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**Nitrous oxide and carbon dioxide emissions from soils
amended with compost and manure from cattle fed diets
containing wheat dried distillers' grains with solubles**

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Title: Nitrous oxide and carbon dioxide emissions from soils amended with compost and manure from cattle fed diets containing wheat dried distillers' grains with solubles

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Abstract: The N₂O and CO₂ emissions from soil amended with cattle manure and compost from animals fed a diet including wheat dried distillers' grains with solubles (DDGS) were evaluated in a 105-day aerobic incubation study in the laboratory. Manure (BM) and compost (BC) from cattle fed a typical finishing diet containing barley, and manure (DDGSM) and compost (DDGSC) from cattle fed a diet containing 60% wheat DDGS replacing barley grain were used. A non-amended control (soil without manure or compost) was included for comparison. Organic amendments significantly increased N₂O and CO₂ emissions compared with the control, and manure resulted in significantly higher CO₂ emissions than compost. Adding DDGS to cattle diet resulted in significantly higher N₂O emission amounts and emission factors from soil regardless of whether the amendment

was manure or compost, mainly due to increased $\text{NH}_4^+\text{-N}$ content. While N_2O emissions were lower in soil amended with DDGSC than DDGSM, there was no difference in N_2O emissions when soils amended with BM and BC. Our results suggest that across diet types and management approaches, application of compost from cattle fed a typical diet could be less detrimental to the environment with relatively lower emissions of CO_2 and N_2O .

Key words: Nitrous oxide; Carbon dioxide; Manure; Compost; DDGS.

Introduction

The increasing demand for renewable fuel in North America has resulted in a rapid increase in the production of ethanol (Renewable Fuels Association 2008). Dried distillers' grains with solubles (DDGS) is the principal by-product of ethanol production, as conversion of 1000 kg of corn into ethanol results in approximately 309 kg of DDGS dry matter (DM) (Renewable Fuels Association 2008). Because DDGS contains 20-35% crude protein and energy values on par with or greater than corn, it is being used to replace a portion of the grain in high energy ruminant diets (Klopfenstein et al. 2008). Rising grain prices are also contributing to this trend (Yacobucci and Schnepf 2007).

Adding DDGS to animal diets could potentially change the properties of manure and the resulting compost, such as their pH, N form and content, and C/N ratio (Yan et al. 2006; Maguire et al. 2007; Hao et al. 2009), and ultimately affect emissions of N_2O and CO_2 . For example, Hao et al. (2011) found that including wheat DDGS at 60% DM in cattle diets doubled the N_2O emission rate during composting due to the high water-extractable N content in DDGS manure, whereas CO_2 emission during composting was similar to that from cattle fed a typical

barley-based finishing diet. Hünerberg et al. (2014) used the Holos GHG model to simulate model farms and found that feeding DDGS resulted in higher emissions of N_2O and CO_2 compared to the control during the cattle life cycle, which includes enteric, manure storage, handling, and land application emissions. However, little information is available on N_2O and CO_2 emissions after soil is amended with manure and compost from cattle fed DDGS.

Most cattle manure in Canada is applied to land for crop or forage feed production, usually near the source feedlot operation due to high transportation cost. Storage and land application of untreated livestock manure increases health risks for both animals and people, returning pathogens to the soil, water and the air and also creating unpleasant odors. Composting is an alternative approach for cattle manure management, which can reduce pathogens (Burton and Turner 2003) and control the emissions of odorous compounds. Moreover, composting is favorable for organic matter (OM) stabilization, while improving handling of the product through safer storage and less costly transportation (Parkinson et al. 2004).

Composting can change manure properties (Gil et al. 2008), increasing pH and NO_3^- concentration while decreasing OM content, NH_4^+ -N concentration, and the C/N ratio. Moreover, labile C forms are promptly consumed during manure composting (Angnes et al. 2013), resulting in recalcitrant C-rich organic fertilizers. These property changes could impact C and N dynamics and potentially affect CO_2 and N_2O emissions from amended soils (Yoo and Kang 2012). Composting manure can significantly decrease N_2O and CO_2 emissions from soils compared to those amended with raw cattle manure (Marcato et al. 2009; Takakai et al. 2010; Zhu et al. 2014; Grave et al. 2015). However, Vallejo et al. (2006) found that applying composted manure increased N_2O emissions by 40% compared to untreated manure, while in another study there were no differences in CO_2 emissions between composted and raw manure amendments (Giacomini and Aita 2008). These conflicting research results indicate that further investigation is needed into how manure management approaches affect

N₂O and CO₂ emissions.

A better understanding of how diet type and manure management approach can affect N₂O and CO₂ emissions from organic amendment is needed in order to develop environmentally-sound livestock management strategies. In this study, we assessed the impact of DDGS in cattle diets on N₂O and CO₂ emissions from manure- and compost-amended soils during a 105-day incubation experiment. Our objectives were to (1) investigate changes in N₂O and CO₂ emissions from soil amended with manure compared with compost and (2) evaluate the effects of diet type on N₂O and CO₂ emissions from soil amended with feedlot cattle manure and compost.

Materials and methods

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 had been 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. Remaining 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 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 were composted for 99 days with manure samples (BM and DDGSM) collected on day 0 and compost

samples (BC and DDGSC) on day 99 from the compost trial reported by Hao et al. (2011). Both manure and compost samples were freeze-dried, ground to pass 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**.

Physical and chemical analysis

Soil and amendment pH was measured at 1:2 soil to water and 1:10 amendment to water (mass to volume) suspension using an Accumet AB pH meter (Fisher Scientific, Hampton, NH). Soil particle size distribution was analyzed by the pipette method after pre-treatment to remove soluble salts, organic matter, and carbonates (Gee and Bauder 1986). 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 techniques using a Carlo Erba CNS analyzer (Carlo Erba Instruments, Milan, Italy). The inorganic C was removed with 6 M HCl prior to soil organic C (SOC) determination. Available N (NO_3^- and NH_4^+) concentrations were determined using a model AA3 autoanalyzer (Bran+Luebbe, Norderstedt, Germany) following extraction of 5-g soil samples or 0.5-g organic amendment with 2 M KCl (25 mL).

Soil incubation

Each soil column was prepared by thoroughly mixing 20-g (dry weight basis) soil and 3.33-g amendment and placing the mixture into a 50-ml polyvinyl chloride tube. Soil columns were packed to a bulk density of 1.0 t m^{-3} . The amount of amendment added to soil was calculated to reflect a field incorporation rate of 160 Mg ha^{-1} into the top 10-cm soil layer, which is typical for barley forage production when organic amendments are applied once every three years. All treatments were replicated three times, including soil samples receiving no amendment which served as the control (CK). Deionized water was added evenly over the soil surface with a

mini-pipette to bring the moisture content to 60% WHC. Then soil columns were placed in 1-L wide mouth sealer jars covered with a piece of parafilm with five small pin holes punched to ensure gaseous exchange during the incubation. All of the jars were incubated at 22°C for 105 days. Each soil column at 60% WHC was weighed soon after setup and the water lost by evaporation was replaced weekly by adding deionized water using a mini-pipette to the pre-specified weight.

Gas samples for N₂O and CO₂ measurements were collected 1, 4, and 7 days after the start of incubation and at 7-day intervals thereafter. At each sampling date, the headspace of each jar was flushed with laboratory air to ensure N₂O and CO₂ were at ambient levels, and then sealed with an aluminum screw cap fitted with a rubber septum for 2 h. After 2 h, a 10-ml gas sample was collected from the headspace of each jar using a 10-ml gas-tight syringe (BD, Franklin Lakes, NJ, USA) and transferred to a pre-evacuated 5.9-ml Exetainer vial (Labco, High Wycombe, Buckinghamshire, England). Blank jars were included to correct for background (i.e., ambient) N₂O and CO₂ concentrations in laboratory air.

The concentrations of N₂O and CO₂ were determined with a 2-channel gas chromatograph (Varian 3800, Varian Inc., Palo Alto, USA) equipped with an electron capture detector, a flame ionization detector, and a thermal conductivity detector. One channel measured CO₂ after separation on a 2.0-m long Poropak QS column and the other measured N₂O following separation on a 2.0-m long Haysep D column. Injector and column temperatures were kept at 55 °C. Helium was used as the carrier gas for CO₂ while P10 gas (10% CH₄ and balance argon) was used as the carrier gas for N₂O. Analyses were calibrated ($0.99995 < R^2 < 0.99999$) against standards certified by the National Oceanic and Atmospheric Administration's Earth Systems Research Laboratory (Boulder, CO) and Linde Canada Ltd (Edmonton, AB). Background N₂O and CO₂ concentrations were subtracted from the measurements prior to data analysis.

Calculations and statistical analysis

Nitrous oxide and CO₂ flux (as µg N₂O-N kg⁻¹ h⁻¹ or mg CO₂-C kg⁻¹ h⁻¹) were calculated from their rates of accumulation in the headspace of each jar assuming a linear increase in gas concentration with time (Velthof et al. 2003). Cumulative N₂O and CO₂ emissions were calculated from the integrated flux over the incubation period.

The N₂O (*f*N₂O) and CO₂ (*f*CO₂) emission factors (EF), expressed in percentage of N or C applied in the amendments, were calculated as follows:

$$fN_2O = [(N_2O-N_{\text{treatment}}) - (N_2O-N_{\text{control}})] / [\text{applied N}] \times 100$$

$$fCO_2 = [(CO_2-C_{\text{treatment}}) - (CO_2-C_{\text{control}})] / [\text{applied C}] \times 100$$

where N₂O-N_{treatment} and CO₂-C_{treatment} are the cumulative emissions of N₂O and CO₂ from the amendment treatment (mg N kg⁻¹ or g C kg⁻¹), N₂O-N_{control} and CO₂-C_{control} are the cumulative emissions of N₂O and CO₂ from the control treatment (mg N kg⁻¹ or g C kg⁻¹), and applied N and C are the total amounts of N and C applied via amendment (mg N kg⁻¹ or g C kg⁻¹).

Two-way ANOVAs were used to analyze the effects of management approach, diet type, and their interactions on N₂O and CO₂ cumulative emissions. A one-way ANOVA analysis and Duncan's multiple range test were applied after testing for normal distribution to examine the statistical significance among cumulative emissions of N₂O and CO₂ in consideration of both management approach and diet type at α=0.05. Relationships between soil properties and N₂O and CO₂ cumulative emissions were examined using Spearman's rank correlation. All statistical calculations were performed using SPSS software (SPSS 22.0).

Results

Properties of amendments

The pH, OC, and C/N ratio of manure were higher than the compost, regardless of diet type, while the inverse was true for TN content (**Table 1**). For the two diet types, the pH and OC of organic amendments from barley-fed cattle were higher than those fed with 60% DDGS. The pH and OC was generally in the order of BM > BC > DDGSM > DDGSC. The manure NH_4^+ -N contents were higher than the compost, and the ranking was reversed for NO_3^- -N regardless of diet type. Adding DDGS in cattle diet increased NH_4^+ -N content in manure and compost by 2.34 and 1.34 times; it also increased NO_3^- -N content in compost by 3.86 times. However, the NO_3^- -N content in DDGSM was significantly lower than that in BM.

N₂O flux from soils

Generally, N₂O flux from soils attained its highest value on the first day of the incubation period, decreased over time, and reached the lowest values towards the end. The DDGSM treatment was an exception; it was characterized by an initial increase, peaking on day 4, followed by a decrease with time as observed for other treatments (**Fig. 1**). In general, all amended treatments had greater N₂O flux than the non-amended control, but the differences decreased with time. Most N₂O flux occurred during the first 7 weeks for all treatments, with flux less than 0.2 $\mu\text{g N kg}^{-1} \text{ h}^{-1}$ from week 8 to the end of incubation.

Diet type had a significant impact on N₂O flux, with the N₂O flux from the DDGSM treatment significantly greater than from the BM treatment for the first 6 weeks with minimal difference afterward. Compared to the BC treatment, N₂O flux from DDGSC was significantly greater at each sampling time for the first 7 weeks but no difference was found between these two treatments after 7 weeks. Applying compost (DDGSC) resulted in higher N₂O flux than manure (DDGSM) at the start of incubation, followed by the opposite pattern as incubation progressed. However, no difference in N₂O flux was found between manure (BM) and compost (BC).

N₂O cumulative emissions

Significant differences were observed in cumulative N₂O emissions among amended and non-amended soils (**Fig. 2A**). N₂O cumulative emissions from BM (0.99 mg N₂O-N kg⁻¹), DDGSM (4.41 mg N₂O-N kg⁻¹), BC (1.18 mg N₂O-N kg⁻¹), and DDGSC (2.22 mg N₂O-N kg⁻¹) were 9.0, 40.1, 10.7, and 20.1 times higher than the non-amended control (0.11 mg N₂O-N kg⁻¹), respectively. There were significant main and interaction effects of management approach, diet type, and their interactions on N₂O cumulative emissions (**Table 2** and **Fig. 2A**). The cumulative N₂O emissions from soil amended with manure and compost with DDGS in the cattle diet were significantly higher than those without. Application of DDGSM resulted in significantly higher N₂O emissions than DDGSC, whereas no difference was found between BM and BC. The cumulative N₂O emissions were positively correlated with soil NH₄⁺ content and to a lesser degree with AN content (**Table 3**). The N₂O emission factor during the 105-day period represented 0.032%, 0.189%, 0.036%, and 0.060% of TN supplied with the BM, DDGSM, BC, and DDGSC amendments, respectively (**Fig. 2B**), with the diet type and management approach effects similar to that of N₂O cumulative emissions.

CO₂ flux from soils

The CO₂ flux from the BM, DDGSM, and BC treatments peaked on day 4, and on day 7 for CK and DDGSC. From then on, flux in all treatments fluctuated but generally decreased (**Fig. 3**). Organic amendments promoted flux of CO₂, as indicated by the significantly higher CO₂ flux from manure- and compost-treated soils in comparison with the non-amended control. CO₂ flux from manure-treated soils was consistently significantly higher than with compost applications regardless of diet type. No diet type effect on CO₂ flux was observed regardless of manure or compost application.

CO₂ cumulative emissions

Organic amendments significantly increased CO₂ cumulative emissions (**Fig. 4A**). Compared with the non-amended control (1.26 g C kg⁻¹), CO₂ cumulative emissions from the BM (11.6 g C kg⁻¹), DDGSM (12.6 g C kg⁻¹), BC (5.38 g C kg⁻¹), and DDGSC treatments (4.96 g C kg⁻¹) were 9.21, 10.0, 4.27, and 3.94 times greater, respectively. The cumulative CO₂ emissions clearly depended on the management approach (**Table 2** and **Fig. 4A**), with the emissions from manure-treated soils significantly higher than those from compost-treated soils regardless of diet type. No significant main effect of diet type and interactions between management approach and diet type occurred for CO₂ cumulative emissions (**Table 2**). There were positive and statistically significant correlations between soil pH, OC, C/N, NH₄⁺-N, and cumulative CO₂ emissions (**Table 3**). The CO₂ emission factor was higher for manure application than compost, with 14.3% and 17.4% of the applied TC emitted as CO₂ from BM and DDGSM treatments, respectively. The values for BC and DDGSC treatments were 6.08% and 6.30%, respectively (**Fig. 4B**), with the difference not significant.

Discussion

Amendment properties

The significantly lower OC contents in BC and DDGSC compost than those of BM and DDGSM manure, respectively, were mainly due to C loss through organic matter decomposition during the composting process (Hao et al. 2011). The relatively lower compost C/N ratio compared to that of manure implies higher losses of C versus N during composting. Including DDGS in cattle diets leads to relatively lower OC contents in manure and compost, given that the C content in DDGS is lower than in unprocessed barley grain as fermentation basically removes starch (Spiehs et al. 2002). The respectively higher NH₄⁺-N in DDGSM and DDGSC than BM and BC reflects greater N excretion into manure originating from the DDGS diet (Hao et al. 2009). Most available N was

in the form of NH_4^+ -N for BM and DDGSM, consistent with results of Canh et al. (1998) who indicated that the proportion of NH_4^+ to AN in manure is generally higher with higher protein diets. The respectively lower pH in DDGSM and DDGSC relative to BM and BC could be due to a higher initial manure NH_4^+ -N content, given the release of H^+ ions as NH_4^+ -N is converted to NO_3^- through nitrification during storage or composting (Sánchez-Monedero et al. 2001). During composting, nitrification and denitrification may change soil NH_4^+ -N and NO_3^- -N content (Hao et al. 2009). Less NH_4^+ -N and more NO_3^- -N in compost relative to manure, regardless of diet type, indicates the rate of nitrification is greater than denitrification which leads to NO_3^- accumulation and greater observed NO_3^- content in compost than manure.

Nitrous oxide emissions

Our study was conducted under aerobic conditions which should favor nitrification. This was confirmed by positive correlations between the cumulative N_2O emission and soil NH_4^+ content. Following amendment application, a sharp peak in N_2O flux occurred during the first day (**Fig. 1**) as has been reported elsewhere (Chadwick et al. 2000; Yang et al. 2002). This indicates that nitrification commences shortly after amendment application, or the denitrification of soil NO_3^- was enhanced by the addition of easily degradable organic substrates. These N_2O flux levelled off by day 49, comparable to the 42-day period reported by Chiyoka et al. (2011) for laboratory incubation and Rochette et al. (2008) for field N_2O flux following fertilization. Therefore, the enhanced N_2O emissions triggered by manure, or compost derived C and N substrates are often short-lived (Rochette et al. 2008).

The positive correlation between N_2O emissions and NH_4^+ -N content (**Table 2**) observed in our study suggests that nitrification plays a major role in N_2O production under aerobic conditions. Our results were consistent with Cavalli et al. (2015) who also reported that N_2O emissions from nitrification increase with

NH_4^+ -N content. It has been reported that nitrogen content in DDGS is approximately three times that of unprocessed grain (Spiehs et al. 2002; Widyaratne and Zijlstra 2007), and adding DDGS to livestock diets could potentially increase the N excretion into manure (Maguire et al. 2007; Hao et al. 2009). In this study, adding DDGS to the cattle diet increased the NH_4^+ -N content in both manure and compost (**Table 1**), which is the main reason for greater N_2O emissions in DDGSM and DDGSC than the BM and BC treatments. The DDGSM amendment had the highest NH_4^+ -N among the four management and diet type combinations, and thus resulted in the highest N_2O emission.

The significantly lower N_2O emission from DDGSC than DDGSM treatment in our study was consistent with results of Takakai et al. (2010) and Zhu et al. (2014), who also reported lower N_2O emission in compost-amended than manure-amended soil. After composting, nitrification leads to a decrease in NH_4^+ -N and less available substrate for nitrification. In this study, the NH_4^+ -N content decreased from 1305 mg kg^{-1} in DDGS manure to 375 mg kg^{-1} in compost, thus contributing to the lower N_2O emission from the DDGSC treatment than DDGSM. However, no difference was found between the N_2O emissions from the BM and BC treatments, although there was significantly less NH_4^+ -N in BC than BM (**Table 1**). Other researchers reported greater N_2O emissions from composted than untreated pig slurry (Vallejo et al. 2006), which they attributed to less soluble C applied through compost. The greater available C content in manure promotes a higher biological O_2 demand (Rochette et al. 2000), which favors the reduction of N_2O to N_2 and leads to lower N_2O emissions relative to compost (Bhandral et al. 2007). During the 105-day incubation, both nitrification and denitrification processes could occur at 60% WHC condition and contribute to N_2O production; the significant relationship between N_2O emission and AN content in soil (**Table 3**) suggests the role of both processes in N_2O production in soil. During denitrification, the greater available C in BM might promote the consumption of N_2O and thus lead to comparable emissions of N_2O compared to BC. The underlying mechanisms should be further investigated.

The amount of N_2O emitted from N sources applied to soils (emission factor, EF), increased when adding DDGS to cattle diet regardless of manure management approach, resulting from the increased ratio of NH_4^+/TN in DDGSM and DDGSC relative to BM and BC, respectively. The EF values observed in our study (0.032 to 0.189%) were lower than those reported in the laboratory study of Zhu et al. (2014), who estimated the N_2O emission factors from cattle manure to be from 1.83 to 7.03% over a period of 100 days. Freeze-drying the organic amendment together with the relatively low soil water content in this study might contribute to these lower emissions. The soil moisture content in this study was 60% WHC, equivalent to soil water content of 16.8%, which is not favorable for the occurrence of denitrification. However, the gravimetric soil water content in Zhu et al. (2014) ranged from 24.2 to 30.0%, close to water saturation, which probably promoted the occurrence of denitrification and greater emission of N_2O , leading to the higher N_2O emission factor relative to our results. The EF measurements in this study were much lower than the IPCC (2013) default of 1% and differed between organic amendments with different diet type and management approach, indicating that it is inappropriate to use a single EF value for all types of organic fertilizer application at different environmental conditions. Velthof et al. (2003) also showed that under controlled laboratory conditions, N_2O emission differs among soil amended with animal manures on different diets or managed by different approaches. Thus, specific emission factors for various organic amendments at different application conditions are needed to improve the precision of the greenhouse gas inventories.

Carbon dioxide emissions

In the laboratory incubation, soil CO_2 emission was caused by microbial respiration and has been used as an important index for evaluating microbial activity (Janssens et al. 2001). In our study, CO_2 flux peaked on day 4 or 7 and then decreased gradually to the end due to the consumption of labile and readily mineralizable C pools.

In contrast, Chiyoka et al. (2011) indicated that CO₂ flux in soils was greatest soon after set-up and decreased to almost constant levels after the first week. This discrepancy may be due to residual effects of rewetting previously air-dried soil (Bertora et al. 2008). Microbial organisms are well adapted to surviving dry conditions and becoming active soon after soil rewetting (Davidson 1992). The delayed peak appearance in CK and DDGSC treatments might be due to the relative lower C contents relative to BM, DDGSM, and BC treatments (Table 1).

Cattle manure is capable of promoting the bioavailable pool of organic carbon (Triberti et al. 2008). In turn, this promotes CO₂ production from readily bioavailable organic carbon utilization by microbes (Iqbal et al. 2009). Non-amended soil had the lowest CO₂ flux and cumulative emissions because microbes need organic C for growth and energy (Flessa and Beese 2000; Rochette et al. 2008). Application of cattle manure or compost increased SOC contents by 1.02 to 1.93 times over the non-amended control, leading to high CO₂ flux and cumulative emissions from amended soils (Grave et al. 2015).

Management approach significantly affected CO₂ emission from soil (Fig. 4A), with the cumulative emissions in BC and DDGSC treatments reduced by 53.7% and 60.6% in comparison with BM and DDGSM treatments, respectively, similar to the results by Grave et al. (2015), who reported that the cumulative emissions of CO₂-C from compost was half of that from raw manure applications. They also noted that OC content and the C/N ratio should be considered when explaining the difference in CO₂ emissions from soils amended with different organic amendments. The higher amount of OC supports greater microbial activities and a higher C/N ratio is favorable for the mineralization of OC (Calderon et al. 2004). In this study, the relatively higher OC content and C/N ratio in BM than BC could contribute to the greater emissions of CO₂ from soil amended with BM. Similarly, the significantly higher OC content and C/N ratio in DDGSM resulted in significantly higher production of CO₂ in comparison with DDGSC amended soil. However, it is worth noting that emissions of CO₂

are also influenced by the nature and complexity of C compounds (Grave et al. 2015). Microbial respiration is mainly controlled by the supply of readily decomposable soil organic matter. The complete oxidation of labile C pools and progressive humification of the manure and sawdust mixture during the composting process results in a highly recalcitrant organic fertilizer (Angnes et al. 2013; Grave et al. 2015), which promotes lower CO₂-C emissions. The correlation analysis indicated that CO₂ emission was highly correlated with pH (**Table 3**). The solubility of SOC is pH-dependent and a significant increase in SOC has been reported when soil pH is raised by addition of amendments (Lambie et al. 2012; Curtin et al. 2016). This maybe another reason leading to the higher CO₂ emissions in DDGSM treatment relative to DDGSC treatment, as more C was available to the microbes.

The CO₂ emission factor ranged from 6.08 to 17.4% across different amendments, similar to the results of Zhu et al. (2014) who indicated that the carbon mineralization of raw manure and compost ranged from 7.62 to 59.0%. On average, 15.9% of the applied organic C was emitted as CO₂ from manure treated soils, while the proportion of C lost was 6.19% in case of compost application. This would mean that more C supplied with the compost was sequestered by the soil, while a larger part of C supplied with manure was lost.

Conclusions

Cattle diet and management approach strongly affect the properties of cattle manure and thereby the potential N₂O and CO₂ emissions. Composting manure significantly decreased soil CO₂ emissions due to the decreased OC content and C/N ratio, while diet type had no effect on soil CO₂ emissions after manure and compost application. Including wheat DDGS in cattle diets at 60% dry matter intake increased plant available N content, but resulted in an undesirable increase in N₂O emissions. This effect was more prominent for the manure from cattle fed with DDGS. Increased N₂O emissions resulted from the increased available NH₄⁺-N content. This

suggests that including DDGS in cattle diets could increase the nutrient value of manure and compost, so less commercial N fertilizer would be needed for crop production, but the higher available N in manure and compost could pose environmental concerns due to increased N₂O emissions after application to soil. Across the four combined treatments of diet type and management approach, application of compost from cattle fed with a typical diet may be more environmentally sound with relatively lower emissions of N₂O and CO₂. However, this study was case-specific and based on laboratory incubation, so caution should be exercised when extrapolating these results to field conditions. Emissions during composting and stockpiling also need to be taken into consideration.

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References

- Angnes, G., Nicoloso, R.S., da Silva, M.L.B., de Oliveira, P.A.V., Higarashi, M.M., Mezzari, M.P., and Miller, P.R.M. 2013. Correlating denitrifying catabolic genes with N₂O and N₂ emissions from swine slurry composting. *Bioresource Technol.* **140**: 368–375.
- Bertora, C., Alluvione, F., Zavattaro, L., van Groenigen, J.W., Velthof, G., and Grignani, C. 2008. Pig slurry treatment modifies slurry composition, N₂O, and CO₂ emissions after soil incorporation. *Soil Biol. Biochem.* **40**: 1999–2006.
- Bhandral, R., Bolan, N.S., Saggar, S., and Hedley, M. 2007. Nitrogen transformation and nitrous oxide emissions from various types of farm effluents. *Nutr. Cycl. Agroecosyst.* **79**: 193–208.

- Burton, C.H., and Turner, C. 2003. Manure Management. Treatment Strategies for Sustainable Agriculture. 2nd ed. Silsoe Research Institute, Wrest Park, Silsoe, Bedford, UK.
- Calderon, F.J., McCarty, G.W., Van Kessel, J.A.S., and Reeves, J.B. 2004. Carbon and nitrogen dynamics during incubation of manured soil. *Soil Sci. Soc. Am. J.* **68**: 1592–1599.
- Canh, T.T., Sutton, A.L., Aarnink, A.J.A., Verstegen, M.W.A., Schrama, J.W., and Bakker, G.C.M. 1998. Dietary carbohydrates alter the faecal composition and pH and the ammonia emission from slurry of growing pigs. *J. Anim. Sci.* **76**: 1887–1895.
- Cavalli, D., Consolati, G., Marino, P., and Bechini, L. 2015. Measurement and simulation of soluble, exchangeable, and non-exchangeable ammonium in three soils. *Geoderma* **259-260**: 116–125.
- Chadwick, D.R., John, F., Pain, B.F., Chambers, B.J., and Williams, J. 2000. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: a laboratory experiment. *J. Agric. Sci.* **134**: 159–168.
- Chiyoka, W.L., Hao, X., Zvomuya, F., and Li, X. 2011. Nitrous oxide emissions from Chernozemic soils amended with anaerobically digested beef cattle feedlot manure: A laboratory study. *Anim. Feed Sci. Tech.* **166-167**: 492–502.
- Curtin, D., Peterson, M.E., and Anderson, C.R. 2016. pH-dependence of organic matter solubility: Base type effects on dissolved organic C, N, P, and S in soils with contrasting mineralogy. *Geoderma* **271**: 161–172.
- Davidson, E.A. 1992. Sources of nitric oxide and nitrous oxide following wetting of dry soil. *Soil Sci. Soc. Am. J.* **56**: 95–102.
- Fierer, N., and Schimel, J.P. 2002. Effects of drying-rewetting frequency on soil carbon and nitrogen transformations. *Soil Biol. Biochem.* **34**: 777–787.
- Flessa, H., and Beese, F. 2000. Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. *J. Environ. Qual.* **29**: 262–268.

- Gee, G.W., and Bauder, J.W. 1986. Particle-size analysis. In: Klute A (Ed.) *Methods of Soil Analysis*. Part 1, physical and mineralogical methods, 2nd ed. Agronomy Monograph 9. Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, WI, USA, pp. 383–411.
- Giacomini, S.J., and Aita, C. 2008. Carbon dioxide emission after application of pig slurry and pig deep-litter. *Pesq. Agropec. Bras* **43**: 107–114.
- Gil, M.V., Carballo, M.T., and Calvo, L.F. 2008. Fertilization of maize with compost from cattle manure supplemented with additional mineral nutrients. *Waste Manage.* **28**: 1432–1440.
- Grave, R.A., da Silveira Nicoloso, R., Cassol, P.C., Aita, C., Corrêa, J.C., Costa, M.D., and Fritz, D.D. 2015. Short-term carbon dioxide emission under contrasting soil disturbance levels and organic amendments. *Soil Till. Res.* **146**: 184–192.
- Hao, X., Benke, M.B., Gibb, D., Stronks, A., Travis, G., and McAllister, T.A. 2009. Effects of dried distillers' grains with solubles (wheat-based) in feedlot cattle diets on feces and manure composition. *J. Environ. Qual.* **38**: 1709–1718.
- Hao, X., Benke, M.B., Larney, F.J., and McAllister, T.A. 2011. Greenhouse gas emissions when composting manure from cattle fed wheat dried distillers' grains with solubles. *Nutr. Cycl. Agroecosyst.* **89**: 105–114.
- Hünerberg, M., Little, S.M., Beauchemin, K.A., McGinn, S.M., O'Connor, D., Okine, E.K., Harstad, O.M., Kröbel, R., and McAllister, T.A. 2014. Feeding high concentrations of corn dried distillers' grains decreases methane, but increases nitrous oxide emissions from beef cattle production. *Agr. Syst.* **127**: 19–27.
- Intergovernmental Panel on Climate (IPCC). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. eds). Cambridge University Press, Cambridge, UK and New York,

USA.

Iqbal, J., Hu, R.G., Lin, S., Hatano, R., Feng, M.L., Lu, L., Ahamadou, B., and Du, L.J. 2009. CO₂ emission in a subtropical red paddy soil (Ultisol) as affected by straw and N-fertilizer applications: A case study in Southern China. *Agr. Ecosyst. Environ.* **131**: 292–302.

Janssens, I.A., Lankreijer, H., Matteucci, G., et al. 2001 Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. *Global Chang Biol.* **7**: 269–278.

Klopfenstein, T.J., Erikson, G.E., and Bremer, V.R. 2008. Board-invited review: use of distillers by-products in the beef cattle feeding industry. *J. Anim. Sci.* **86**: 1223–1231.

Lambie, S.M., Schipper, L.A., Balks, M.R., and Baisden, W.T. 2012. Solubilisation of soil carbon following treatment with cow urine under laboratory conditions. *Soil Res.* **50(4)**: 320–327.

Maguire, R.O., Crouse, D.A., and Hodges, S.C. 2007. Diet modification to reduce phosphorus surpluses: a mass balance approach. *J. Environ. Qual.* **36**: 1235–1240.

Marcato, C.E., Mohtar, R., Revel, J.C., Pouech, P., Hafidi, M., and Guiresse, M. 2009. Impact of anaerobic digestion on organic matter quality in pig slurry. *Int. Biodeter. Biodegr.* **63**: 260–266.

Parkinson, R., Gibbs, P., Burchett, S., and Misselbrook, T. 2004. Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. *Bioresource Technol.* **91**: 171–178.

Renewable Fuels Association. 2008. Feeding the Future: The Role of the U.S. Ethanol Industry in Food and Feed Production. Washington, DC, USA. Available at http://www.ethanolrfa.org/wp-content/uploads/2015/09/feed_co-products.pdf.

Rochette, P., Angers, D.A., Chantigny, M.H., Gagnon, B., and Bertrand, N. 2008. N₂O flux in soils of contrasting textures fertilized with liquid and solid dairy cattle manures. *Can. J. Soil. Sci.* **88**: 175–187.

- Rochette, P., van Bochove, E., Prévost, D., Angers, D.A., Côté, D., and Bertrand, N. 2000. Soil carbon and nitrogen dynamics following application of pig slurry for the 19th consecutive year. II. Nitrous oxide flux and mineral nitrogen. *Soil Sci. Soc. Am. J.* **64**: 1396–1403.
- Sánchez-Monedero, M.A., Roig, A., Paredes, C., and Bernal, M.P. 2001. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC, and maturity of the composting mixtures. *Bioresource Technol.* **78**: 301–308.
- Spiehs, M.J., Whitney, M.H., and Shurson, G.C. 2002. Nutrient database for distillers dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. *J. Anim. Sci.* **80**: 2639–2645.
- Takakai, F., Takeda, M., Kon, K., Inoue, K., Nakagawa, S., Sasaki, K., Chida, A., Sekiguchi, K., Takahashi, T., Sato, T., and Kaneta, Y. 2010. Effects of preceding compost application on the nitrogen budget in an upland soybean field converted from a rice paddy field on gray lowland soil in Akita, Japan. *Soil Sci. Plant Nutr.* **56**: 760–772.
- Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G., and Toderi, G. 2008. Can mineral and organic fertilization help sequester carbon dioxide in cropland? *Eur. J. Agron.* **29**: 13–20.
- Vallejo, A., Skiba, U.M., García-Torres, L., Arce, A., López-Fernández, S., and Sánchez-Martín, L. 2006. Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. *Soil Biol. Biochem.* **38**: 2782–2793.
- Velthof, G.L., Kuikman, P.J., and Oenema, O. 2003. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biol. Fertil. Soils* **37**: 221–230.
- Widaratne, G.P., and Zijlstra, R.T. 2007. Nutritional value of wheat and corn distillers' dried grains with solubles; digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. *Can. J. Anim. Sci.* **87**: 103–114.

- Yacobucci, B.D., and Schnepf, R. 2007. Ethanol and biofuels: Agriculture, infrastructure, and market constraints related to expanded production. CRS Report for Congress RL33928. Available at <http://www.ncseonline.org/NLE/CRSreports/07Apr/RL33928.pdf> (verified 3 Apr. 2009). Congressional Res. Serv., Washington, DC.
- Yan, T., Frost, J.P., Agnew, R.E., Binnie, R.C., and Mayne, C.S. 2006. Relationships among manure nitrogen output and dietary and animal factors in lactating dairy cows. *J. Dairy Sci.* **89**: 3981–3991.
- Yang, X.M., Drury, C.F., Reynolds, W.D., McKenney, D.J., Tan, C.S., Zhang, T.Q., and Fleming, R.J. 2002. Influence of composts and liquid pig manure on CO₂ and N₂O emissions from a clay loam soil. *Can. J. Soil Sci.* **82**: 395–401.
- Yoo, G., and Kang, H. 2012. Effects of biochar addition on greenhouse Gas emissions and microbial responses in a short-term laboratory experiment. *J. Environ. Qual.* **41**: 1193–1202.
- Zhu, K., Christel, W., Bruun, S., and Jensen, L.S. 2014. The different effects of applying fresh, composted or charred manure on soil N₂O emissions. *Soil Biol. Biochem.* **74**: 61–69.

Table 1. Main chemical properties of soil and organic amendments used in the incubation experiment

(means±sd).

Property	Soil	BM	DDGSM	BC	DDGSC
pH	6.58±0.06	8.03±0.02	7.56±0.01	8.02±0.04	7.19±0.04
Organic C (g kg ⁻¹)	27.6±1.33	434±2.4	391±22.3	407±5.8	353±4.7
Total N (g kg ⁻¹)	2.78±0.12	16.7±0.28	13.7±0.28	18.0±0.64	23.6±0.43
C/N ratio	9.93±0.28	26.0±0.59	28.6±1.66	22.7±1.06	15.0±0.24
NH ₄ ⁺ -N (mg kg ⁻¹)	4.13±0.22	391±6.0	1305±28	160±9.0	375±15.2
NO ₃ ⁻ -N (mg kg ⁻¹)	13.9±0.21	232±5.1	114±1.5	545±13.5	2641±111
Available N ^a (mg kg ⁻¹)	18.0±0.43	623±5.8	1419±27	705±20.5	3016±124

^a sum of NH₄⁺-N and NO₃⁻-N.

Table 2. Results of two-way ANOVAs (*P* values) testing the effects of management approach (A), diet type (D), and their interactions (A×D) on N₂O and CO₂ cumulative emissions from soils.

Source of variation	A	D	A×D
N ₂ O emissions	<0.05	<0.001	<0.05
CO ₂ emissions	<0.001	0.659	0.275

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Table 3. Relations (Pearson correlation coefficients) of cumulative N₂O and CO₂ emissions to non-amended and amended soil properties ($n=15$).

Properties of non-amended soil and soil after amendment application and prior to incubation							
Variable	pH	OC	TN	C/N	NH ₄ ⁺ -N	NO ₃ ⁻ -N	AN
N ₂ O	0.279	0.508	0.407	0.498	0.905**	0.113	0.563*
CO ₂	0.747**	0.816**	0.413	0.952**	0.738**	- 0.251	0.132

*, Significant at $P < 0.05$.

**, Significant at $P < 0.01$.

Fig. 1. N₂O flux during incubation as affected by management approach and diet type. *CK*, non-amended soil; *BM* and *BC*, manure and compost from cattle fed a typical finishing diet; *DDGSM* and *DDGSC*, manure and compost from cattle fed a diet containing 60% wheat DDGS replacing barley grain. *Vertical bars* indicate standard deviations of the means ($n=3$).

Fig. 2. N₂O cumulative emissions (A) and N₂O emission factor (B) during 105-day incubation as affected by management approach and diet type. *CK*, non-amended soil; *BM* and *BC*, manure and compost from cattle fed a typical finishing diet; *DDGSM* and *DDGSC*, manure and compost from cattle fed a diet containing 60% wheat DDGS replacing barley grain. Different letters indicate significant differences across all treatment combinations at $P < 0.05$. Vertical bars are standard deviations of the means ($n=3$).

Fig. 3. CO₂ flux during incubation as affected by management approach and diet type. *CK*, non-amended soil; *BM* and *BC*, manure and compost from cattle fed a typical finishing diet; *DDGSM* and *DDGSC*, manure and compost from cattle fed a diet containing 60% wheat DDGS replacing barley grain. Vertical bars indicate standard deviations of the means ($n=3$).

Fig. 4. CO₂ cumulative emissions (A) and CO₂ emission factor (B) during 105-day incubation as affected by management approach and diet type. *CK*, non-amended soil; *BM* and *BC*, manure and compost from cattle fed a typical finishing diet; *DDGSM* and *DDGSC*, manure and compost from cattle fed a diet containing 60% wheat DDGS replacing barley grain. Different letters indicate significant differences across all treatment combinations at $P < 0.05$. Vertical bars are standard deviations of the means ($n=3$).