil fertility to provide more nutrients for crop growth. However, this benefit may be offset by leaching losses of N, P, and NPOC. Although our study was based on a laboratory investigation which is not a perfect representation of field conditions, our results should provide an assessment of the relative risk among the organic amendments tested. Further in situ field research needs to be conducted to confirm our results. Moreover, plants should be taken into account in the field investigation to better understand the nutrient balance in the total ecosystem.

5 Conclusions

Although our study was conducted in the laboratory, which does not precisely mimic field conditions, we were able to assess the relative leaching risk among the organic amendments tested. Management approach and diet type strongly affected the properties of cattle

manure and thereby the leaching of nutrients. Application of composted manure increased leaching losses of total N, total P, $\text{PO}_4^{3-}\text{-P}$, and $\text{NO}_3^-\text{-N}$ from soil and decreased leaching losses of $\text{NH}_4^+\text{-N}$ and NPOC. Replacing barley with DDGS in cattle diets significantly increased nutrient contents in manure and compost, and led to a higher proportion of total P leaching losses for the manure and a greater proportion of total N leaching losses for the compost. Although composting manure is used as a strategy to stabilize C and N, composted DDGS manure has a greater risk for N and P losses than manure from beef cattle fed a typical finishing diet.

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