

## Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure

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### Abstract

Greenhouse gas emissions from the agricultural sector can be reduced through implementation of improved management practices. For example, the choice of manure storage method should be based on environmental decision criteria, as well as production capacity. In this study, greenhouse gas emissions from three methods of storing dairy and beef cattle manure were compared during the summer period. The emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> from manure stored as slurry, stockpile, and compost were measured using a flow-through closed chamber. The largest combined N<sub>2</sub>O–CH<sub>4</sub> emissions in CO<sub>2</sub> equivalent were observed from the slurry storage, followed by the stockpile and lastly the passively aerated compost. This ranking was governed by CH<sub>4</sub> emissions in relation to the degree of aerobic conditions within the manure. The radiative forcing in CO<sub>2</sub> equivalent from the stockpiled manure was 1.46 times higher than from the compost for both types of cattle manure. It was almost twice as high from the dairy cattle manure slurry and four to seven times higher from the beef cattle manure slurry than from the compost. The potential reduction of GHG was estimated, by extrapolating the results of the study to all of Canada. By composting all the cattle manure stored as slurry and stockpile, a reduction of 0.70 Tg CO<sub>2</sub>-eq year<sup>-1</sup> would be achieved. Similarly, by collecting and burning CH<sub>4</sub> emissions from existing slurry facilities, a reduction of 0.76 Tg CO<sub>2</sub>-eq year<sup>-1</sup> would be achieved. New CH<sub>4</sub> emission factors were estimated based on these results and incorporated into the IPCC methodology. For North-America under cool conditions, the CH<sub>4</sub> emission factors would be 45 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for dairy cattle manure rather than 36 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup>, and 3 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for beef cattle manure rather than 1 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup>.

### Introduction

On-farm agricultural practices account for almost 10% of the anthropogenic greenhouse gas (GHG) emissions in Canada (Desjardins et al. 2001). Over half of the total N<sub>2</sub>O emissions, and over a third of the total CH<sub>4</sub> emissions come from agriculture.

The primary sources of these emissions are enteric fermentation, chemical fertilizers, and manure management. Based on direct effects, the 20- and 100-year global warming potentials for CH<sub>4</sub> are 62 and 23 times, and for N<sub>2</sub>O 275 and 296 times that of CO<sub>2</sub> on a mass basis, respectively (IPCC 2001). The major reasons why changes in agricultural

practices have the potential to significantly impact climate change are the high emission rates and high warming potential of CH<sub>4</sub>, and N<sub>2</sub>O. Several authors have suggested that altering the storage and handling of manure could reduce GHG emissions, as well as the overall contribution of agriculture to global warming (Sommer et al. 2000; Amon et al. 2001; Hao et al. 2001; Kulling et al. 2003).

Between 5 to 30% of global CH<sub>4</sub> emissions are derived from livestock manure (Svenson et al. 1991; Sommer et al. 2000; Kulling et al. 2002). In Canada, manure accounts for approximately 20% of the total CH<sub>4</sub> emissions from agriculture (Desjardins and Riznek 2000). CH<sub>4</sub> emissions from livestock manure are affected by the type of livestock (pig, dairy cattle, etc.), storage conditions (slurry, solid, pasture), and temperature (Husted 1994; Amon et al. 2001; Su et al. 2003). Because CH<sub>4</sub> is produced by anaerobic decomposition of organic matter (Gaudy and Gaudy 1988) it is expected that conditions that promote aerobic decomposition will result in less CH<sub>4</sub> emissions.

Observations of N<sub>2</sub>O emissions should also be included in studies of livestock manure because manure accounts for approximately 18% of the total N<sub>2</sub>O emissions. Sound recommendations for manure storage should take into account the tradeoff between CH<sub>4</sub> and N<sub>2</sub>O, which depends on the level of oxygen in the manure during the storage. The objectives of this study are the following: (1) investigate the effect of manure storage types on the emission of GHGs, (2) compare GHG emissions from dairy cattle manure to emissions from beef cattle manure, (3) determine the environmental- and chemical variables that account for most of the variations in GHG emissions, and (4) provide management recommendations for reducing GHG emissions.

## Materials and methods

### *Study site*

The measurements were carried out at the Central Experimental Farm of Agriculture and Agri-Food Canada, in Ottawa Ontario (latitude 45°22' N, longitude 75°43' W, 79 m above sea level) during two consecutive summers; first over dairy cattle manure and then over beef cattle manure. The

manure was produced by a small herd equivalent to 20 animal units. The dairy cow manure contained about 10% bedding material, consisting of dry straw and wood shavings, while the beef cattle manure contained about 50%. The manure was mixed with a spreader to produce a homogenous material before transferring it to experimental storage bins.

### *Manure storage experiment*

The GHG emissions from three different methods of manure storage – slurry (S), stockpile (P), and compost (C) were quantified. Overall, the slurry was mostly anaerobic (except the crust that formed at the surface), the compost was mainly aerobic, and the stockpile was in between. The emissions from three replicates of each storage type were monitored for 14 weeks for the dairy cattle manure and for 11 weeks for the beef cattle manure. Each manure storage bin, made of a wood frame, was 1.00 m deep, 1.22 m wide and 2.13 m long (internal dimensions). In order to minimize the changes in the water content of the manure and simulate the environment of the core of the stored manure while keeping the bin size to a minimum, different film types were installed around the sides of the bins. For the slurry treatment, a heavy black plastic was used to retain water, and the walls of the bins were reinforced. The slurry treatment was designed to mimic the environmental conditions of above-ground tanks. For the stockpiled manure treatment, white polyethylene sheeting backed by chicken wire was used to retain moisture in the manure. For the compost treatment, house wrap, a porous synthetic material used in building houses, was used to maintain air exchange while minimizing evaporation. In addition, two polyvinyl chloride pipes with two rows of perforations were placed on the bottom of the bins to increase aeration and promote the composting of manure (as in the Passively aerated Windrow System of Agriculture and Agri-Food Canada; Mathur 1991, 1992; Hayes et al. 1993). In the passively aerated system, exothermic reactions create a chimney effect within the windrow, which in turn causes oxygen to move into the pipes and through the composting material. To minimize ammonia volatilization, the manure being composted had a 15 cm layer of pre-composted manure added to

the bottom and another one at the top of the bin. To limit rain and the drying of stored manure, a roof made of white plastic was installed over each bin. Each bin was aerated naturally by the wind.

#### *GHG emission measurements*

Because manure carbon originates from autotrophic fixation which is released as  $\text{CO}_2$  to the atmosphere over a relatively short period of time, manure  $\text{CO}_2$  emissions are not considered to contribute to global warming and are not included in the calculation of manure storage contribution to GHG emissions. However,  $\text{CO}_2$  emissions were measured concomitantly to  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  emissions for monitoring the aerobic decomposition and for evaluating if the enclosure was tightly installed over the bin, as explained further.

In the dairy cattle manure experiment, the sampling of slurry, stockpile and compost treatments for  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{CO}_2$  emissions was rotated among the three storage methods so that two of the three storage methods were sampled each day and all storage methods were sampled twice per week. GHG emissions were measured for a total of 14 weeks from May 21 to August 18 (Calendar Day: CD, 141–230). For the beef cattle manure experiment, the sampling of each storage bin was completed in one day, twice weekly for 11 weeks from June 2 to August 15 (CD 153–227). However, from June 6 to 22 (CD 157–173),

sampling was completed as described for the dairy cattle experiment. Since the slurry treatment was still emitting high levels of  $\text{CH}_4$  on August 15, the sampling for this treatment continued until October 25 (CD 298).

Emissions of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{CO}_2$  from the storage bins were measured using a flow-through closed chamber (Figure 1). The enclosure was placed over the to be measured bin. Four fans were used to ensure good air mixing within the enclosure. These were positioned so that air was forced away from the surface of the manure. In order to measure  $\text{CH}_4$  and  $\text{N}_2\text{O}$  concentrations, 10-ml air samples were taken through a rubber septum within 2 min after the bins were enclosed, and subsequently every 2.5 min over a 10 min period. A sample of ambient air was taken 3 cm above the manure surface prior to enclosure. All these  $\text{CH}_4$  and  $\text{N}_2\text{O}$  concentration samples measured over time were used to determine the initial slope (at  $t=0$ ), required to calculate the flux. The air samples were stored at room temperature and analyzed within 48 h using a gas chromatograph (Varian, Walnut Creek, CA).

An infrared  $\text{CO}_2$  analyzer (LI-6251 from LI-COR, Lincoln, NE) was put in parallel with the tube that was equipped with the septum (Figure 1). Air was circulated in the closed loop using a diaphragm pump located downstream of the gas sampling port. The slopes of  $\text{CO}_2$  concentrations over time were measured using the LI-6251 analyzer in three series of 1-min readings recorded at

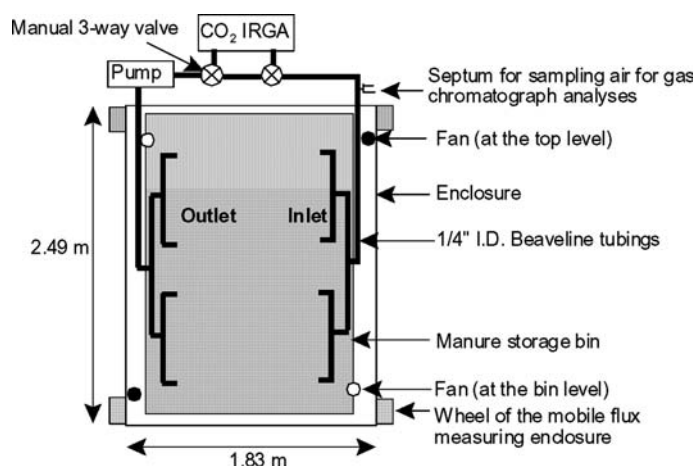


Figure 1. Top view of the flow-through closed-loop gas sampling enclosure assembly placed over each manure storage bin during GHG emissions determination.

1-s intervals on a CR-21X data logger (Campbell Scientific, Logan, UT). Measurements began within 2 min after the bins were covered. The change of CO<sub>2</sub> concentration over time was displayed in real time on a laptop computer for diagnostic purposes. A steady CO<sub>2</sub> slope over time indicated that the system was leak free, and that a thorough mixing of the air within the enclosure was being achieved. The LI-6251 analyzer was flushed with ambient air between measurements over the different bins.

GHG emissions ( $F_G$ , mg kg<sup>-1</sup> DM s<sup>-1</sup>; DM: dry manure) were calculated using the following equation:

$$F_G = \frac{\partial C_G(0)}{\partial t} \frac{V_E M_G}{V_G} \frac{1}{m_m}$$

Where  $\partial C_G(0)/\partial t$  is the rate of change in GHG concentration at time  $t=0$  (mmol mol<sup>-1</sup> s<sup>-1</sup>),  $V_E$  is the chamber headspace volume (m<sup>3</sup>),  $M_G$  is the molecular mass of the GHG (CO<sub>2</sub> and N<sub>2</sub>O: 44 g mol<sup>-1</sup>, CH<sub>4</sub>:16 g mol<sup>-1</sup>),  $V_G$  is the volume of the gas at 21 °C (0.024 m<sup>3</sup> mol<sup>-1</sup>), and  $m_m$  is the initial dry mass of manure (kg).

The fluxes of CH<sub>4</sub> and N<sub>2</sub>O across the manure-atmosphere interface are a function of the diffusion coefficients and concentration gradients between sites of generation (or transformation) and the manure surface. Within a flow-through closed chamber, the gradient of the gas concentration changes over time, hence the rate of change of the concentration of the gas within the enclosure decreases continuously (Rochette et al. 1997). A non-linear model is used for describing the change of GHG concentration with time when the period is not short enough to have a linear change (Hutchinson and Livingston 1993). Since the gas concentration within the manure is much higher than in the headspace atmosphere, it takes some time before the gradient between manure and the atmosphere above is affected significantly. A linear approximation was adequate for about 75% of the GHG concentration slopes measured over 10 min. For the cases when it was not adequate, a quadratic model was used.

#### *Determination of CH<sub>4</sub> and N<sub>2</sub>O concentrations*

Methane and N<sub>2</sub>O concentrations were measured using a gas chromatograph coupled to a flame

ionization detector for CH<sub>4</sub> and an electron capture detector for N<sub>2</sub>O. For CH<sub>4</sub>, the following conditions were used: (i) 10-ml air sample injection at ambient temperature through a 2-ml sample loop; (ii) the detector temperature, was at 390 °C and oven temperature was at 60 °C; (iii) the column was made of 80/100 mesh Porapak-N packed into a 4.8 m long × 3.18 mm internal diameter stainless steel column (Superlco, PA, USA) and (iv) the gas flow rates were 30 ml min<sup>-1</sup> for nitrogen, 30 ml min<sup>-1</sup> for hydrogen and 300 ml min<sup>-1</sup> for air. Methane (retention time 1.8 min) was quantified by comparing the peak area with that of 1.36, 51.0 and 100.1 ppmv custom standards prepared by Matheson Gases (Ottawa, Canada). For N<sub>2</sub>O, an electron capture detector was used with Ar-CH<sub>4</sub> as carrier gas, a 2 ml-sample loop, and a column packed with Poropak Q (Superlco, PA, USA). The two N<sub>2</sub>O standards used were 1.17 ppmv and 10.0 ppmv (Matheson Gas, Ottawa, Canada). For both gases, the minimum detection level was determined to be between 10 and 20 ppbv. A standard was run between each series of five air samples.

#### *Measurement of CO<sub>2</sub> concentration*

The infrared CO<sub>2</sub> analyzer was operated in absolute mode within the 0 to 1500 ppmv CO<sub>2</sub> range. A scrubber that contained soda lime was used to provide CO<sub>2</sub>-free air to the reference cell. During regular operation, the scrubber was changed biweekly. The LI-6251 analyzer was calibrated before each series of measurements in the field using a reference concentration at 618 ppmv of CO<sub>2</sub> in nitrogen gas (Matheson Gas, Ottawa, Canada).

#### *Chemical composition of the manure*

Carbon, nitrate and ammonium concentrations in dairy cattle manure were measured on CD 141, 148 and 176. Initial moisture content was also measured.

Beef manure was sampled seven times from all the bins on CD 150, 152, 164, 178, 192, 220, 227 and three additional times from slurry bins on CD 251, 279 and 300. Moisture determination was done gravimetrically. The pH was measured after

dilution with deionized water (1:5 ratio). Around 10 g of fresh manure were extracted with 100 ml 2 M KCl after shaking for 1 h. The extracts were filtered and analyzed (Keeney and Nelson 1982) for mineral N ( $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N) using a TRAACS 800 Auto Analyzer (Method 325.2 of Bran-Luebbe, Inc., Technicon Industrial Systems Corp., Elmsford, NY). Total soluble and inorganic C in the KCl extracts were measured using a Total Carbon Analyzer (Shimadzu TOC-5050). Total soluble organic C was determined by subtracting the total soluble inorganic C from total soluble C. Total C and N were determined by combustion on a Carlo Erba (NA 1500, Nitrogen/Carbon/Sulfur Analyzer). Wet manure bulk density was determined on  $\text{g l}^{-1}$  basis by using 1 l of wet manure.

#### *Environmental conditions of the storage bins*

Hourly temperatures at the surface of the manure and in the middle of the bin were recorded over the duration of the experiment. Observations of ambient temperature and pressure (PX961-16A5V pressure transducer, Omega Engineering Inc., Stamford, CT), relative humidity (HMP 35A Humidity Probe, Vaisala, Helsinki, Finland), wind speed and wind direction were also recorded at the site of the experiment, and averaged hourly. When meteorological data were missing due to instrument failure, data from the Ottawa airport ( $\sim 7.4$  km away) were used. Three- and six-hour mean ambient temperature and pressure values were calculated over four time intervals (9:00–12:00, 6:00–9:00, 6:00–12:00, 0:00–6:00 am EDT) prior to emission measurements to determine which interval influenced GHG emissions the most. The pressure trend was calculated as being the difference in ambient pressure between the emission measurement time and 3, 6, 12, and 24 h prior to it.

#### *Statistical analyses*

Repeated measures analysis (O'Brien and Kaiser 1985) was used to analyze the effect of manure storage on GHG emissions. Repeated measures of an experimental unit over time are rarely independent (O'Brien and Kaiser 1985; Von Ende

1993). Therefore, because GHG emissions were measured from the same nine storage bins for many weeks, we expected a lack of independence in emissions over time. A repeated measures analysis partitions the variation into a treatment effect, time effect, and time by treatment interaction.

The data were divided into three periods based on the level of emissions, which corresponded to initial (P1), intermediate (P2), and final (P3) phases of GHG emission as illustrated in Figures 2–4. We used repeated measures analysis to study the effect of manure storage, measurement week, and their interaction on GHG emissions for the three key periods. A weekly estimate of GHG emissions was calculated by averaging emissions from samples within a week. If only one sample was taken in a week, it was used as the weekly estimate. A repeated measures analysis cannot be done when there are missing values unless additional assumptions are made about the data. Therefore, if after averaging within each week there were still missing estimates of GHG emissions, the week was excluded from the analysis. In the dairy cattle manure experiment,  $\text{N}_2\text{O}$  emissions from the third week, and  $\text{CO}_2$  emissions from the second week were unavailable. In the beef cattle manure experiment, the initial  $\text{CH}_4$  emissions, and  $\text{CO}_2$  emissions from week five were unavailable. Separate repeated measures analyses were performed for each period and for each gas using SAS version 6 PROC GLM with the REPEATED statement. This procedure provides both univariate and multivariate analyses of repeated measures. Following the recommendation of Potvin et al. (1990) conclusions were based on the univariate tests when the significance levels adjusted by the Greenhouse-Geisser correction and the Huynh-Feldt correction agreed. In this case, we report the Huynh-Feldt adjusted significance levels. When the corrected significance levels did not agree we used the multivariate tests with the level of significance  $\alpha = 0.1$ , since we had a large number of weeks compared to the number of replicates (Stevens 1992). Stepwise multiple regressions were used to determine if GHG emissions were correlated with environmental variables. Specifically, we tested for relationships between GHG emissions and the mean ambient temperature ( $T_a$ ), mean ambient pressure ( $P$ ), pressure change ( $\Delta P$ ), relative humidity (RH), wind speed ( $U$ ), wind direction ( $\Theta$ ), surface temperature ( $T_s$ ) and core temperature ( $T_c$ ) of the manure. We also used stepwise multiple

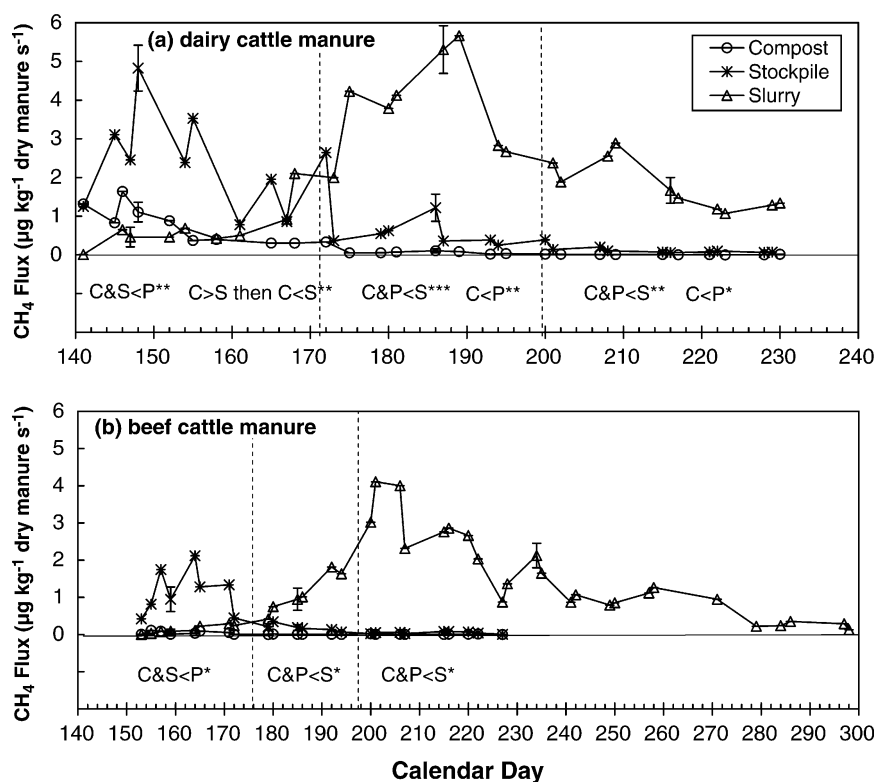


Figure 2. Methane emissions from (a) dairy cattle manure and (b) beef cattle manure stored during the summer period as compost, stockpile and slurry. Significant differences between storage methods resulting from the repeated measures analysis are indicated for periods delineated with the dashed lines. \* $P=0.05$ , \*\* $P=0.01$ , \*\*\* $P=0.001$ .

regressions to determine if variations in GHG emissions could be explained by changes in the chemical composition of beef manure. We tested for relationships between emissions and the following twelve chemical variables:  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ , inorganic nitrogen (INN), total carbon (TC), inorganic carbon (IC), total organic carbon (TOC), percent moisture (%W), pH, %N, %C, bulk density (BD), and ash content (ASH).

#### Estimation of annual GHG emissions

The overall GHG emissions from various storage methods were quantified by measuring GHG emissions from a known mass of manure. No fresh manure was added in the storage facility as is the usual practice on animal farms. This approach was selected in order to be able to assign the overall measured GHG emissions to a known mass of manure. The cumulative GHG emissions measured over the sampling period were considered

to be about 90% of the total emissions over the year.

#### Conversion of GHG emissions from a dry manure basis to a per head basis over a year

The average dairy cattle (IPCC, 2001, Table B-1 p4.39) and non-dairy cattle (IPCC, 2001, Table B-3 p4.43) dry manure produced per day and per head for North America were converted to volatile solids (VS) by dividing them by 92% (considering a proportion of 8% ash (IPCC, 2001)). The daily VS production was multiplied by 365 d to estimate the yearly production to be 1909 kg VS  $\text{hd}^{-1} \text{ year}^{-1}$  for dairy cattle and to be 858 kg VS  $\text{hd}^{-1} \text{ year}^{-1}$  for non-dairy cattle. The average non-dairy cattle manure production was applied to beef cattle production. The yearly GHG emissions in  $\text{CO}_2\text{-eq}$  estimated from the measurements were divided by the proportion of VS (92%) and then multiplied by the yearly

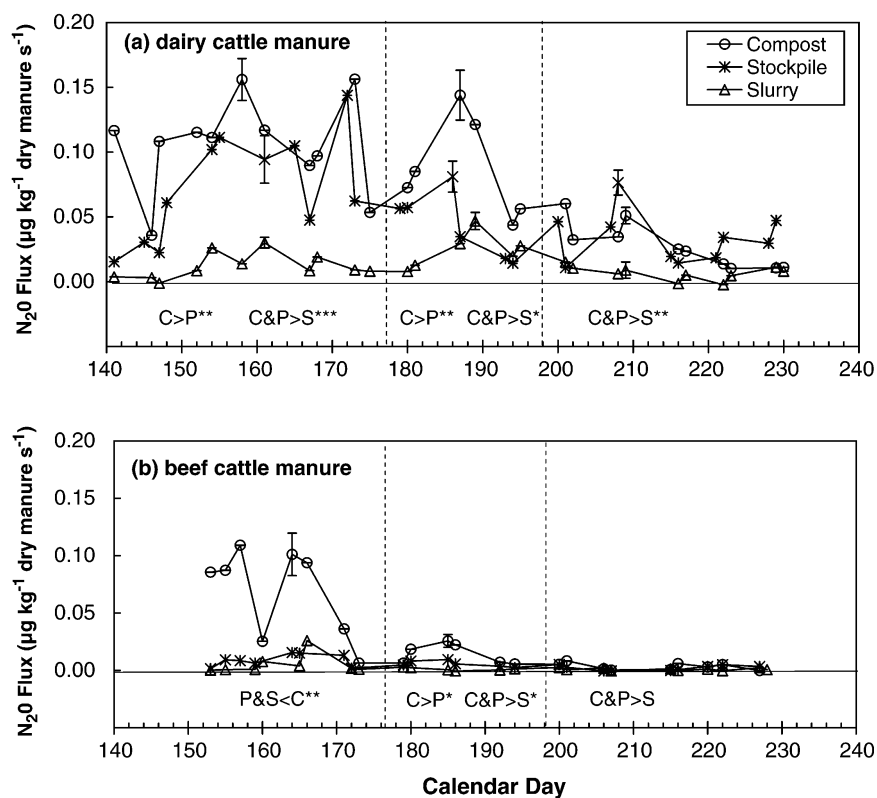


Figure 3. Nitrous oxide emissions from (a) dairy cattle manure and (b) beef cattle manure stored during the summer period as compost, stockpile and slurry. Significant differences between storage methods resulting from the repeated measures analysis are indicated for periods delineated with the dashed lines. \* $P=0.05$ , \*\* $P=0.01$ , \*\*\* $P=0.001$ .

averaged production of VS to express them on a per head and year basis.

#### Total GHG emissions in Canada from manure storage facility relevant to the experiment

The Canadian dairy cattle population is totaling 1.06 million cows and 0.72 million heifers (Statistics Canada 2003). Because the manure produced by a heifer is about half that of a dairy cow, the effective dairy cattle population was estimated to be 1.48 million heads. The beef cattle population on farms equipped with manure storage systems was estimated at 6.80 millions (Statistics Canada 2003). Because the proportion of beef calves is about 40% of the beef cattle and the proportion of manure produced by heifers is similar to that of beef cows, the effective beef cattle population was estimated to be 4.09 millions. The yearly  $\text{CH}_4$  plus  $\text{N}_2\text{O}$  emissions in  $\text{CO}_2\text{-eq}$  from manure produced per cattle were multiplied by the effective cattle

population in Canada on manure storage systems and the proportion of manure storage facility relevant to the experiment (for dairy cattle: 33% liquid/slurry and 40% solid; for beef cattle: 6% liquid/slurry and 57% solid) (Statistics Canada 2003) to obtain the total emissions in Canada from manure storage facility relevant to the experiment.

The total emissions for dairy and beef cattle manure by fully adopting a given storage system was obtained by multiplying the yearly  $\text{CH}_4$  plus  $\text{N}_2\text{O}$  emissions in  $\text{CO}_2\text{-eq}$  from manure produced per cattle by the product of the effective cattle population in Canada times the proportion of all the manure storage facilities relevant to the experiment, which is totaling 1.09 million dairy cattle and 2.59 millions beef cattle.

#### Reduction in emissions

The reduction in GHG emissions was calculated by removing from the actual total emissions in

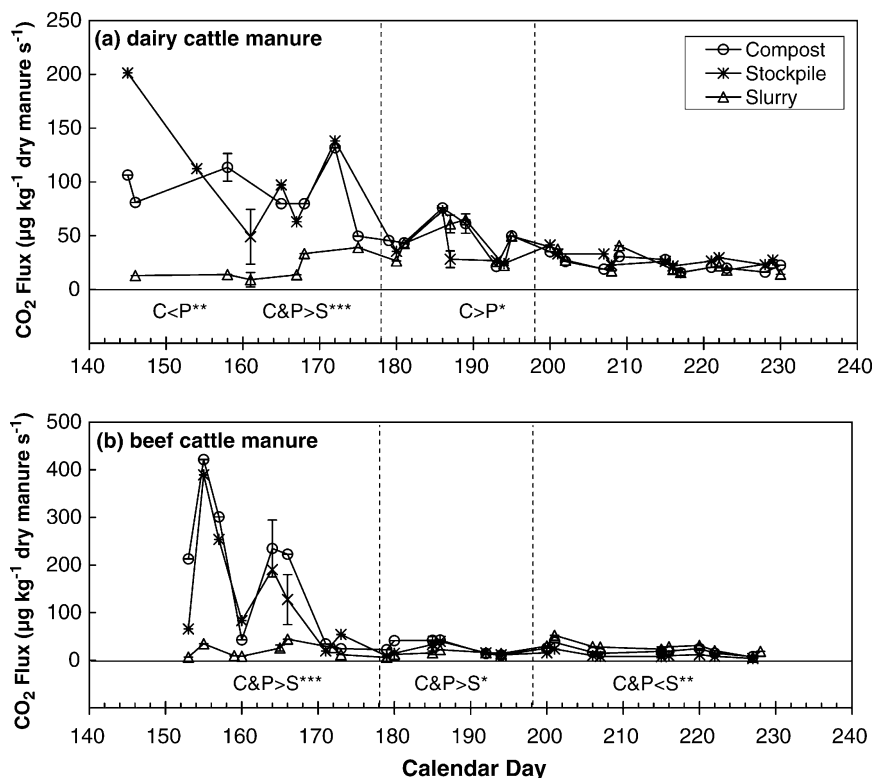


Figure 4. Carbon dioxide emissions from (a) dairy cattle manure and (b) beef cattle manure stored during the summer period as compost, stockpile and slurry. Significant differences between storage methods resulting from the repeated measures analysis are indicated for periods delineated with the dashed lines. \* $P=0.05$ , \*\* $P=0.01$ , \*\*\* $P=0.001$ .

Canada from either dairy cattle manure storage ( $0.57 \pm 0.35$ ) Tg CO<sub>2</sub>-eq year<sup>-1</sup> or beef cattle manure storage ( $0.08 \pm 0.15$ ) Tg CO<sub>2</sub>-eq year<sup>-1</sup> the total emissions by fully adopting a given storage method. No results were reported for slurry since adopting this storage method would generate a surplus when methane emissions are not recycled.

## Results and discussion

### Methane emissions

Methane emissions from composting dairy manure were initially low ( $< 2 \mu\text{g kg}^{-1} \text{ DM s}^{-1}$ ) and decreased throughout the experiment (Figure 2a). Large episodic CH<sub>4</sub> emissions from the stockpiled manure were measured in the initial period with peaks ranging from 2 to  $5 \mu\text{g kg}^{-1} \text{ DM s}^{-1}$ , which then decreased in the intermediate and final periods. Methane emissions from the slurry were low initially but did increase in the first period, peaked

in the intermediate period at  $5.7 \mu\text{g kg}^{-1} \text{ DM s}^{-1}$ , and then declined in the final period. Methane was still being emitted at the end of the experiment. Methane emissions from the stockpiled manure were significantly higher than from the slurry and from composting manure in the initial period (P1  $P < 0.001$ ) and higher than from the composting manure in the intermediate and final periods (P2  $P < 0.01$ , P3  $P < 0.05$ ).

Methane emissions from the composting beef manure were very low (Figure 2b). Methane emissions from the stockpiled beef cattle manure showed a similar pattern to the stockpiled dairy cattle manure, but the emissions were significantly lower ( $P=0.0012$ ), being a third of those of the dairy cattle manure. Seasonal CH<sub>4</sub> emissions from the beef cattle manure slurry were similar to CH<sub>4</sub> emissions from the dairy cattle manure slurry (Figure 2a and b).

Methane emissions from the composting beef manure were positively correlated with total inorganic nitrogen (Table 1), which consisted



Table 1. Effects of beef manure chemical composition on GHG emissions.

Treatment	Gas	Variable 1	Partial $R^2$	Variable 2	Partial $R^2$	Variable 3	Partial $R^2$	Other sig. variables	$R^2$
Compost	CH <sub>4</sub>	+INN	0.71						0.71
	N <sub>2</sub> O	+NH <sub>4</sub> <sup>+</sup>	0.64	-%N	0.13				0.77
	CO <sub>2</sub>	+NH <sub>4</sub> <sup>+</sup>	0.52	-%N	0.21	-BD	0.09		0.81
Stockpile	CH <sub>4</sub>	+IC	0.89	+Ash	0.04				0.92
	N <sub>2</sub> O	+pH	0.35	+IC	0.19				0.53
	CO <sub>2</sub>	+IC	0.81	-Ash	0.09	+%W	0.06	-%N	0.98
Slurry	CH <sub>4</sub>	+pH	0.27						0.27
	N <sub>2</sub> O	No significant variables							
	CO <sub>2</sub>	No significant variables							

Models were created using Proc Stepwise in SAS. Only variables which were significant at  $\alpha=0.05$  using the Type II SS are included. %W – water content; INN – Inorganic nitrogen; TC – Total carbon; IC – Inorganic carbon; BD – Bulk density; TOC – Total organic carbon.

mostly of NH<sub>4</sub><sup>+</sup> in the first period and of NO<sub>3</sub><sup>-</sup> in the second period. Ammonium is a primary source of N for methanogenic bacteria (Knowles 1993). Consequently, ammonium promotes bacterial growth and CH<sub>4</sub> production. In the stockpiled manure, CH<sub>4</sub> emissions were positively correlated with the concentration of inorganic carbon, which was initially high in P1 and tended to decrease over time. In the slurry, CH<sub>4</sub> emissions were positively correlated with pH. However, the low  $R^2$  of the regression model indicates that different descriptors are needed to better predict CH<sub>4</sub> emissions.

Methane emissions were positively correlated with core and surface temperatures (Tables 2 and 3).

As temperature increased, higher rates of methanogenesis occurred in all manure storage types, although overall increases in slurry temperature resulted in the largest increase in CH<sub>4</sub> production. The methanogenic bacteria responded to the increased temperature and enhanced anaerobic environment. Anaerobic microsites were less common in the stockpiled manure, thus increases in temperature resulted in less increase in CH<sub>4</sub> production than in the slurry. In the initial period, small amounts of CH<sub>4</sub> were produced in the composting manure when core temperatures increased and some anaerobic sites remained. In the stockpiled manure and compost, CH<sub>4</sub> production was low in the intermediate and final

Table 2. Effects of environmental conditions on GHG emissions from dairy cattle manure.

Treatment	Gas	Variable 1	Partial $R^2$	Variable 2	Partial $R^2$	Variable 3	Partial $R^2$	Other significant variables	$R^2$
Compost	CH <sub>4</sub>	+T <sub>S</sub>	0.58	-T <sub>a</sub> 3	0.07				0.65
	N <sub>2</sub> O	+T <sub>C</sub>	0.36	-Δ P 1	0.05				0.40
	CO <sub>2</sub>	+T <sub>C</sub>	0.54	+RH	0.03				0.57
Stockpile	CH <sub>4</sub>	+T <sub>S</sub>	0.50	+T <sub>C</sub>	0.08	-θ	0.06	-T <sub>a</sub> 1; -Δ P 3	0.70
	N <sub>2</sub> O	NONE							
	CO <sub>2</sub>	+T <sub>S</sub>	0.50	-U	0.04	+T <sub>C</sub>	0.04	+RH	0.62
Slurry	CH <sub>4</sub>	+T <sub>C</sub>	0.52	+T <sub>S</sub>	0.03				0.55
	N <sub>2</sub> O	+T <sub>S</sub>	0.20	-Δ P 3	0.05				0.25
	CO <sub>2</sub>	+T <sub>C</sub>	0.45	-U	0.05				0.50

Models were created using Proc Stepwise in SAS. Only variables which were significant at  $\alpha=0.05$  using the Type II SS are included.

T<sub>a</sub> – Mean ambient temperature averaged over: 1 = 9:00–12:00, 2 = 6:00–9:00, 3 = 6:00–12:00, 4 = 0:00–6:00

P – Mean ambient pressure averaged over: 1 = 9:00–12:00, 2 = 6:00–9:00, 3 = 6:00–12:00, 4 = 0:00–6:00

ΔP = Pressure change. Change calculated over: 1 = 3 h, 2 = 6 h, 3 = 12 h, 4 = 24 h

RH – Relative humidity

U – Wind speed

θ – Wind direction

T<sub>S</sub> – Surface temperature

T<sub>C</sub> – Core temperature

Table 3. Effects of environmental conditions on GHG emissions from beef cattle manure.

Treatment	Gas	Variable 1	Partial $R^2$	Variable 2	Partial $R^2$	Variable 3	Partial $R^2$	Other significant variables	$R^2$
Compost	CH <sub>4</sub>	$T_S$	0.60	$U$	0.16				0.75
	N <sub>2</sub> O	$T_S$	0.68	$\Theta$	0.06	$\Delta P$ 1	0.02	RH	0.80
	CO <sub>2</sub>	$T_S$	0.74	$U$	0.11	$\Theta$	0.001		0.86
Stockpile	CH <sub>4</sub>	$T_C$	0.43	$U$	0.05				0.48
	N <sub>2</sub> O	$T_C$	0.08	$T_a$ 3	0.07				0.20
	CO <sub>2</sub>	$T_C$	0.68	$U$	0.10	$T_S$	0.02		0.81
Slurry	CH <sub>4</sub>	$T_a$ 1	0.20	$U$	0.05				0.25
	N <sub>2</sub> O	No significant variables							
	CO <sub>2</sub>	$U$	0.37	$T_a$ 1	0.10	$\Theta$	0.07		0.54

Models were created using Proc Stepwise in SAS. Only variables which were significant at  $\alpha=0.05$  using the Type II SS are included.

$T_a$  – Mean ambient temperature averaged over: 1: 9:00–12:00, 2: 6:00–9:00, 3: 6:00–12:00, 4: 0:00–6:00

$P$  – Mean ambient pressure averaged over: 1: 9:00–12:00, 2: 6:00–9:00, 3: 6:00–12:00, 4: 0:00–6:00

$\Delta P$  – Pressure change calculated over: 1: 3 h, 2: 6 h, 3: 12 h, 4: 24 h

RH – Relative humidity

$U$  – Wind speed

$\theta$  – Wind direction

$T_S$  – Surface temperature

$T_C$  – Core temperature

periods. As temperatures decreased and organic material decomposed, the manure became more porous and aerated, which caused CH<sub>4</sub> emissions to decline.

#### Nitrous oxide emissions

Nitrous oxide emissions from composted and stockpiled dairy cattle manure were variable in the first period, ranging from 0.05 to 0.16  $\mu\text{g kg}^{-1} \text{DM s}^{-1}$  (Figure 3a), and decreased considerably during the final period ( $<0.08 \mu\text{g kg}^{-1} \text{DM s}^{-1}$ ). Nitrous oxide emissions from the composting manure were significantly higher than emissions from stockpiled manure in the initial and intermediate periods ( $P < 0.01$ ,  $P < 0.01$ ). Nitrous oxide emissions from slurry were relatively low ( $<0.05 \mu\text{g kg}^{-1} \text{DM s}^{-1}$ ) and significantly lower than from the composted and stockpiled manure ( $P < 0.05$ ).

Nitrous oxide emissions from composted beef cattle manure were highly variable initially (0.03–0.11  $\mu\text{g kg}^{-1} \text{DM s}^{-1}$ ), and were low in the intermediate and final periods ( $<0.03 \mu\text{g kg}^{-1} \text{DM s}^{-1}$ ) (Figure 3b). Nitrous oxide emissions from the stockpiled manure and slurry were low throughout the experiment ( $<0.03 \mu\text{g kg}^{-1} \text{DM s}^{-1}$ ). Nitrous oxide emissions from the composting manure were higher

than from the stockpiled manure and slurry in the initial period ( $P < 0.001$ ), whereas they were similar from the stockpiled manure and slurry. In the intermediate and final periods, the N<sub>2</sub>O emissions from both the composted and stockpiled manure were higher than from the slurry ( $P < 0.01$ ,  $P < 0.05$ ).

Chemical changes in composted and stockpiled beef cattle manure indicate that initial N<sub>2</sub>O emissions were a result of nitrification, while later N<sub>2</sub>O emissions were a result of low levels of denitrification (Table 4). During composting NH<sub>4</sub><sup>+</sup> reached a peak value after 12 days at 4.2 mg g<sup>-1</sup> then decreased to 0.2 mg g<sup>-1</sup> (data not shown). Inorganic C concentration followed a similar trend to that of NH<sub>4</sub><sup>+</sup> concentration. NO<sub>3</sub><sup>-</sup> peaked at 1300 mg g<sup>-1</sup>, right after ammonium decreased and stabilized at 700 mg g<sup>-1</sup>. Ammonium concentration remained low in the stockpiled manure, while inorganic C increased from 40 to 78 ppmv in 12 days then decreased to 19 ppmv. Shortly after the decrease in inorganic C, NO<sub>3</sub><sup>-</sup> concentration increased, indicating that inorganic C was the primary source of N for nitrification

Because there were limited N<sub>2</sub>O emissions from the slurry, both the chemical and environmental statistical models were ineffective at partitioning the variance and had little predictive value (Tables 1, 2 and 3). For both types of composted cattle manure, measurements of temperature

Table 4. Changes in the chemical composition of manure stored under different conditions.

Storage Condition	Sampling time	NH <sub>4</sub> <sup>+</sup> $\mu\text{g g}^{-1}$	NO <sub>3</sub> <sup>-</sup> $\mu\text{g g}^{-1}$	pH	C/N	Bulk Density $\text{g l}^{-1}$	% Moisture
<i>Dairy cattle manure</i>							
	Start	1383	9	N/A	20.1	N/A	74.2
Compost	37 days	2010	1790	N/A	16.5	N/A	74.2
Stockpile	37 days	850	679	N/A	14.8	N/A	74.3
Slurry	37 days	940	0	N/A	19.9	N/A	82.2
<i>Beef cattle manure</i>							
	Start	1670	4	9.01	35.0	69.2	58.0
Compost	End	197	722	9.15	17.6	113.8	57.7
Stockpile	End	265	1078	8.65	17.4	79.0	63.1
Slurry	End	492	53	7.31	21.5	89.7	86.2

Measurements were taken at the start, after 37 days (end of first period) for dairy cattle manure, and at the end of the beef cattle manure experiment. N/A indicates where a measurement was not taken.

(surface and core) accounted for most of the variations in N<sub>2</sub>O emissions (Tables 2 and 3). Composted dairy and beef cattle manure had the highest mean core temperatures in the initial period (50–72 °C). This result indicates that the Passively Aerated Windrow System was effective at increasing the aeration of the manure and that there were high levels of exothermic reactions with O<sub>2</sub>. Stockpiled manure and slurry core temperatures were higher than ambient air temperature during the daytime by about 10–60 and 5–15 °C respectively.

Seasonal N<sub>2</sub>O emissions from dairy cattle manure and beef cattle manure were very different (Figure 3a and b). There were more N<sub>2</sub>O emissions from stockpiled dairy cattle manure than from stockpiled beef cattle manure. Nitrous oxide emissions from composted dairy cattle manure were similar to those of beef cattle manure in the initial period, but were higher in the intermediate and final periods. Greater denitrification from dairy cattle manure in the intermediate and final periods may account for the higher N<sub>2</sub>O emissions.

#### Carbon dioxide emissions

Carbon dioxide emissions from composted and stockpiled dairy cattle manure were high initially (50–200  $\mu\text{g kg}^{-1} \text{DM s}^{-1}$ ) but decreased with time (Figure 4a). Carbon dioxide emissions from the slurry slowly increased to a maximum of 65  $\mu\text{g kg}^{-1} \text{DM s}^{-1}$  on CD 189 and then decreased. Carbon dioxide emissions from the composting manure and the stockpiled manure

were significantly higher than for the slurry ( $P < 0.001$ ) in the initial period. In the intermediate period, CO<sub>2</sub> emissions from the composting manure and slurry were higher than from the stockpiled manure ( $P < 0.05$ ). By the final period, CO<sub>2</sub> emissions were low ( $< 50 \mu\text{g kg}^{-1} \text{DM s}^{-1}$ ), and there were no significant differences among treatments.

Carbon dioxide emissions from the composting and stockpiled beef cattle manure increased in the first week up to  $\sim 400 \mu\text{g kg}^{-1} \text{DM s}^{-1}$  then decreased rapidly (Figure 4b). There was no seasonal trend in CO<sub>2</sub> emissions from the slurry. Initially, CO<sub>2</sub> emissions from the composting manure and stockpiled manure were higher than the slurry ( $P < 0.001$ ), but CO<sub>2</sub> emissions from the composting manure and stockpiled manure were not significantly different. Emissions were low for the rest of the season ( $< 50 \text{mg kg}^{-1} \text{DM s}^{-1}$ ), but emissions from the composting manure and the stockpiled manure were still greater than from the slurry ( $P < 0.01$ ).

Carbon dioxide emissions from the composting beef cattle manure were correlated with NH<sub>4</sub><sup>+</sup> concentration. In the stockpiled manure, CO<sub>2</sub> emissions were correlated with inorganic C concentrations. There were little CO<sub>2</sub> emissions from the slurry, thus correlation between chemical variables and CO<sub>2</sub> emissions were limited.

Carbon dioxide emissions from the composting and stockpiled manure were positively correlated with manure temperatures (surface and core, Tables 2 and 3) which were much higher than ambient temperatures. These results indicate that, initially, there were high levels of aerobic decomposition. The decrease in CO<sub>2</sub> emissions over time

indicates that most of the organic material may have been consumed by microbes.

Trends in CO<sub>2</sub> emissions were similar for both experiments, although initial emissions from beef cattle manure were higher than from dairy cattle manure. Beef cattle manure was better aerated due to a higher proportion of bedding material. The rapid respiration of organic carbon causing the peak in CO<sub>2</sub> emissions was likely caused by higher O<sub>2</sub> levels. Carbon dioxide emissions from dairy cattle manure slurry reached a peak in the middle of the experiment, whereas CO<sub>2</sub> emissions from beef cattle manure slurry were consistently low.

### Management recommendations and potential impact for Canada

Total emissions of CH<sub>4</sub> and N<sub>2</sub>O (g kg<sup>-1</sup> DM) were calculated for each storage system for both types of manure (Table 5). To obtain an estimate of the effect of each manure storage treatment on global warming, CH<sub>4</sub> and N<sub>2</sub>O emissions were multiplied by their respective global warming potential (IPCC 2001). The largest combined N<sub>2</sub>O–CH<sub>4</sub> emissions in CO<sub>2</sub> equivalent were observed from the slurry storage, followed by the stockpile and lastly the passively aerated compost. This ranking was governed by CH<sub>4</sub> emissions in relation to the degree of aerobic conditions within the manure. The radiative forcing in CO<sub>2</sub> equivalent from the stockpiled manure was 1.46 times higher than from the compost for both types of cattle manure. It was almost twice as high from the dairy cattle manure slurry and four to seven times higher from the beef cattle manure slurry than from the compost. Negligible methane emissions were found (Lessard et al. 1997) following field application of stockpiled or composted dairy manure at a rate of up to 100Mg ha<sup>-1</sup> (equivalent to ~20 Mg DM ha<sup>-1</sup>), while N<sub>2</sub>O emissions were 10 times lower than the emissions during storage, being equivalent to 1% of N added (Lessard et al. 1996) or equivalent to 0.047 g N<sub>2</sub>O–N kg<sup>-1</sup> DM. Using the model of Sommer et al. (2004) and the dairy cattle slurry chemical composition of Paul and Zebart (1997), to estimate N<sub>2</sub>O emissions following the field application of slurry provide estimates in the range of 0.20 g N<sub>2</sub>O–N kg<sup>-1</sup> DM, which is twice as much as during storage. Rochette

Table 5. GHG emissions in g kg<sup>-1</sup> and in CO<sub>2</sub> equivalent over a 3-month summer storage period using global warming potentials of 23 for methane and 296 for N<sub>2</sub>O.

Storage conditions	CH <sub>4</sub> gCH <sub>4</sub> kg <sup>-1</sup> DM	N <sub>2</sub> O gN <sub>2</sub> O kg <sup>-1</sup> DM	CO <sub>2</sub> gCO <sub>2</sub> kg <sup>-1</sup> DM	CH <sub>4</sub> gCO <sub>2</sub> -eq kg <sup>-1</sup> DM	N <sub>2</sub> O gCO <sub>2</sub> -eq kg <sup>-1</sup> DM	CH <sub>4</sub> +N <sub>2</sub> O gCO <sub>2</sub> -eq kg <sup>-1</sup> DM
<i>Dairy cattle manure</i>						
Compost	1.52	0.582	398.58	35.0	172.3	207.2
Stockpile	7.92	0.403	440.00	182.2	119.3	301.4
Slurry	15.96	0.101	208.13	367.1	29.9	397.0
Slurry (5-month estimates) <sup>a</sup>	24.77	0.101	231.25	569.8	29.9	599.7
<i>Beef cattle manure</i>						
Compost	0.14	0.162	340.06	3.2	48.0	51.2
Stockpile	2.85	0.034	358.11	65.6	10.1	75.6
Slurry	9.76	0.017	141.69	224.5	5.0	229.5
Slurry (5 months)	15.15	0.017	157.43	348.5	5.0	353.5

<sup>a</sup> Estimation obtained by multiplying the 3-month slurry dairy cattle manure emissions by the ratio of 5-month over 3-month of the slurry beef cattle manure emissions.

et al. (2000) derived an emission factor of 1.65% of N applied for pig slurry. Combining storage and field application, confirmed that the highest N<sub>2</sub>O–CH<sub>4</sub> emissions in CO<sub>2</sub>-eq kg<sup>-1</sup> DM came from manure stored as slurry followed by stockpiled and then compost. Indeed, emissions following manure application were estimated to be less or equal to 7% of the combined storage and field application N<sub>2</sub>O–CH<sub>4</sub> emissions expressed in CO<sub>2</sub>-eq kg<sup>-1</sup> DM.

The results of this study (Table 5) were extrapolated for Canada (Table 6), as detailed in the material and method section, using the dry manure produced per head per year and using the conversion of dry manure into volatile solids given by IPCC (2001) and the results from the 2001 census and special survey (Statistics Canada 2003). The extrapolation does not account for possible variations in weather conditions and manure composition across Canada. The reduction of GHG emissions brought by several mitigation scenarios was estimated using the extrapolation for Canada. A reduction of 0.70 Tg CO<sub>2</sub>-eq year<sup>-1</sup> could be achieved by composting all the cattle manure stored as slurry and stockpile in Canada, using the passively aerated windrow system (Table 6). Composting would generate only minor additional costs (i.e. the perforated pipes) if the technique used in this study is adopted since no

mechanical aeration is required. Another mitigation option could be to collect and burn the CH<sub>4</sub> emitted from the existing slurry facilities. In this case a reduction of 0.76 Tg CO<sub>2</sub>-eq year<sup>-1</sup> could be achieved. If all the cattle manure stored in facilities relevant to the experiment was stored as slurry and CH<sub>4</sub> collected and burned, then a reduction of 1.08 Tg CO<sub>2</sub>-eq year<sup>-1</sup> could be achieved. Collecting and using CH<sub>4</sub> on farm involve additional costs that can be offset to some extent by the energy saving (e.g. Martin 2003; Engler et al. 2003). Based on the 6% GHG reduction commitment by 2008–2012 in the Kyoto protocol, it is anticipated that the Canadian agricultural sector will need to reduce GHG emissions by about 7.75 Tg CO<sub>2</sub>-eq year<sup>-1</sup> (Boehm et al. 2004). If one assumes full adoption of the proposed mitigation options, the cattle manure storage practice might contribute between 9–14% of the objective. Manure stored as slurry could also be applied to fields as fertilizer prior to crop growth to avoid the increase in temperature during the summer, which would reduce GHG emissions. If slurry must be stored during the summer, Sommer et al. (2000) suggest that surface covers, such as straw, could reduce GHG emissions. The dairy cattle manure had higher radiative forcing than that of the beef cattle manure for all the storage methods (Table 5).

Table 6. Annual GHG emissions during storage expressed in t CO<sub>2</sub> equivalent per head, which are relevant to cool conditions in North America.

	Dairy cattle			Beef cattle		
	Slurry	Stockpile	Compost	Slurry	Stockpile	Compost
CH <sub>4</sub> emissions (t CO <sub>2</sub> -eq hd <sup>-1</sup> year <sup>-1</sup> ) <sup>a</sup>	1.301	0.416	0.080	0.357	0.067	0.003
N <sub>2</sub> O emissions (t CO <sub>2</sub> -eq hd <sup>-1</sup> year <sup>-1</sup> ) <sup>a</sup>	0.068	0.272	0.393	0.005	0.010	0.049
Thousands of effective animals/storage system in Canada <sup>b</sup>	491	597		249	2345	
Total emissions for relevant storage systems in Canada (Tg CO <sub>2</sub> -eq year <sup>-1</sup> )	0.672	0.411		0.090	0.182	
Total Canadian emissions from dairy/beef cattle manure by fully adopting a given storage system (Tg CO <sub>2</sub> -eq year <sup>-1</sup> )	1.489	0.749	0.515	0.941	0.201	0.136
Reduction in Canadian emissions (Tg CO <sub>2</sub> -eq year <sup>-1</sup> )		-0.334	-0.568		-0.071	-0.136

Actual and potential annual GHG emissions for Canada during storage for systems relevant to the experiment and potential reduction by converting to a given storage system, all expressed in Tg CO<sub>2</sub> equivalent.

<sup>a</sup>Assuming an increase of 10% in emissions to account for emissions beyond the sampling period. Using 100-year global warming potentials, yearly dry manure production per cattle head and conversion of dry manure into volatile solids provided by IPCC (2001).

<sup>b</sup># of effective cattle animals multiplied by the proportion of storage facilities relevant to the experiment extracted from Statistics Canada (2003).

In order to estimate this impact of the study's results for North America under cool conditions, new CH<sub>4</sub> emission factors were calculated by first dividing the mass of the dry manure by 0.92 to convert it into volatile solids and then incorporating the measured emissions into the IPCC methodology, which had proportions of storage practices already assigned. Emission factors were calculated (i) using the measured emissions as input and (ii) assuming a 10% increase in the measured emissions to account for emissions outside the sampling period. For North-America under cool conditions, the new CH<sub>4</sub> emission factors were estimated to be 45.2 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for dairy cattle manure rather than 36 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup>, and 2.7 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for beef cattle manure rather than 1 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup>. By using the proportion of manure storage practices relevant to Canada the emission factors become 35.8 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for dairy cattle manure and 4.1 kg CH<sub>4</sub> hd<sup>-1</sup> year<sup>-1</sup> for beef cattle manure. This estimation shows how sensitive the emission factors are to the allocation of the manure storage practices proportion.

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