Front. Environ. Sci. Eng. 2017, 11(3): 15
DOI 10.1007/s11783-017-0955-1

RESEARCH ARTICLE

Greenhouse gas emissions during co-composting of cattle feedlot manure with construction and demolition (C&D) waste

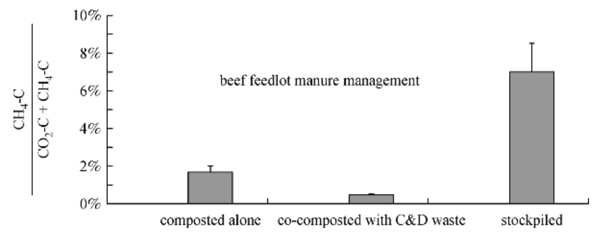
Xiying Hao (✉), Francis J. Larney

Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, Alberta T1J 4B1, Canada

HIGHLIGHTS

- Co-composted cattle manure and construction & demolition (C&D) waste.
- Studied two types of cattle manure, from typical vs. dried distillers' grain with solubles (DDGS) diets.
- C&D waste reduces CH_4 emission from cattle manure composting.
- Cattle manure composting emits lower CH_4 than stockpiling.
- No difference in GHG emissions between types of cattle manure.

GRAPHIC ABSTRACT



ABSTRACT

Manure management strategies should reflect current animal feeding practices and encourage recycling of organic waste to help protect our environment. This research investigated greenhouse gas (GHG) emissions during cattle manure stockpiling or composting with and without construction and demolition (C&D) waste. Manure was collected from cattle fed a typical finishing diet (CK manure) and from cattle on diets which included 30% dried distillers grains with solubles (DG manure). The CK and DG manures were co-composted with (4:1) C&D waste (treatments: CK_CD, DG_CD), composted alone (treatments: CK and DG) in 13 m^3 bins or stockpiled without C&D waste (treatments: CK_ST and DG_ST) for 99 days. Manure type (CK vs. DG manure) had no effect on GHG emissions over the 99 day manure composting or stockpiling. Composting with C&D waste produced similar CO_2 emissions, about double that from manure stockpiling (7.0 $kgC \cdot m^{-2}$). In contrast, CH_4 emissions were reduced by the inclusion of C&D waste (64 $gC \cdot m^{-2}$ with C&D vs. 244 $gC \cdot m^{-2}$ without C&D) while the manure stockpile emitted the greatest amount of CH_4 (464 $gC \cdot m^{-2}$). Additionally, only 0.48% of C was emitted in CH_4 form with C&D waste, compared to 1.68% when composting without C&D waste and 7.00% when cattle manure was stockpiled. The N_2O emissions (12.4 to 18.0 $gN \cdot m^{-2}$) were similar across all treatments. The lower CH_4 emissions with C&D waste are beneficial in reducing overall GHG emissions from manure composting, while reducing the amount of material entering landfills.

ARTICLE INFO

Article history:
Received 12 October 2016
Revised 1 March 2017
Accepted 30 April 2017
Available online 30 May 2017

Keywords:
Livestock manure
greenhouse gas flux
straw bale compost bin
N_2O
CH_4
CO_2

1 Introduction

In 2006, 180 million Mg of manure were produced annually by Canadian livestock [1] and manure management emitted 8 Mt CO_2 equivalents, accounting for 17% of total agriculture sector emissions and 1.1% of the total 2014 Canadian inventory [2]. According to Statistics Canada [3], about 16% of Canadian farms reported using composting as one of their livestock manure management strategies in order to reduce total weight and volume, weed seed viability and odour during field application [4,5]. However, increased CH_4 and N_2O emissions have been

✉ Corresponding author
E-mail: xiying.hao@agr.gc.ca

*Special Issue—Livestock Waste Management and Resource Recovery (Responsible Editors: Xinmin Zhan & Liwen Xiao) reported during livestock manure composting [6,7]. For the United States, manure also contributed 1.1% of the total CO_2 equiralents USA 2014 inventory [8].

Dried distillers grains with solubles (DDGS), an ethanol energy industry co-product, is increasingly used in livestock diets. Replacing 40% of barley (*Hordeum vulgare* L.) grain with corn (*Zea mays* L.)-based DDGS reduced enteric CH_4 emissions while replacing 40% of barley grain with wheat (*Triticum aestivum* L.)-based DDGS had no effect [9,10]. The reduction with corn-based DDGS was mainly due to its higher level of fat than wheat DDGS. Manure and compost from cattle on DDGS diets has been reported to have higher nitrogen (N), phosphorus (P) and soluble salt content [11,12].

Using life cycle assessment techniques, feeding cattle either corn- or wheat-based DDGS at 40% of dietary dry matter (DM) is estimated to increase both total (in CO_2 equivalent) GHG emissions and their intensity compared to the baseline scenario [13]. This increase is mainly attributed to estimated higher emissions of N_2O from manure as cattle N excretion increases. Increased N_2O, but not CO_2 and CH_4, emissions during cattle manure composting have been reported when replacing 60% barley grain with wheat-based DDGS [14]. However, there were no differences in CO_2, CH_4 and N_2O emissions when composting manure from cattle on diets with or without corn-based DDGS replacing 40% barley grain [12].

Landfills accounted for approximately 25.7% of total US anthropogenic methane (CH_4) emissions in 2014 [15] and 20% of Canadian CH_4 emissions [16]. As much as one-third of the 20 million tonnes of solid waste in municipal waste streams is generated by construction, renovation and demolition activities in Canada [17]; thus, any diversion of construction and demolition (C&D) waste, particularly lumber and drywall, can potentially reduce CH_4 emissions from landfills.

Recently in Alberta, Canada, C&D waste, particularly the wood and drywall fractions, has been diverted to replace cereal straw for bedding cattle feedlot pens in winter months or for co-composting with livestock manure. Composting various types of C&D wood waste with poultry manure and green waste produces compost which enhances plant growth [18]. Higher Ca levels in the final compost were reported after co-composting dairy manure with paper scraps from drywall production at a manure/paper ratio of 2.5:1 (fresh weight) [19]. Compost produced by adding drywall to biosolids or manure is a good soil amendment with no detrimental effects on vegetation when establishing native and non-native plant species on reclamation sites [20].

With the increased availability of DDGS as cattle feed and the need to recycle organic waste, particularly C&D waste, the possibility of co-composting C&D waste with cattle feedlot manure deserves to be studied. Therefore, the overall objectives of our research were to assess (1) the feasibility of co-composting cattle manure with C&D waste, (2) agronomic properties of the final compost and (3) greenhouse gas (GHG) emissions during C&D waste and cattle manure co-composting relative to the typical farm practice of manure stockpiling. Results for objectives (1) and (2) were published following completion of the experiment and we demonstrated that it is feasible to co-compost C&D waste with cattle feedlot manure and the resulting compost has higher sulfur (S) content that is beneficial to crops with high S requirements, such as canola (*Brassica napus* L.) [21]. We are now reporting the results for our third objective that compares GHG emissions during manure stockpiling and co-composting with C&D waste.

2 Materials and methods

2.1 Experiment design

The experimental site, design, materials used, compost temperature and properties were previously reported [21]. Briefly, the compost experiment was conducted from 8 Apr. to 16 July, 2013 (99 days) in a semiarid climate at the Agriculture and Agri-Food Canada (AAFC) Research and Development Centre in Lethbridge, AB, Canada, centered in the major beef production area in Canada. The weather data were downloaded from an AAFC weather station located < 500 m from the experimental site (Fig. 1). Temperature was more variable during the first 29 days (−5°C to 15°C), then increased over time and became less variable (Fig. 1). During the first two weeks, there was 25 mm precipitation in the form of snow, and 66 mm rain fell on Day 72.

Two types of beef feedlot manure were collected: (1) CK manure, from cattle fed a typical western Canada finishing diet containing 860 g rolled barley grain, 100 g barley silage, and 40 g supplement·kg^{-1} DM, and (2) DG manure, from cattle fed a diet similar to CK manure but with 300 g·kg^{-1} DM barley grain replaced by corn DDGS. The

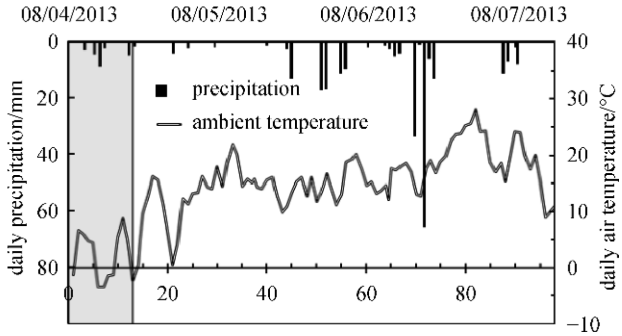


Fig. 1 Daily precipitation and ambient temperatures during the composting period (precipitation covered by shaded area from Day 0 to 14 was in the form of snow while the remaining compost period precipitation was in the form of rain)

C&D waste, supplied by Desviar (High River, AB), was mainly lumber and drywall wastage from new housing construction in southern Alberta, Canada which they chipped to < 5 cm for use in their composting operations. A truck load of the chipped C&D waste was delivered to our experimental site two weeks prior to the start of our compost experiment.

At the start of experiment, 13 m^3 compost bins, (each 2.50 m long by 2.22 m wide by 2.35 m high), were constructed by stacking rectangular-shaped cereal straw bales. Bales were used to construct relatively small bins to retain heat because limited DG manure was produced from the feeding trial. On composting Day 1 (8 and 9 Apr. 2013), the CK and DG manures were mixed with or without C&D waste (treatments: CK_CD, DG_CD, CK and DG) and randomly placed into the 13 m^3 bins with three replications per treatment. About 7028±17 kg (wet weight) of materials (averaging 1.75±0.04 m in height) were placed into each compost bin with a top surface area of 5.6 m^2. The manure to C&D waste ratio was 5:0 without (-) and 4:1 with (+) C&D addition. Compost materials were turned on Days 14, 37, and 64 with a front-end loader by flipping materials to adjacent empty bins. For comparison, both CK and DG manure (shaped in open windrow style) were also stockpiled (treatments CK_ST and DG_ST), each with three replications, for the same length of time as the composting treatments. The average manure stockpile windrow was about 4522±429 kg (wet weight), 1.8±0.1 m in height, and 8.4±0.8 m long, with an emitting surface area of 42.6±3.7 m^2.

2.2 Temperature monitoring

Compost temperatures in each compost bin were measured at 40, 70, and 100 cm below the compost surface by thermocouple sensors connected to a CR8 data logger (Campbell Scientific, Edmonton, Canada). The temperatures were recorded every 20 min and averaged to give mean hourly values. The temperature devices were installed on Days 0 and 1 (April 8 and 9, 2013), removed just before each turning, and reinstalled immediately thereafter. The hourly ambient temperature was also monitored over the experimental period. Temperatures were not monitored in the manure stockpiles (CK_ST, CK_DG).

2.3 Solid sample collection and analyses

Solid samples were collected at the start (Day 1), before each turning event (Days 14, 37, and 64), and at the end of the experiment (Day 99). For stockpiled manure, samples were collected only on Days 1 and 99. Compost and stockpiled manure samples (1 kg wet weight) were collected at 7, 20, 50, 90, and 140 cm below the compost surface. Samples from each depth were manually homogenized and divided into two portions for analysis.

For water-extractable C and N determination, methods similar to Hao et al. [7,12] were used. Briefly, 25 g samples (wet weight) were placed into 100 mL of deionized water, shaken for 15 min, and filtered (0.45 μm filter), with the supernatant solution used to determine the water-extractable organic C, water-extractable N, and NH_4^+concentrations. The water-extractable OC and N contents were measured with a Shimadzu TOC-Vcsh/TNM-1 analyzer (Shimadzu Corporation, Kyoto, Japan) and NH_4^+ with a Dionex ICS-1000/DX-600 (Dionex Corporation, Sunnyvale, California, USA). Water-extractable N includes both mineral and organic N that dissolves in water. For water-extractable NO_3 and SO_4 determination, 1 g of finely ground freeze-dried sample was placed into 25 mL of ultrapure water and shaken for 15 min. After filtering (0.45 μm filter), NO_3 and SO_4 concentrations in the supernatant solution were determined using a Dionex ICS-1000/DX-600. The moisture content was calculated using the weight difference before and after freeze drying.

2.4 Greenhouse gas emission determination

Greenhouse gas (GHG) surface fluxes were measured twice in the first week and weekly thereafter with a vented static chamber technique [6]. One static chamber was placed at the center of the top surface for each composting bin. Similarly, one chamber was also placed at the peak of each open windrow manure stockpile. Surface gas flux samples were collected 0, 5, 10, 20 and 30 min after chamber lid closure. Each gas sample was extracted with an air-tight syringe and injected into a 5.9 mL pre-evacuated, septum-sealed vial (Exetainer; Labco Limited, High Wycombe, Bucks., UK). Samples were analyzed for CO_2, CH_4 and N_2O contents using a gas chromatograph (Varian 3800; Varian Instruments, Walnut Creek, CA) equipped with an electron capture detector, flame ionization detector, thermal conductivity detector, and a micro-gas chromatograph (Varian 4900) equipped with an electron capture detector and thermal conductivity detector. The concentration versus time relationships for each GHG in each chamber were fitted with a second-order polynomial equation for each sampling time, and the flux at $t = 0$ was calculated by taking derivatives of the 2nd order polynomials [6]. Cumulative emissions were approximated by assuming that daily fluxes represented the average for each period. Cumulative GHG emissions over 99 days were expressed on both a per surface area and initial DM basis.

2.5 Data handling and statistical analysis

The mean daily temperature (Fig. 2) was calculated based on the hourly data previously reported by Hao et al. [21]. The weekly GHG surface fluxes were analyzed using Proc MIXED [22] with treatment (manure type and management strategies), sampling date, and treatment × sampling

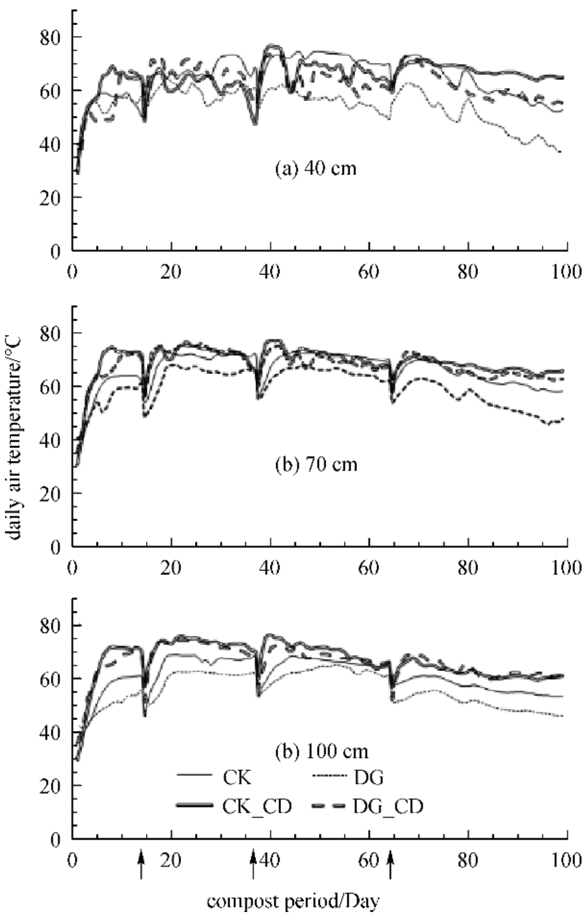


Fig. 2 Daily compost temperatures as affected by C&D waste addition. Arrows indicate dates (Day 14, 37 and 64) when compost was turned

date in the model as fixed effects and replicate × treatment as a random effect. Sampling date was treated as a repeated measure to account for potential correlations and different variances between phases. The cumulative GHG emissions over the 99 days were reported as per initial surface area, per initial total dry matter (DM) and per initial TC or TN amount. In addition, we also calculated the cumulative N_2O emissions per initial NH_4-N amount and the percentage of CH_4 in the total C emissions ($CO_2 + CH_4$) and CO_2-equivalent (CO_2-eq) emissions per unit weight manure composted ($kgCO_2\text{-eq}\cdot Mg^{-1}\cdot DM$) using global warming potentials of 26 for CH_4 and 298 for N_2O. The cumulative emissions, CH_4 percentage and CO_2-eq were analyzed using Proc MIXED with treatment in the model as a fixed effect. The UNIVARIATE procedure was used to check residuals for normality and potential outliers. When treatment effects were not significant, data were pooled and re-analyzed. When any of the fixed effects were significant ($P < 0.05$), means were compared using a protected LSD test ($P < 0.05$).

3 Results and discussion

3.1 Initial materials used for composting

As previously reported [21], the DG manure had higher water-extractable N, NH_4^+-N and SO_4-S contents but similar moisture content, pH, TC, TN, and C/N ratio (Table 1). The higher water-extractable N, NH_4-N and SO_4-S reflect the higher N and S content in DDGS compared to barley grain in cattle diets, while similar pH, TC, TN C/N ratio and water-extractable OC resulted from animal treading in the feedlot pen that mixed urine and dung with soil particles, narrowing any difference between the two types of manure. The C&D waste used consisted mainly of chopped drywall and wood, so it had lower moisture, pH, TN, water-extractable OC, N and NH_4-N, but higher TC content C/N ratio and SO_4-S content, than both types of manure (Table 1).

3.2 Daily compost temperatures

At the start of the composting experiment, daily average

Table 1 Selected basic properties [a)] of the materials used in the compost experiment

property	C&D waste	CK manure	DG manure
water content/($kg\cdot kg^{-1}$)	0.144±0.010 [b)]	0.609±0.014	0.619±0.010
pH	7.6±0.1	8.0±0.1	8.1±0.0
total C/($g\cdot kg^{-1}$)	312.2±23.6	266.2±12.5	275.5±17.2
total N/($g\cdot kg^{-1}$)	3.47±0.19	15.15±0.87	16.46±0.89
C/N ratio	90.4±6.1	17.7±0.6	16.8±0.6
NPOC/($g\cdot kg^{-1}$)	0.9±0.1	16.9±2.5	19.5±2.2
water-extractable N/($g\cdot kg^{-1}$)	0.05±0.01	4.26±0.65	6.19±0.43
water-extractable NH_4-N/($mg\cdot kg^{-1}$)	43±3	2489±443	4207±512
water-extractable NO_3-N/($mg\cdot kg^{-1}$)	– [c)]	–	–
water-extractable SO_4-S/($mg\cdot kg^{-1}$)	11212±192	518±114	1690±200

Notes: a) adapted from Hao et al. [21]; b) Mean±standard error (n = 6), and c) Below the detection limit.
All properties are expressed on a dry matter weight basis, except water content, which is based on wet weight.

temperature increased to>55°C within 3 to 6 days at all three monitoring depths (40 cm, 70 cm and 100 cm below the compost surface), one or two days sooner with C&D waste (CK_CD and DG_CD treatments) than without (CK and DG). The exception was at the bottom depth for the DG_CD treatment, which took 18 days to reach 55°C, four days after the first compost turning on Day 14 (Fig. 2). Daily compost temperatures at 40 cm depth were more variable than values at 70 and 100 cm, largely reflecting the impact of ambient temperature fluctuation and precipitation (Fig. 1), and greater heat loss through the compost surface. On average, temperatures after turning generally increased faster and reached new maximum values three days sooner with C&D waste than without. Daily compost temperatures remained>55°C for most of the 99 day composting period with C&D added (except on the day of turning). However, daily temperatures dropped below 55°C on Day 75 for DG manure and on Day 86 for CK manure without the C&D waste addition (Fig. 2). The narrow differences in daily temperature between the two manure types largely reflect the similar manure properties while faster increases and higher temperatures associated with C&D waste addition were mainly due to improved aeration and a greater rate of O_2 supply that promotes organic matter degradation.

Temperatures in the stockpiled manure were not monitored, but they should be similar to those for composting during the first 14 days prior to first compost turning. Xu et al. [23] found that stockpile manure temperatures were generally lower than compost manure temperatures; stockpiles were>55°C for only 2 days compared to 35 days for compost manure treatments, over a 100 day monitoring period.

3.3 Changes in selected solid properties during the 99 day composting

Moisture content on Day 1 ranged from 0.57 to 0.62 $kg \cdot kg^{-1}$, increased to their highest values on Day 14 (0.58 to 0.66 $kg \cdot kg^{-1}$), then decreased steadily afterwards reaching their lowest values on Day 99 (0.43 to 0.58 $kg \cdot kg^{-1}$). The high moisture values on Day 14 largely reflect snowfalls occurring between Days 4 and 12 (Fig. 1). Averaged over the 99 days, moisture content in C&D amended treatments (0.51 and 0.53 $kg \cdot kg^{-1}$ for CK_CD and DG_CD, respectively) were lower with than without C&D waste (0.59 and 0.61 $kg \cdot kg^{-1}$, for CK and DG, respectively).

There was little difference in water-extractable OC and N content between the two types of manure; however, values in C&D amended treatments (CK_CD and DG_CD manure) were lower than the un-amended treatments (CK and DG manure) (Table 2) on most sampling dates. Additionally, water-extractable OC content peaked on Day 14 and decreased afterwards, dropping to values similar to Day 1 by Day 99. Water-extractable NH_4-N content followed similar patterns as water-extractable OC and N, highest on Day 14, decreasing over time, and reaching their lowest values on Day 99. Water-extractable NH_4-N on Day 99 was similar to Day 1 for the CK, DG and CK_CD treatments; however, values on Day 99 were much lower than Day 1 for the DG_CD treatment. On the other hand, the water-extractable NO_3-N was near zero for all sampling dates, except on Day 99 when values ranged from 1 to 54 $mg \cdot kg^{-1}$. The peak water-extractable OC, N and NH_4^+-N on Day 14 reflected the high rate of decomposition that converted organic C and N into water extractable form. The near-zero NO_3-N and high NH_4-N contents throughout the composting were mainly due to the inhibition of nitrification by high temperatures that prevented conversion of NH_4 to NO_3 [21].

Water-extractable SO_4-S was consistently lowest in CK (349 to 541 $mg \cdot kg^{-1}$), followed by DG (955 to 2005 $mg \cdot kg^{-1}$) with highest values in the C&D amended treatments (3682 to 6806 $mg \cdot kg^{-1}$ for CK_CD and 4302 to 7033 $mg \cdot kg^{-1}$ for DG_CD) throughout the 99 days (Table 2).The higher SO_4-S content in C&D amended treatments reflected their higher content of $CaSO_4$, which is the main ingredient of drywall in C&D waste, while higher values in the DG than CK treatment reflected the higher SO_4 in the DDGS diet which produced manure with higher SO_4 content.

3.4 CO_2 surface fluxes and cumulative emissions

The CO_2 fluxes ranged from as low as 0.3 $mgCm^{-2} \cdot min^{-1}$ to as high as 387.4 $mgC \cdot m^{-2} \cdot min^{-1}$ over the course of 99 days (Fig. 3(a)) and were affected by manure management strategy (compost alone, with C&D waste or stockpiled) and sampling date ($P < 0.001$), but not by (P = 0.34) manure type (CK vs DG manure) or any of their interactions (Table 1). The average CO_2 fluxes from CK manure (95.1 $mgC \cdot m^{-2} \cdot min^{-1}$) did not differ from DG manure (82.4 $mgC \cdot m^{-2} \cdot min^{-1}$) over the 99 day experimental period. However, CO_2 fluxes from composting alone (118.7 $mgC \cdot m^{-2} \cdot min^{-1}$) were similar to those from co-composting with C&D waste (106.0 $mgC \cdot m^{-2} \cdot min^{-1}$), and both were higher than from manure stockpiling (41.3 $mgC \cdot m^{-2} \cdot min^{-1}$). Additionally, CO_2 fluxes were generally ($P < 0.05$) higher earlier (128.9 to 219.2 mgC $\cdot m^{-2} \cdot min^{-1}$ from Day 1 to 22) than later (18.6 to 71.3 mgC $\cdot m^{-2} \cdot min^{-1}$ from Day 57 to 97) in the experimental period (Fig. 3(a)).

Cumulative CO_2 emissions, expressed on a per unit surface area basis, were affected ($P < 0.05$) by manure management strategy, but not by manure type ($P = 0.37$) or their interaction ($P = 0.95$) (Table 3). Composting CK and DG manure with and without C&D waste led to higher per-surface-area CO_2 emissions (12.94 to 15.99 $kgC \cdot m^{-2}$) than manure stockpiling (6.28 and 7.64 $kg \cdot m^{-2}$). The higher per surface area emissions from composting than stockpiling largely reflects the greater decomposition in a compost

Table 2 Responses of selected properties to manure type and C&D waste addition over the 99 day experimental period

property	sampling date	treatment					**Avg[a]**
		CK	DG	CK_CD	DG_CD		
water content/(kg·kg^{-1})	1	0.61	0.62	0.57	0.56		**0.59**
	14	0.63	0.66	0.56	0.61		**0.61**
	37	0.58	0.60	0.53	0.53		**0.56**
	64	0.56	0.60	0.46	0.49		**0.52**
	99	0.57	0.58	0.43	0.47		**0.51**
	Avg	**0.59**	**0.61**	**0.51**	**0.53**		
water-extractable-OC/(g·kg^{-1})	1	16.9	19.5	10.1	13.5		**15.0**
	14	29.9	30.1	32.9	26.4		**29.7**
	37	30.0	28.5	28.0	25.5		**28.0**
	64	29.5	25.5	27.9	25.0		**26.7**
	99	22.4	21.8	11.4	9.4		**15.6**
	Avg	**25.7**	**25.1**	**22.1**	**20.0**		
water-extractable N/(g·kg^{-1})	1	4.26	6.19	2.73	5.74		**4.73**
	14	7.93	8.19	8.02	6.58		**7.66**
	37	6.88	7.23	6.51	6.38		**6.74**
	64	7.34	6.99	6.18	6.66		**6.69**
	99	4.66	6.78	3.27	3.39		**4.35**
	Avg	**6.21**	**7.08**	**5.34**	**5.75**		
water-OC/water-TN ratio	1	4.0	3.1	3.7	2.5	3.3	**4.0**
	14	4.0	3.8	4.1	4.0	4.0	**4.0**
	37	4.4	4.1	4.3	4.0	4.2	**4.4**
	64	4.1	3.6	4.7	3.5	4.0	**4.1**
	99	4.8	3.2	3.6	2.8	3.6	**4.8**
	Avg	**4.3**	**3.6**	**4.1**	**3.3**		
water-extractable NH_4-N/(mg·kg^{-1})	1	2489	4207	1767	4095		**3139**
	14	5185	7236	6584	6051		**6264**
	37	4150	5391	3529	5806		**4719**
	64	3582	6213	2313	3363		**3868**
	99	2307	4025	1756	2231		**2569**
	Avg	**3543**	**5414**	**3190**	**4309**		
water-extractable NO_3-N/(mg·kg^{-1})	1	0	0	0	0		**0**
	14	0	0	0	0		**0**
	37	0	0	0	0		**0**
	64	0	0	0	0		**0**
	99	4	9	5	54		**18**
	Avg	**1**	**2**	**1**	**11**		
water-extractable SO_4-S/(mg·kg^{-1})	1	518	1690	6806	6018		**3758**
	14	532	956	6287	4302		**3019**
	37	349	1275	5558	5541		**3181**
	64	468	1084	3682	7033		**3067**
	99	541	2005	6318	6189		**3763**
	Avg	**482**	**1402**	**5730**	**5817**		

*Note [a)] adapted from Hao et al. [21], all properties are presented on a dry matter basis, except water content which is wet weight.

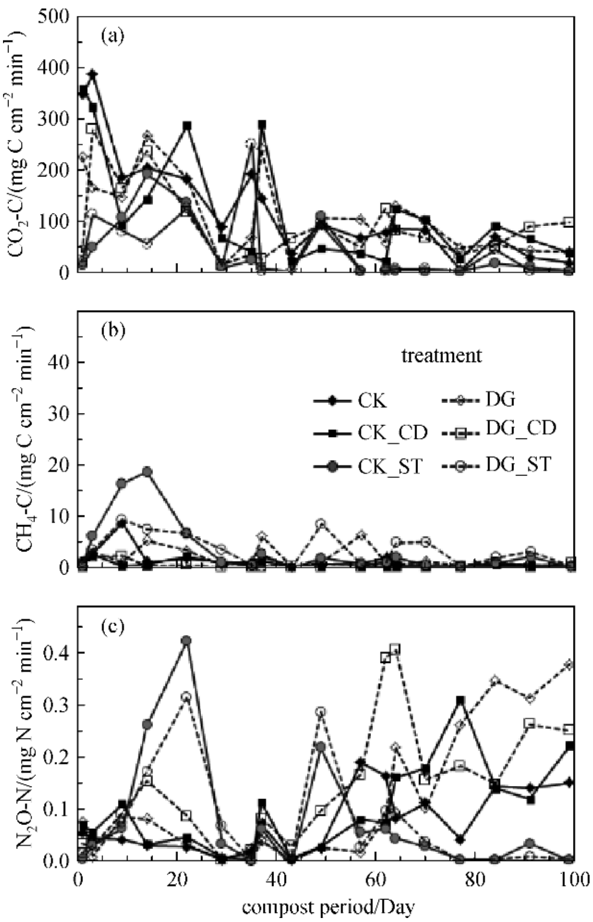


Fig. 3 Greenhouse gas fluxes over 99 days. CK and DG manure were stockpiled and co-composted with and without C&D waste. CK and DG represent composting manure from regular and DDG diets; _CD indicates C&D waste was added during composting while _ST indicates manure was stockpiled. Arrows indicate dates (Day 14, 37 and 64) when compost was turned

pile. Additionally, the rectangular shape of composting materials in the bin compared to the cone/spherical shape of stockpile means there is a greater amount of DM per unit surface area in compost than stockpiled manure, leading to the higher per surface area emissions rate. Adding C&D waste improved aeration and could potentially increase the organic matter decomposition. The similar CO_2 emission rates with and without C&D waste suggest that improved aeration did not translate into greater CO_2 emissions. The more stable and less water-extractable C in the C&D wood chips might have offset improved aeration in the C&D amended treatment. The higher temperature in the C&D amended treatment is consistent with its lower moisture content (Table 2). The heat capacity of water is much larger than air, so less heat is needed to increase the temperature with C&D waste than without it.

There were no significant differences in CO_2 emissions between the two types of manure. The CK manure emitted 7.64 to 15.99 $kgC \cdot m^{-2}$ and the DG manure 6.28 to 14.83 $kgC \cdot m^{-2}$. However, when CO_2 emission was expressed on a per initial DM basis, or per initial TC amount, differences among management strategies were no longer significant although cumulative emissions were still lowest when manure was stockpiled (Table 4). Compared to initial conditions, the CO_2 emissions at 277 to 578 $kgC \cdot Mg^{-1}$ TC suggest that 28% to 58% TC at the start of composting was emitted as CO_2-C over the 99 days (Table 4).

The increased biological activity and gas diffusion rates due to turning led to the significantly higher CO_2 emissions from composting than stockpiling observed in our study, consistent with results [6] showing active turning produced higher CO_2 emissions than passive (no turning) open windrow composting. The greater flux rates and cumulative CO_2 emissions from composting than stockpiling reflect greater organic matter decomposition with increasing O_2 supply through compost turning than manure stockpiling, while a greater availability of more easily degraded material was responsible for the observed higher CO_2 flux at start of the experiment. Sura et al. [24] reported that the outer layer of stockpiled manure often does not achieve thermophilic temperatures, especially in environments where ambient temperatures are below freezing. Consequently, rates of organic matter decomposition and hence GHG emissions in surface layers of stockpiles may be less than compost manure treatments. As the experiment progressed, less degradable material was available resulting in a decreased rate of CO_2 emissions.

3.5 CH_4 surface fluxes and cumulative emissions

The CH_4 fluxes were both much lower than CO_2 and less variable (0.01 to 18.56 $mgC \cdot m^{-2} \cdot min^{-1}$) (Fig. 3(b)), and were affected by manure management strategy ($P < 0.01$), sampling date ($P < 0.01$), and their interaction ($P < 0.01$), but not by manure type (Table 3). The average CH_4 fluxes from CK manure (1.68 $mgC \cdot m^{-2} \cdot min^{-1}$) did not ($P > 0.05$) differ from DG manure (1.74 $mgC \cdot m^{-2} \cdot min^{-1}$) over the 99 day experimental period. For most sampling dates, there were no differences in CH_4 surface fluxes among the three manure management strategies, except on Days 9, 14, 22 and 49, where emissions from the manure stockpile were higher ($P < 0.05$) than from composting (with and without C&D waste) (Fig. 3(b)). The CH_4 surface fluxes did not differ ($P > 0.0003$) among the 18 sampling dates when manure was composted; however, stockpiled manure had higher CH_4 fluxes on Days 9, 14 and 22 than other sampling dates ($P < 0.0003$) (Fig. 3(b)).

The cumulative CH_4 emissions, expressed on a per unit surface area basis, were affected ($P < 0.01$) by management strategy, but not by manure type or their interaction ($P > 0.05$) (Table 3). Composting with C&D waste generated the least CH_4 emissions per surface area, initial DM and initial TC amount, while manure stockpiling was the highest over the 99 days (Table 4).

Table 3 Analyses of variance of GHG fluxes and cumulative emissions over the 99 day experimental period

	CO_2-C	CH_4-C	N_2O-N
surface flux/($mg\cdot m^{-2}\cdot min^{-1}$)		——— probability level ———	
manure type (MT)	0.34	0.91	0.05
management strategy (MS)	< 0.01	< 0.01	0.02
MT × MS	0.53	0.79	0.33
sampling date (SD)	< 0.01	< 0.01	< 0.01
SD × MT	0.84	0.81	0.84
SD × MS	0.68	< 0.01	< 0.01
SD × MT × MS	0.56	0.65	0.82
cumulative emissions per surface area/(gC or $N\cdot m^{-2}$)			
MT	0.37	0.51	0.26
MS	< 0.01	< 0.01	0.49
MT × MS	0.95	0.77	0.54
cumulative emissions per initial DM/(kgC or $N\cdot Mg^{-1}$ DM)			
MT	0.11	0.03	0.98
MS	0.13	< 0.01	0.20
MT × MS	0.82	0.07	0.23
cumulative emissions per initial TC or TN (NH_4-N)/($kgC\cdot Mg^{-1}$ TC) or /($kgN\cdot Mg^{-1}$ TN (NH_4-N))			
MT	0.09	0.03	0.80 (< 0.01)
MS	0.12	< 0.01	0.47 (0.09)
MT × MS	0.92	0.06	0.18 (< 0.10)
CH_4 fraction CH_4-C/(CO_2-C + CH_4-C)			
MT		0.70	
MS		< 0.01	
MT × MS		0.93	

Manure type: CK vs DG manure; Management strategy: manure compost alone, co-composted with C&D waste or stockpiled; sampling dates: Days 1, 3, 9, 14, 22, 29, 35, 37, 43, 49, 57, 62, 64, 70, 77, 84, 91 and 97.

Co-composting with C&D waste led to the lowest cumulative CH_4 emissions (0.071 $kgC\cdot m^{-2}$ for CK_CD and 0.56 $kgC\cdot m^{-2}$ for DG_CD), followed by compost manure alone (0.173 $kgC\cdot m^{-2}$ for CK and 0.255 $kgC\cdot m^{-2}$ for DG), and the highest for manure stockpiling (0.455 $kgC\cdot m^{-2}$ for CK_ST and 0.483 $kgC\cdot m^{-2}$ for DG_ST). The cumulative CH_4 emissions from CK manure (average 0.230 $kgC\cdot m^{-2}$) did not differ from DG manure (average 0.285 $kgC\cdot m^{-2}$). Similar trends were observed when CH_4 emissions were expressed on a per initial DM or initial TC amount basis (Table 4). The CH_4 emission rates when composting with C&D manure (2.70 and 1.93 $kgC\cdot Mg^{-1}$ initial TC for CK_CD and DG_CD, respectively) were reduced by 57% compared to CK manure (6.24 $kgC\cdot Mg^{-1}$ initial TC) and by 77% for DG manure composting (8.32 $kgC\cdot Mg^{-1}$ initial TC) without C&D waste. The reductions are even greater when comparing C&D waste co-composting to manure stockpiling, 81% compared to CK_ST (13.93 $kgC\cdot Mg^{-1}$ initial TC) and 91% compared to DG_ST (21.32 $kgC\cdot Mg^{-1}$ initial TC).

Compared to the total amount of C at the start of composting, CH_4 emissions at 1.93 to 21.32 $kgC\cdot Mg^{-1}$ TC suggest that 0.19 to 2.1% of original manure C was emitted as CH_4-C over the 99 days, much smaller than the 28 to 58% C lost as CO_2-C (Table 4). Additionally, composting led to a lower fraction of total C emitted as CH_4 (0.47% to 0.50% with C&D waste and 1.13% to 1.73% without C&D waste) than manure stockpiling (6.87% to 7.13%) and reduced the proportion of CH_4 relative to the total CO_2-eq emissions (Fig. 4).

The higher CH_4 flux from manure stockpiles than compost largely reflects the poor aeration in manure stockpiling, as turning increases aeration introducing O_2 into the compost and promotes CH_4 oxidation by methanotrophs. Additionally, at a 4:1 ratio of manure:C&D waste, water-extractable SO_4 increased from 484 $mg\cdot kg^{-1}$ in CK and 1402 $mg\cdot kg^{-1}$ in DG treatments to 5730 mg $\cdot kg^{-1}$ in CK_CD and 5817 in DG_CD treatments (Table 1), along with a decrease in pH (from 8.3 to 8.0 as previously reported [21]). The effect of C&D waste in reducing CH_4

Table 4 Cumulative CO_2 and CH_4 emissions over the 99 day experimental period

	CO_2-C			CH_4-C		
	CK	DG	Avg	CK	DG	Avg
per surface area/(kgC·m^{-2})						
compost with C&D waste	15.39	12.94	14.1 a	0.071	0.056	0.064 c
compost without C&D waste	15.99	14.83	15.4 a	0.173	0.255	0.214 b
stockpiled	7.64	6.28	7.0 b	0.445	0.483	0.464 a
Avg	13.01 A	11.35 A		0.230 A	0.265A	
per initial DM/(kgC·Mg^{-1} DM)						
compost with C&D waste	148.0	111.6	129.8 a	0.69	0.50	0.59 c
compost without C&D waste	147.7	132.4	140.0 a	1.62	2.29	1.95 b
stockpiled	114.5	73.6	94.0 a	3.71	5.66	4.68 a
Avg	136.7 A	105.9 A		2.00 B	2.82 A	
per initial TC/(kgC or N·Mg^{-1} C)						
compost with C&D waste	577.8	434.9	496.2 a	2.70	1.93	2.27 c
compost without C&D waste	570.4	481.2	525.8 a	6.24	8.32	7.28 b
stockpiled	430.0	277.2	348.7 a	13.93	21.32	17.64 a
Avg	519.3A	394.5 A		7.62 B	10.52 A	
CH_4 fraction (CH_4-C/(CO_2-C + CH_4-C)/%						
compost with C&D waste				0.50	0.47	
compost without C&D waste				1.13	1.73	
stockpiled				6.87	7.13 a	
Avg				2.83 a	3.27 a	

Manure type: CK vs DG manure; Management strategy: manure co-composted with C&D waste, manure composted without C&D waste or stockpiled. For each parameter, data in a column followed by different lower-case letters and in a row followed by different upper-case letters differ at 0.05 probability level.

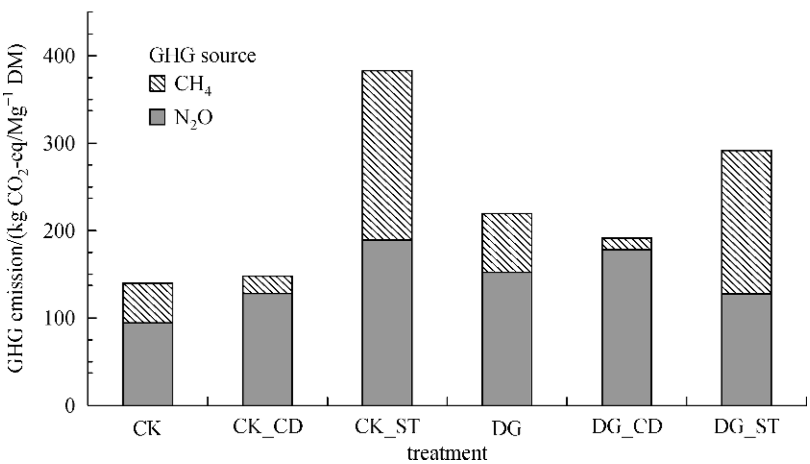


Fig. 4 Effect of C&D waste addition on CO_2 equivalent emission for each tonne of manure (DM) composted

emission was consistent with previous studies when phosphogypsum was added to cattle manure composting [7].

The C&D waste used in our study contains drywall materials, and the main ingredient in drywall is $CaSO_4$. Both sulfur reducing bacteria (SRB) and methane producing bacteria (MPB) compete for the same organic C and energy sources under anaerobic conditions [7]. Other studies have shown that the toxic effect of sulfur compounds on methanogens inhibits CH_4 production. Additionally, the reduction in pH associated with C&D waste addition from 8.3 to 8.0 [21] could increase the rate of CH_4 oxidation, as the optimum pH for CH_4 oxidation is reported to be near neutral pH [25].

3.6 N_2O surface fluxes and cumulative emissions

The N_2O fluxes, ranging from 0.001 to 0.369 $mgC \cdot m^{-2} \cdot min^{-1}$ (Fig. 3(c)), were affected by manure management strategy (P = 0.03), sampling date ($P < 0.001$) and their interaction ($P < 0.001$), and were marginally affected by manure type (P = 0.05) (Table 3). The average N_2O fluxes from DG manure (0.110 $mgC \cdot m^{-2} \cdot min^{-1}$) were higher ($P$ = 0.05) than CK manure (0.081 $mgC \cdot m^{-2} \cdot min^{-1}$). This is mainly due to the initially higher NH_4 content associated with DG manure. Among the three manure management strategies, N_2O fluxes from the manure stockpile from Days 1 to 57 were similar to those from composting (both with and without C&D waste), except on Days 14, 22 and 49, when fluxes from stockpiling were higher ($P < 0.05$) than composting. From Days 62 to 97, N_2O fluxes from manure stockpile were always lower ($P < 0.05$) than from composting. There were no differences in N_2O fluxes between composting with and without C&D waste for all sampling dates (Table 3).

The lower N_2O fluxes observed from manure composting than stockpiling during early composting might be due to the high compost temperature that inhibits nitrification and denitrification. Compost bins constructed with straw bales insulated the compost pile and maintained compost temperature > 60°C for most of the composting period [21]. Increases in N_2O flux when temperature was lowered by turning suggest that temperature is the main factor inhibiting N_2O emissions during our composting experiment. High compost temperatures hindering the nitrification of N_2O are also consistent with the high NH_4 content (2569–6264 $mg \cdot kg^{-1}$) and low NO_3 content (0–18 $mg \cdot kg^{-1}$) throughout the 99 day composting [21]. Venglovsky et al. [26] also reported no nitrification activities during the thermophilic stage (temperature is > 45°C) when composting the swine slurry solid fraction as the nitrification bacteria are limited by high temperatures. Although we did not monitor the temperatures in the manure stockpile, neither nitrification of NH_4 in manure nor denitrification of NO_3 were inhibited during early manure stockpiling (Days 0 to 49). Stockpiles do not encounter the early high temperatures observed for composting [23,24], thus the higher early N_2O emissions from manure stockpiling than composting. The higher N_2O fluxes during the second half of the experiment (Days 50 to 99) from composting than stockpiling were mainly due to decreases in temperature reducing inhibition to N_2O production in the compost pile. Reduced N_2O emissions at higher temperatures have also been reported elsewhere [27].

Cumulative N_2O emissions, expressed on a per initial surface area, initial DM or initial total N amount basis, were not affected by manure type, management strategy or their interaction (Table 3). The cumulative N_2O emissions, ranging from 0.107 to 0.217 $kgN \cdot m^{-2}$ (0.099 to 0.201 $kgN \cdot Mg^{-1}$ DM, or 6.65 to 14.32 $kgN \cdot Mg^{-1}$ TN) (Table 5), were similar regardless of treatment. The C&D waste addition did not affect the N_2O emissions amount (Table 5) or the contribution to the total CO_2-eq (Fig. 4).

Table 5 Cumulative N_2O emissions over the 99 day experimental period

	manure type		
	CK	DG	Avg
per surface area/(kg N_2O-N $\cdot m^{-2}$)			
compost with C&D waste	0.0143	0.0217	0.018 a
compost without C&D waste	0.0107	0.0180	0.145 a
stockpiled	0.0133	0.0117	0.125 a
Avg	0.0128 A	0.0172 A	
per initial DM/(kg N_2O-N $\cdot Mg^{-1}$ DM)			
compost with C&D waste	0.135	0.188	0.162 a
compost without C&D waste	0.099	0.161	0.130 a
stockpiled	0.201	0.134	0.168 a
Avg	0.145 A	0.161 A	
per initial TN amount/(kg N_2O-N $\cdot Mg^{-1}$ TN)			
compost with C&D waste	8.9	14.3	11.6 a
compost without C&D waste	6.6	9.5	8.1 a
stockpiled	13.3	8.2	10.7 a
Avg	9.6 A	10.7 A	
per initial NH_4-N amount/(kg N_2O-N $\cdot Mg^{-1}$ NH_4-N)			
compost with C&D waste	76.6	45.9	61.3 a
compost without C&D waste	39.6	33.6	36.6 a
stockpiled	113.9	25.8	69.8 a
Avg	76.7 A	35.1 B	

Manure type: CK vs DG manure; Management strategy: manure co-composted with C&D waste, manure composted without C&D waste or stockpiled. For each parameter, data in a column followed by different lower-case letters and in a row followed by different upper-case letters differ at 0.05 probability level.

Compared to the amount of total N at the start, the N_2O emissions, ranging from 6.6 to 14.3 $kgN \cdot Mg^{-1}$ TN, suggest that 0.66 to 1.43% TN was emitted as N_2O-N over the 99 days. The similar emissions among treatments mainly reflect lower N_2O fluxes during early and higher N_2O fluxes during later composting than manure stockpiling, which led to no overall difference among manure management strategies. However, when cumulative N_2O emissions are expressed on a per initial NH_4-amount basis, there is a significant manure type effect ($P < 0.01$).

The extended high daily average temperature (> 55°C to 77°C) period during most of the 99 day composting (Fig. 2) might be responsible for the low emissions and small differences among treatments in CH_4 and N_2O emissions although moisture content was lower and aeration better with C&D waste (Table 2). The extremely high temperature might have hindered microbial activity and CH_4 and N_2O production in all composting piles. The reported higher fraction of C emitted as CH_4 for manure stockpiles than composting in our study is consistent with other studies using cattle manure [6]

4 Implications for manure management strategies

There is a need to develop on-farm strategies to mitigate net GHG emissions from livestock manure. In Canada, animal manure from confined livestock operations is most often stored on-farm before being applied to agricultural land. Increasingly, manure is composted before land application. One mitigation strategy is adding straw or woodchips (C-rich amendments) as bedding materials in the feedlot pen or during manure storage and composting to reduce CH_4 and N_2O emissions as straw influences the dry matter content, C/N ratio and aeration of the manure [28,29]. Other strategies include managing compost pile size as larger piles increase CH_4 and N_2O emissions due to poor aeration [30]; forced aeration and turning generally reduces CH_4 emissions [31] while increasing compost pile porosity could reduce N_2O emissions [32]. Co-composting with C&D waste could be one manure management strategy to reduce CH_4 emissions as demonstrated in our study. In addition to the increased available SO_4 for crop production, particularly in S-deficient sandy soil [21], there is also the added bonus of recycling the C in the C&D waste and reducing waste at landfill sites.

5 Conclusions

Co-composting cattle manure with C&D waste (mainly lumber and drywall waste materials from new housing construction) had little impact on CO_2 and N_2O emissions while CH_4 emissions were reduced. The CO_2 emissions and CH_4 emissions were lower and N_2O emissions similar when comparing stockpiling manure to composting cattle feedlot manure using small bins constructed with cereal straw bales. The lower CH_4 emissions with C&D waste is beneficial in reducing overall GHG emissions from manure composting, while reducing the amount of material entering landfills.

Acknowledgements Funding for this research was provided by Agriculture and Agri-Food Canada Growing Forward 2 program (Project # J-000251). Technical assistance was provided by Brett Hill, Greg Travis, Pam Caffyn and Andrew Olson.

References

1. Statistics Canada. A geographical profile of livestock manure production in Canada, 2015. available at http://www.statcan.gc.ca/pub/16-002-x/2008004/tbl/manure-fumier/tbl001-man-fum-eng.htm (Last accessed March 1, 2017)
2. Environment and Climate Change Canada. National inventory report 1990–2014: Greenhouse gas sources and sinks in Canada-Executive summary, 2016. Available online at https://ec.gc.ca/ges-ghg/default.asp?lang = En&n = 662F9C56-1#es-2(Last accessed March 1, 2017)
3. Census of Agriculture, manure and manure application methods in the year prior to the census 2011. Available at http://www5.statcan.gc.ca/cansim/a26?lang = eng&retrLang = eng&id = 0040207&pattern = manure&tabMode = dataTable&srchLan =-1&p1 = 1&p2 =-1 (Last accessed March 1, 2017)
4. Larney F J, Olson A F, Carcamo A A, Chang C. Physical changes during active and passive composting of beef feedlot manure in winter and summer. Bioresource Technology, 2000, 75(2): 139–148
5. Larney F J, Blackshaw R E. Weed seed viability in composted beef cattle feedlot manure. Journal of Environmental Quality, 2003, 32 (3): 1105–1113
6. Hao X, Chang C, Larney F J, Travis G R. Greenhouse gas emissions during cattle feedlot manure composting. Journal of Environmental Quality, 2001, 30(2): 376–386
7. Hao X, Larney F J, Chang C, Travis G R, Nichol C K, Bremer E. The effect of phosphogypsum on greenhouse gas emissions during cattle manure composting. Journal of Environmental Quality, 2005, 34(3): 774–781
8. Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014. Available at https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf (Accessed January 15, 2017)
9. Hünerberg M, Beauchemin K A, McGinn S M, Okine E K, Harstad O M, McAllister T A. Effect of dried distillers' grains with solubles on enteric methane emissions and nitrogen excretion from finishing beef cattle. Canadian Journal of Animal Science, 2013, 93(3): 373–385
10. Hünerberg M, McGinn S M, Beauchemin K A, Okine E K, Harstad O M, McAllister T A. Effect of dried distillers grains plus solubles on enteric methane emissions and nitrogen excretion from growing beef cattle. Journal of Animal Science, 2013, 91(6): 2846–2857
11. Hao X, Benke M B, Gibb D J, Stronks A, Travis G, McAllister T A. Effects of dried distillers' grains with solubles (wheat-based) in feedlot cattle diets on feces and manure composition. Journal of Environmental Quality, 2009, 38(4): 1709–1718
12. Hao X, Benke M B, Li C, Larney F J, Beauchemin K A, McAllister T A. Nitrogen transformations and greenhouse gas emissions during composting of manure from cattle fed diets containing corn dried distillers grains with soluble and condensed tannins. Animal Feed Science and Technology, 2011, 166–167: 539–549
13. Hünerberg M, Little S M, Beauchemin K A, McGinn S M, O'Connor D, Okine E K, Harstad O M, Kröbel R, McAllister T A. Feeding high concentrations of corn dried distillers' grains decreases methane, but increases nitrous oxide emissions from beef cattle production. Agricultural Systems, 2014, 127: 19–27
14. Hao X, Benke M B, Larney F J, McAllister T A. Greenhouse gas emissions when composting manure from cattle fed wheat dried distillers' grains with solubles. Nutrient Cycling in Agroecosystems, 2011, 89(1): 105–114
15. U.S. Environmental Protection Agency. DRAFT Inventory of U.S. Greenhouse Gas 7 Emissions and Sinks: 1994–2014. Available

online at http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf (Last accessed 11/10/16)

16. Environment Canada. Municipal Solid Waste and Greenhouse Gases. 2014, Available online at http://www.ec.gc.ca/gdd-mw/default.asp?lang = En&n = 6f92e701-1 (Last accessed 11/10/16)
17. Public Works and Government Services Canada. Chapter 8-Construction, Renovation and Demolition Waste. In The Environmentally Responsible Construction and Renovation Handbook. 2014, Available online at http://publications.gc.ca/collections/collection_2013/tpsgc-pwgsc/P4-53-2001-eng.pdf (Last accessed 11/10/16)
18. McMahon V, Garg A, Aldred D, Hobbs G, Smith R, Tothill I E. Composting and bioremediation process evaluation of wood waste materials generated from the construction and demolition industry. Chemosphere, 2008, 71(9): 1617–1628
19. Saludes R B, Iwabuchi K, Miyatake F, Abe Y, Honda Y. Characterization of dairy cattle manure/wallboard paper compost mixture. Bioresource Technology, 2008, 99(15): 7285–7290
20. Naeth M A, Wilkinson S R. Can we build better compost? Use of waste drywall to enhance plant growth on reclamation sites. Journal of Environmental Management, 2013, 129: 503–509
21. Hao X, Hill B, Caffyn P, Travis G, Olson A F, Larney F J, McAllister T, Alexander T. Co-composting of beef cattle feedlot manure with construction and demolition waste. Journal of Environmental Quality, 2014, 43(5): 1799–1808
22. SAS Institute Inc. SAS OnlineDoc® 9.2. Cary, NC: SAS Institute Inc. 2008
23. Xu S, Sura S, Zaheer R, Wang G, Smith A, Cook S, Olson A F, Cessna A J, Larney F J, McAllister T A. Dissipation of antimicrobial resistance determinants in composted and stockpiled beef cattle manure. Journal of Environmental Quality, 2016, 45(2): 528–536
24. Sura S, Degenhardt D, Cessna A J, Larney F J, Olson A F, McAllister T A. Dissipation of three veterinary antimicrobials in beef cattle feedlot manure stockpiled over winter. Journal of Environmental Quality, 2014, 43(3): 1061–1070
25. Scheutz C, Kjeldsen P. Environmental factors influencing attenuation of methane and hydrochlorofluorocarbons in landfill cover soils. Journal of Environmental Quality, 2004, 33(1): 72–79
26. Venglovsky J, Sasakova N, Vargova M, Pacajova Z, Placha I, Petrovsky M, Harichova D. Evolution of temperature and chemical parameters during composting of the pig slurry solid fraction amended with natural zeolite. Bioresource Technology, 2005, 96(2): 181–189
27. Ermolaev E, Jarvis Å, Sundberg C, Smårs S, Pell M, Jönsson H. Nitrous oxide and methane emissions from food waste composting at different temperatures. Waste Management (New York, N.Y.), 2015, 46: 113–119
28. Yamulki S. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agriculture, Ecosystems & Environment, 2006, 112(2-3): 140–145
29. Mahimairaja S, Bolan N S, Hedley M J. Denitrification losses of N from fresh and Composted manures. Soil Biology & Biochemistry, 1995, 27(9): 1223–1225
30. Fukumoto Y, Osada T, Hanajima D, Haga K. Patterns and quantities of NH_3, N_2O and CH_4 emissions during swine manure composting without forced aeration–effect of compost pile scale. Bioresource Technology, 2003, 89(2): 109–114
31. Lopez-Real J, Baptista M. A preliminary comparative study of three manure composting systems and their influence on process parameters and methane emissions. Compost Science & Utilization, 1996, 4(3): 71–82
32. Sommer S G, Møller H D. Emission of greenhouse gases during composting of deep litter from pig production – effect of straw content. Journal of Agricultural Science (Cambridge), 2000, 134(3): 327–335