Chamber measurement methods and aeration effect on greenhouse gas fluxes during composting

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Abstract: Composting has the potential to mitigate methane (CH_4) and nitrous oxide (N_2O) emissions from manure. The heterogeneous nature of emitting surfaces makes it difficult to quantify these emissions. CH_4 and N_2O fluxes measured using eight small chambers (0.72 m^2) and a mega chamber (90 m^2) were compared, and the effect of aeration on the fluxes during composting was studied. Two batches of compost were placed in three channels and 2-3 small flux chambers were deployed on each channel. The channels were enclosed by a building serving as a mega chamber. Chamber location significantly affected gas fluxes, pointing to strong spatial heterogeneity. Mean CH_4 fluxes from the small chambers were similar or 1.4 times higher compared to the mega chamber. Mean N_2O fluxes from the small chambers were 50%-55% lower compared to the mega chamber. Channel edges, not captured by the small chambers, were potentially significant 'hot spots' for N_2O production. When only small chambers are used for flux measurements, a large number should be strategically positioned to cover different areas of the emitting surface so as to capture a representative flux. On the other hand, if a few small chambers are used, they should be moved frequently to different locations on the emitting surface. Temporal variations in CH_4 and N_2O fluxes were similar for all the chambers, including periods with active aeration. Correlation of total aeration time with CH_4 fluxes was insignificant (r = -0.097), but was positive with N_2O (r = 0.556). The flushing of stored CH_4 at the onset of aeration, likely promoted fluxes, as opposed to the expected flux decrease with higher aeration time. The purging of stored N_2O enhanced the expected stimulation of N_2O production at high aeration times, resulting in the positive trend observed for N_2O fluxes. Our results suggest that a mega chamber that covers a larger emitting surface area can avoid biases in flux estimates due to spatial variability of the source.

Keywords: chamber measurements, compost, greenhouse gases, aeration, flux

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1 Introduction

Increased concentrations of greenhouse gases (GHG) are of environmental concern because of its negative implications to the global climate. Manure management is an important source of anthropogenic methane (CH_4) and nitrous oxide (N_2O) (Mosier et al., 1998a, b), and alternative manure management has the potential of contributing to GHG emission reduction (Desjardins et al., 2001).

Methane is produced by acetoclastic methanogens (Husher et al., 1982) and hydrogen utilizing methanogens (König, 1984) under anaerobic conditions. Nitrous oxide is generated by several different processes, including the nitrification process when nitrifiers confront microaerophilic conditions (Poth and Focht, 1985; Remde and Conrad, 1990; Wrage et al., 2001), and by

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denitrification in anaerobic conditions (Knowles, 1982). Anaerobically stored liquid manure is favorable for CH_4 production, but not for N_2O (Park et al., 2006), while solid manure storage is a significant source of both CH_4 and N_2O (Janzen et al., 1998; Pattey et al., 2005). Close to 86% of swine production in Canada utilize liquid manure storage systems (Statistics Canada, 2003), leading to environmental concerns related to air and water quality (Jongbloed and Lenis, 1998).

Composting is a livestock manure treatment process based on biological decomposition of organic matter under controlled aerobic conditions (Epstein, 1997). It is considered an ecologically efficient management system with benefits of destroying most parasites, pathogens, and plant seeds contained in the organic substrate, and reducing malodors and the volume of material to be applied to agricultural land (Peigné and Girardin, 2004). Manure with high-moisture content and low carbon-to-nitrogen (C/N) ratio require mixing with a carbon source, which also serves as a bulking agent, to create conditions suitable for composting to occur (Haug, 1993). Forced aeration or aeration by mechanical turning is needed during composting to ensure enough oxygen is delivered to maintain aerobic conditions (Rynk et al., 1992). However, despite aeration, partial anaerobic zones may still be present in compost, so that aerobic and anaerobic decomposition of composting materials coexist (Epstein, 1997; Rynk and Richard, 2001).

Composting liquid swine manure after mixing with straw in mechanically and forced-aeration channels (Fleming et al., 1999), or after mixing with sawdust (Keener et al., 2001; Zhu et al., 2004) has been proposed to mitigate malodors and other environmental concerns associated with liquid manure storage (Honeyman, 1996). While most existing studies indicated that the composting process can be a source of GHG for high-moisture and low C/N materials (Brown et al., 2008), composting has been proposed to mitigate GHG emissions when sufficient aeration is used (Lopez-Real and Baptista, 1996; Thompson et al., 2004; Pattey et al., 2005).

Several methods have been used to quantify GHG emissions during composting, such as static chambers (Andersen et al., 2010a; Hao et al., 2001, 2004; Sommer et al., 2004) and dynamic chambers (Eckley et al., 2010; Fukumoto et al., 2003; Thompson et al., 2004). Dynamic chambers allow a steady-state gas concentration gradient at the surface-air interface due to continuous flow of external air through the chamber, which makes it possible for a continuous measurement of fluxes (Breuninger et. al., 2012; Lapitan et al., 1999). Spatial variability of the emitting surface is a major problem in making estimates of gas fluxes using the chamber method. The small measuring area (mostly <0.5 m^2) of chamber methods can therefore produce biased results of gas emissions depending on the chamber location, especially with heterogeneous sources such as compost (Sommer et al., 2004). This has prompted the need for chamber standardization (Parker et al., 2013) for easy comparison of fluxes. Despite the standardisation, larger chambers may still produce better results since the spatial variability and the number of replicates on the emitting surface can be reduced. For example, Thompson et al. (2004) used a dynamic mega chamber, which was made by enclosing an entire composting facility, in order to quantify CH_4 and N_2O emissions without disturbing the composting procedure, while integrating emissions over the whole source area. Comparison of different chamber approaches is necessary to increase confidence in measurement techniques and allow for inter-comparison of studies (McGinn, 2006; Rochette and Eriksen-Hamel, 2008).

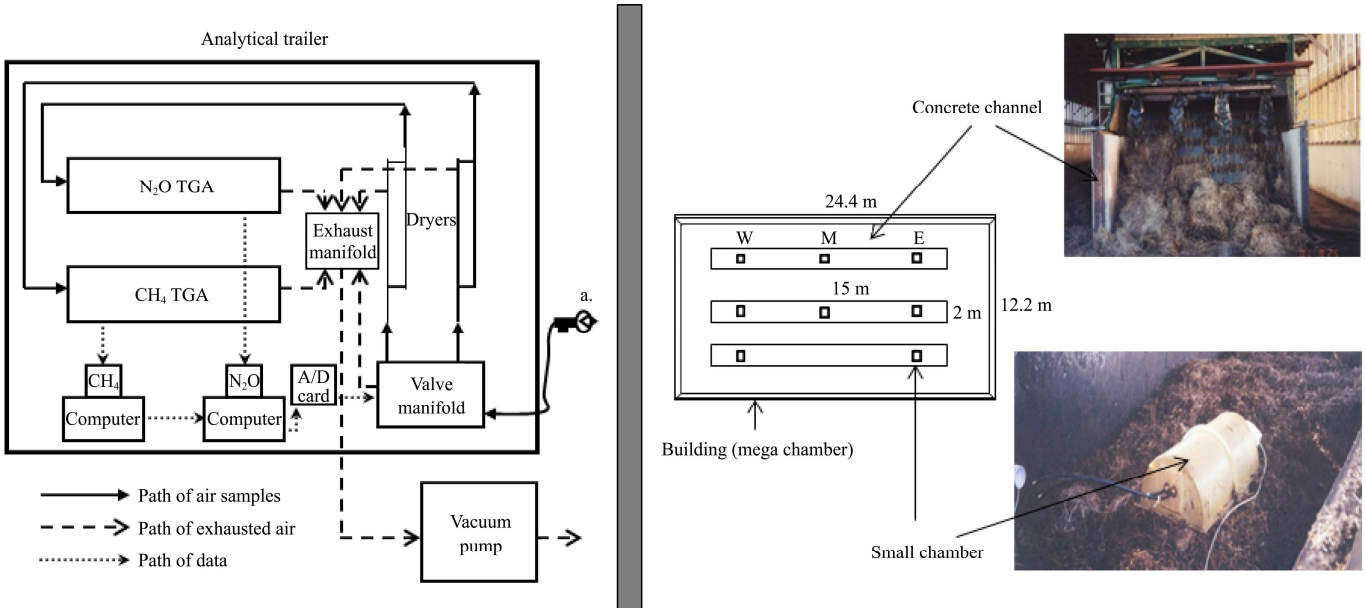
The overall objective of this study was to assess the use of chambers in relation to their size and location to measure gas fluxes during composting. Specifically, it was aimed at comparing CH_4 and N_2O fluxes measured using conventional dynamic chambers and a mega chamber during the in-vessel composting of liquid swine manure with straw. In addition, the effect of aeration on CH_4 and N_2O emissions during the composting process was also characterized.

2 Materials and methods

2.1 Composting facility

This study was carried out at the composting facility of the University of Guelph, Ridgetown campus, Canada

(42.26°N, 81.73°W). The facility is an in-vessel system, with forced aeration and mechanical turning designed to compost liquid swine manure through mixing with a bulking agent such as wheat straw (Fleming et al., 1999). It has three open-end concrete channels, each 15 m long, 2 m wide, and 1.6 m deep. The channels are enclosed by a 24.4 m long by 12.2 m wide building (Figure 1). The composting process was started by placing straw bales into the channels (Table 1). Swine manure was then pumped from a holding tank and added to the straw through a hose mounted on a hydraulic compost turner (Marvel, Global Earth Products, Utopia, ON), which ran along steel tracks on the top of each channel wall (speed, 1.2 m/min) while mixing both materials. Typically, during the two-week composting process, manure was applied three times on 1st, 4th or 5th, and 8th day. Sub-channels for aeration were present below the floors of the compost channels (a plenum system), each connected to its own aeration fan attached to the outside of the building and aerated at a rate of 1.883 m^3/s at a static pressure of 0.5 kPa (Thompson et al., 2004). Aeration was automatically controlled by feedback from six temperature probes (T 24-AWG, Omega Technologies Inc. USA) in each channel.



Note: The left part shows the layout of the equipment comprising the tunable diode laser trace gas analyzers (TGA) for N_2O and CH_4 analyses, computers and air sampling system (pump, dryers, valve and exhaust manifold) housed in a mobile trailer. One of 16 intakes the valve manifold can sample are shown (labeled a.). The right part shows a schematic of the facility used for in-vessel composting of liquid swine manure. Letters indicate chamber location within each channel (W: West end, M: Middle, E: East end). It also includes pictures of the concrete channel and one of the small chambers.

Figure 1 Equipment layout and a schematic of the composting facility

Two batches of compost were processed in July and in September, 2004 (Table 1). Measurement periods of about two weeks were chosen for each batch to provide an in-depth assessment of the temporal dynamics of emissions captured by the two chamber techniques. Additional measurement campaigns would have been ideal, but were limited by the available resources. Nevertheless, we did not identify any specific reasons for large variability in results *a priori* given that a standard composting procedure was followed for each batch. The channels were seeded with previously made compost. Different aeration regimes were used for each of the three channels when compost temperature exceeded 66°C (Table 2). All the channels were subjected to the same low aeration rate when the temperatures were below 66°C. Times were recorded when the aeration fans were operated.

2.2 Experimental setup

Measurements of CH_4 and N_2O fluxes during composting was carried out with in-house designed dynamic fiberglass chambers, henceforth referred to as small chambers, and a mega chamber approach from July

30 to August 15 (Batch 1) and from September 14 to October 1 (Batch 2). The small chambers were a 60 cm diameter semi-circular dome with a rectangular base (60 cm in width and 120 cm in length), and a total air headspace volume of 170 L (Figure 1). The bottom of the dome had a 20 cm skirt with a 5 cm ledge at the top. Eight small chambers were available for this experiment. Two air inlets with 15.9 mm bulkhead unions (Swagelok, Niagara Falls, ON) were placed on one end, and one 10 cm diameter air outlet was placed on the other end of each small chamber. Sixteen air flow meters (each with a maximum setting of 0.788 L/s) were attached to a blower, and two air flow meters per small chamber were used for controlling the air flow rate through each small chamber at 1.58 L/s (2.19 L/s per m^2 surface area of the small chamber).

Table 1 Quantity of straw and seeding material used for composting of liquid swine manure

Batch	Starting date (composting duration)	Seeding/kg	Straw/kg	Volume of manure applied[1]/L	Manure application rate[2]/L kg^{-1}
1	July 30 (15 days)	1057	3360	21457	6.4
2	Sept. 14 (18 days)	1872	4210	23763	5.6

Note: 1. Approximately 40%, 40% and 20% during first, second and third manure applications; 2. Manure applied per weight of straw used.

Table 2 Aeration regimes used during the composting process

Channel	Batch 1 (July 30–Aug. 19)	Batch 2 (Sept. 14–Oct. 1)
Channel 1 (spigot)[1]	2 min / 10 min[2] (L)	4 min / 10 min (H)
Channel 2 (gutter)	3 min / 10 min (N)	3 min / 10 min (N)
Channel 3 (gutter)	4 min / 10 min (H)	2 min / 10 min (L)

Note: 1. Aeration system used in each channel; 2. Aeration time per designated time period (e.g., 2 min aeration per 10 min); 3. When composting temperature was below 66℃, all channels received aeration at a rate of 3 min/h. High (H), medium (N), and low (L) rates were applied to different channels as shown, when composting temperature exceeded 66℃.

The criteria we used for placement was to attempt to evenly space the chambers in the compost channels. We were limited to eight chambers available and hence, three small chambers were placed in each of channels 1 and 2 while two small chambers were placed in channel 3 (Figure 1). In an effort to have a representative coverage of each channel, the small chambers were placed towards the end and in the middle section (Figure 1). All chambers were placed parallel to the length of the 2 m wide channels, half-way between the surrounding concrete walls, so as to avoid any edge effects. The area covered by the small chambers was quite large (0.72 m^2) and hence did not require and/or allow for a systematic grid-based sampling. The small chambers were removed during manure application and compost mixing.

The building housing the composting system allowed for complete enclosure of the composting area, permitting the application of the 'mega chamber' concept (Denmead, 1994). Two electric barn fans (Model 6–91, Wickham, Johnson, QB) were placed in the front and rear entrances of the building and used to provide the airflow, with one fan used to draw air into the chamber and the other to expel air, as per setup used at the same site by Thompson et al. (2004). Monitoring of the fluxes from all three channels, even during manure application, was possible with this approach. Details on the measurement of the fans' wind speed profile and of N_2O tracer release experiment to verify the air flow rate (5.7 m^3/s) are given in Thompson et al. (2004). The average air flow rate of 5.7 m^3/s was equivalent to 0.02 m^3/s per m^2 surface area of the mega chamber.

The trace gas analyzing system, used for quantifying CH_4 and N_2O concentrations, consisted of two tunable diode laser trace gas analyzers (TGA100, Campbell Scientific Inc., Logan, UT), a 16-intake manifold unit, two air dryers for each TGA100 analyzer, and a vacuum pump (RA0021, Busch, Virginia Beach, VA). The measured concentrations were within the range of operation of the analyzer which was calibrated using reference gases with typical concentrations of 2500 ppm

and 20000 ppm for N_2O and CH_4, respectively. Online calibration was continuously carried out during field measurements. The trace gas analyzer has a 10 Hz concentration measurement noise of 1.5 and 7 ppb for N_2O and CH_4 respectively. Air was sampled at 0.7 L/min through a filter and needle valve (SS-4MG2, Nupro Company, Willoughby, OH) and was then directed to the 16-intake manifold unit through polyethylene tubing (6.4 mm o.d., 3.2 mm i.d.). The manifold unit switched intakes every 15 s and the first 3 s data were discarded to make sure that previous air samples were purged out. At any given time, air flow from two intakes was directed to the CH_4 and N_2O analyzers, respectively, while the 14 other intakes were discarded. Air samples were analyzed 10 times per second, and the averaged data were saved after each cycle of measurement was completed (every four minutes). To collect the background air, two out of the sixteen air intakes were placed at the inlet of the blower to the small chambers, and one intake was installed at the inhaling fan of the mega chamber. Background gas concentrations measured at the inlet air to all the eight small chambers were the same since it was supplied by the same blower. To sample the air from the small chambers, one air intake was placed at the outlet of each small chamber, and two were installed at the exhaling fan for the mega chamber. The remaining three of the sixteen sampling intakes were used to flush the air inside the TGA100 system, as the high gas concentration from the small chambers could potentially affect the next gas concentration measurement. Measured CH_4 concentrations above 30 ppm were adjusted according to correction derived by Park et al. (2009).

2.3 Flux calculations

Fluxes of CH_4 and N_2O were determined using Equation (1):

??? (1)

where, F_c is the flux, μg m^{-2} s^{-1}; Q is the air flow rate through the chambers, m^3/s; Δc is the difference in gas concentration (μg/m, expressed per volume of dry air at the corresponding temperatures and 760 mmHg) between the air outlet and inlet of the chamber and A is the compost surface area covered by the chamber, m^2. The surface area of the small chamber was 0.72 m^2 and that of the mega chamber was 90 m^2.

2.4 Chemical analyses

Compost samples were taken five times (one shortly before and after each turning, and two after the final turning) during the composting process according to the method by Carnes and Lossin (1970), who combined sub-samples (50-100 g) to make about 1 kg of sample for analysis. Three locations near the small chambers in each channel were selected to sample compost at a depth of 20-30 cm, and one composite sample was made by mixing the twenty-four sub-samples. The composite samples were stored at -25°C until further analyses. Total carbon (TC), total Kjeldahl nitrogen (TKN), total solid (TS), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), redox potential, and pH were measured. The composts samples were ground with a commercial mixer after which 5 g of material with 25 mL of 2 M KCl was shaken for 30 minutes and then was filtered for NH_4^+-N and NO_3^--N analyses. Regarding the TS, 10 g of material was heated at 105°C in an oven for 24 h. Samples for TKN and TC were sent to the Soil and Nutrient Laboratory at the University of Guelph for analysis. Redox potential and pH were measured on site as per Brown et al. (2000).

3 Results and discussion

3.1 Chemical analyses

Results from the analyses of the straw, untreated liquid swine manure and compost during the composting process are shown in Tables 3.

As a result of mixing with straw, the compost had higher dry matter content, higher C/N ratio, lower total nitrogen and ammonium concentration than liquid swine manure. The TKN and TC values of the straw/manure mixture were closer to the straw values as they were reported on a dry basis. As it was expected, compost redox potential was much higher than typical values for liquid swine manure (e.g., -233 mV measured at the same farm, Thompson et al., 2004). Some temporal trends were observed in the compost composition, mainly an increase in total N, decrease in NH_4^+-N, C/N ratio, and redox potential (Tables 3).

Table 3 Straw, manure and compost chemical characteristics during different phases of the composting process

Start date	Sample	TS/%	TKN/%dry	TC/%dry	C/N ratio	NH_4^+-N/mg kg^{-1}	NO_3^-N/mg kg^{-1}	Redox£/mV	pH£
				Batch 1					
July 30	Straw	88.8	0.158	45.8	290	12.8	3.9		
	Manure	1.2	9.400	30.4	3.2	1077.3	0.0		
	Straw/manure*	27.9	0.720	44.9	62.4	215.6	4.8		
Aug. 03	Compost (B)	34.3	0.650	44.3	68.2	27.0	3.8	104.8	7.9
	Compost (A)	19.7	1.005	44.4	44.2	171.9	5.0		
Aug. 06	Compost (B)	18.1	1.238	44.0	35.5	21.4	2.6	36.4	7.9
	Compost (A)	16.3	1.603	44.0	27.4	85.6	3.0		
Aug. 09	Compost	15.6	1.571	43.9	27.9	78.4	4.8	43.7	8.1
Aug. 11	Compost	15.9	1.843	43.6	23.7	61.6	5.3	47.3	8.0
				Batch 2					
Sept. 14	Straw	89.1	0.215	45.6	212	21.2	3.6		
	Manure	1.2	9.500	23.6	2.5	868.5	0.0		
	Straw/manure*	28.5	0.982	45.2	46.0	134.3	4.2		
Sept. 17	Compost (B)	31.3	1.061	44.4	41.8	29.6	3.5		
	Compost (A)	20.1	1.184	43.8	37.0	162.0	5.3		
Sept. 21	Compost (B)	18.6	1.242	43.9	35.3	47.4	3.1		8.3
	Compost (A)	16.4	1.390	43.1	31.0	97.1	3.8		
Sept. 23	Compost	16.9	1.592	44.1	27.7	84.6	5.1		8.2
Oct. 01	Compost	17.2	1.779	44.0	24.7	22.8	2.6		

Note: Fresh mixture of straw and manure, TS: total solids, TKN: total Kjeldahl nitrogen, TC: total carbon, C/N: carbon-to-nitrogen ratio, (B): Measured just before liquid manure application, (A): Measured just after liquid manure application. Liquid manure was mixed with straw on the starting date (first application), and was mixed with compost on August 3 and 6 for Batch 1. £Missing data was due to instrument unavailability during the second batch of composting. Liquid manure was mixed with straw on the starting date (first application), and was mixed with compost on September 17 and 21 for Batch 2.

3.2 Small versus mega chamber methods for flux measurements

The mean fluxes of CH_4 and N_2O measured with the small chambers and the mega chamber during the composting process are presented in Figure 2. Small chamber CH_4 fluxes averaged 23-326 μg m^{-2} s^{-1}, while N_2O fluxes averaged 0.3-2.5 μg m^{-2} s^{-1}. The magnitude of the flux was related to the channel, chamber position, and to the batch. In particular, chamber position within each channel significantly affected the mean CH_4 and N_2O fluxes, pointing to strong spatial heterogeneity of fluxes (Figure 2). In general, positions with high CH_4 fluxes yielded low N_2O fluxes, and vice-versa (e.g. Figure 2c as compared to Figure 2d). It should be noted that the small chambers used in this study measured gas emissions from a larger area than conventional chambers used in other studies of gas emissions from composting (e.g. 0.019, 0.292, and 0.018 m^2 used by Hellebrand and Kalk (2001), Hao et al. (2004), and Sommer et al. (2004), respectively), which should have decreased the spatial variability between chambers.

Overall, there were significant differences between fluxes measured with the mega chamber and the mean fluxes obtained by merging all the small chamber data, except for CH_4 fluxes during Batch 2 (Table 4). The small chamber CH_4 flux for Batch 1 was 1.4 times higher than the flux from the mega chamber. Small chamber N_2O fluxes were 50%-55% lower than fluxes measured using the mega chamber.

Table 4 Mean CH_4 and N_2O fluxes measured with a mega and small chambers during the in-vessel composting process

Batch	CH_4/μg m^{-2} s^{-1}		N_2O/μg m^{-2} s^{-1}	
	Mega chamber	Small chambers	Mega chamber	Small chambers
1	121.8*a*(14, 28.5)	168.1*b*(14, 46.5)	2.01*b*(14, 0.190)	0.72*a*(14, 0.103)
2	112.7*a*(16, 25.7)	110.9*a*(16, 27.8)	2.69*b*(14, 0.218)	1.33*a*(14, 0.186)

Note: Fluxes measured with eight small chambers were combined to calculate mean fluxes. Numbers in bracket (n, SE) indicate the number of average daily observations and the standard error of the mean. Means followed by the same letter within a batch were not statistically different at 0.05 level.

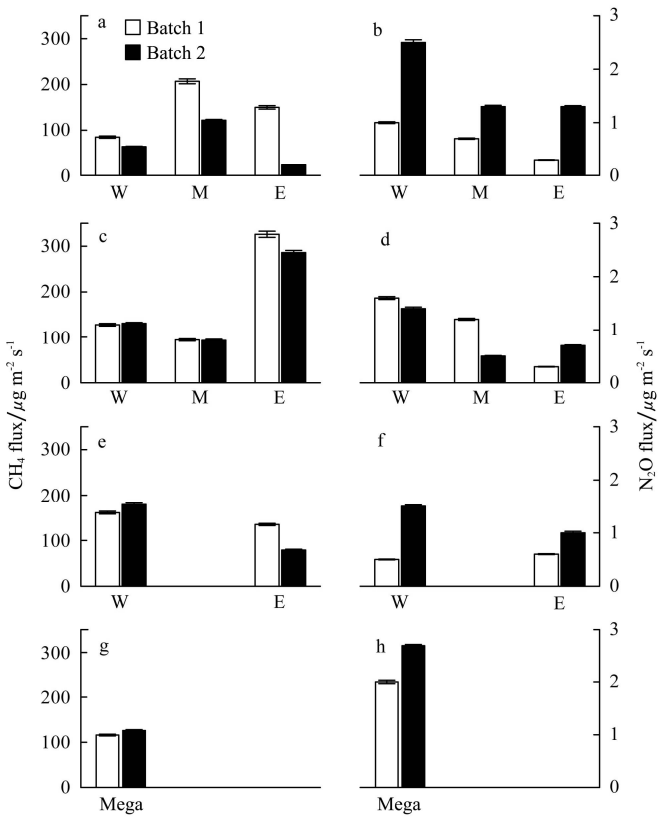
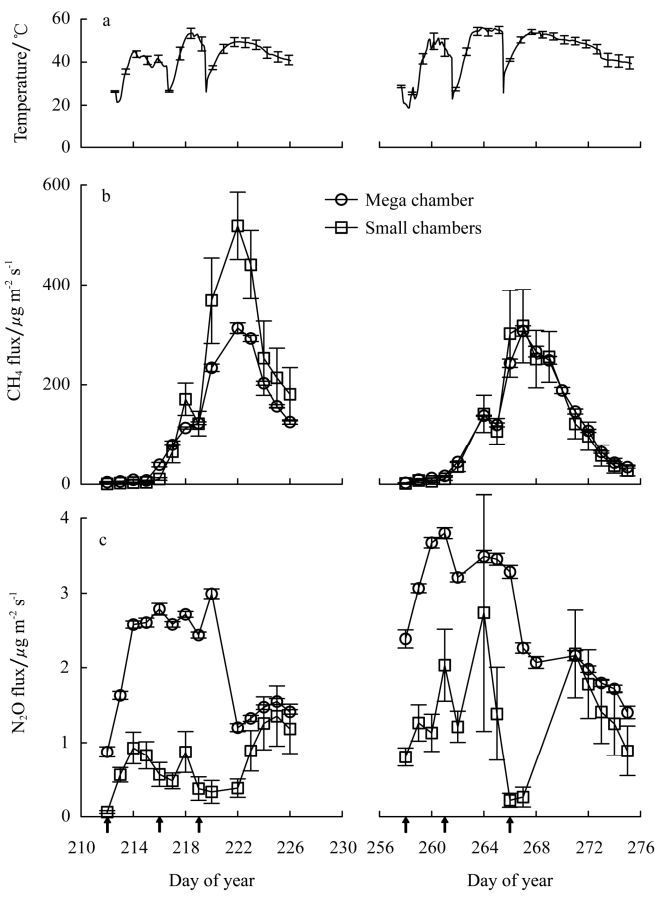


Figure 2 Mean fluxes of CH_4 (left) and N_2O (right) measured with small chambers placed in composting channel 1 (a, b), 2 (c, d) and 3 (e, f) according to chamber position within channel Note: (W: West end, M: Middle, E: East end) during Batches 1 (no-fill bars) and 2 (filled bars). Only two chambers were used in channel 3, so no data are available for the middle position. Fluxes measured with the mega chamber (plots g, h) are shown in the bottom graphs. Vertical bars represent the standard error of the mean

Temporal trends of compost temperature indicated a sharp decrease after each manure application and turning, followed by a fast increase to values in the 40 to 60°C range (Figure 3a). Overall, Batch 1 had a mean compost temperature of 45.6±4.3°C, and Batch 2 of 48.5±9.8°C over the whole in-vessel composting period.

Temporal variations in the daily CH_4 fluxes over the sampling durations of Batch 1 (Figure 3b, left) and Batch 2 (Figure 3b, right) were very similar for both measurement methods with sharply rising fluxes on the fifth day after the start of composting. The highest daily mean CH_4 fluxes measured with both methods occurred 1−2 days after the third manure application or 9−10 days after the start of composting. This was followed by a decrease in fluxes for the remainder of the in-vessel composting period. However, peak CH_4 fluxes measured with the small chambers for Batch 1 were higher than CH_4 fluxes measured with the mega chamber method after the third manure application. The temporal pattern of N_2O fluxes was not as well-defined as that of CH_4 fluxes, and differed between the two measurement methods (Figure 3c). The mega chamber method clearly showed higher N_2O fluxes in the early stage than in the later stage of the in-vessel composting process (Figure 3c).



Note: Results are shown for batches 1 (left) and 2 (right). Arrows indicate manure application dates. Bars on the hourly temperature are standard error of the means from all temperature sensors (six per composting channel), shown for every 20th data point for clarity. Bars on daily fluxes represent standard error of the mean. Arrows show time of manure addition to compost/straw.

Figure 3 Temporal trends of hourly compost temperature (a), daily mean CH_4 (b) and N_2O (c) fluxes measured with a mega chamber and eight small chambers during in-vessel composting

There are several possible explanations for the differences in fluxes measured with the small and mega chamber methods (i.e., small chamber N_2O fluxes < mega chamber N_2O fluxes; but vice-versa for CH_4 fluxes). The composting area from which emissions were measured was quite different for each method. The mega chamber method provided integrated fluxes over

the whole emitting area of the three channels. In contrast, the small chambers were placed lengthwise in 2 and 3 positions within the center line of each channel. The center area of composting piles has been observed to have the highest temperature (Hao et al., 2001; Sommer et al., 2004) causing convection, or air circulation. High temperatures (>45°C) promote CH_4 production, but inhibit N_2O production through nitrification (Hellmann et al., 1997; Fukumoto et al., 2003; Sommer et al., 2004; Pattey et al., 2005). The surrounding compost area (towards the edges and ends of the channels) would have had lower temperatures, and hence, lower CH_4, but higher N_2O fluxes than measured by the small chambers positioned in the center line of the channels. Indeed, some of the temperature sensors randomly placed in the compost recorded mean values <45°C. In addition, samples of compost taken close to the small chamber positions showed redox potential <50 mV for all sampling dates except during the start of composting (data not shown). Brown et al. (2000) reported an approximate linear increase of N_2O emissions at redox potentials ranging from 25 to 150 mV. It is possible that compost near the ends of the channels had a higher redox potential, particularly in the early stages of composting (first eight days). Potentially high N_2O production and emission at these peripheral positions would have been captured by the mega chamber, but not by the small chambers (Figure 3c).

A larger number of small chambers position so as to cover most of the emitting area would potentially have been desirable in order to have similar 'footprints' for both methods. However, this would have had the potential to further disturb the emitting area due to chamber placement. It is likely that environmental conditions (wind speed, turbulence, pressure, temperature and humidity) inside the small chamber were different from the overall conditions inside the mega chamber, but unfortunately we did not quantify this. However, as all chambers were vented some of the environmental effects would have been minimized. Kolari et al. (2012) showed that the magnitude of a standard gas emission was underestimated with higher error at high relative humidity than in drier conditions. In the present study, the difference in headspace height between the small chambers and the mega-chamber might have resulted in different environmental conditions within the chambers (Parkin and Venterea, 2010).

Skiba et al. (2006) placed nine chambers on different positions over a dung heap and found low N_2O fluxes on low, shallow parts of the heap, and high N_2O fluxes on the ridge of the heap. Sommer et al. (2004) reported that CH_4 fluxes measured with chambers placed on the top of the stockpile were the highest, while N_2O fluxes were the highest on the side of the stockpile. This agreed with our findings for this composting approach. Comparison of fluxes measured with the small and mega chambers indicated that the edges of the composting channels in the present study were potentially significant 'hot spots' for N_2O production, but less important for CH_4 production. Indeed, the data revealed that only one small chamber was placed on such an N_2O 'hot spot' (Batch 2, channel 1, west end, Figure 2b). This finding needs to be further studied as it has important implications for small chamber positioning. In particular, it was noted that biases in flux measurements using our small chambers were observed despite the higher number and larger measuring area, compared to conventional chamber methods for quantifying gas emissions from composting (Hellebrand and Kalk, 2001; Hao et al., 2004; Sommer et al., 2004; Skiba et al., 2006). Hence, extreme care must be exerted when placing small chambers and a systematic grid-based approach is recommended. Experience and pre-trial random sampling measurements may provide useful information about the nature of emitting surfaces. Such care can be avoided when using a mega-chamber approach as the whole emitting area is enclosed, meaning that all gas fluxes can be captured.

3.3 Effects of aeration on greenhouse gas fluxes

Small chambers have the advantage of allowing for side-by-side comparison of treatments. In this study we investigated the effect of aeration applied to each individual compost channel. Even though biases in absolute fluxes were observed with small chambers as discussed above, a comparison of aeration treatments was still feasible using this approach (Rochette and

Eriksen-Hamel, 2008). A similar study involving the mega-chamber approach would have required the use of at least three individual composting batches introducing potential differences that would have made comparison of results difficult.

Fluxes measured with the small chambers in each channel for different aeration regimes were merged and compared (Table 5). Mean fluxes varied from 147.0 to 182.5 μg m^{-2} s^{-1} for CH_4 and 0.507 to 1.039 μg m^{-2} s^{-1} for N_2O in Batch 1, and from 72.2 to 170.3 μg m^{-2} s^{-1} for CH_4 and 1.038 to 1.722 μg m^{-2} s^{-1} for N_2O in Batch 2. There were significant differences in CH_4 and N_2O fluxes between channels during each batch presumably due to aeration effects, but the trends were not consistent. For example, N_2O fluxes were the lowest for the 'High' aeration rate in Batch 1, but lowest for the 'Medium' rate in Batch 2. Highest CH_4 fluxes were observed for the 'Medium' rate in both batches, but no significant differences were observed between 'High' and 'Low' aeration rates in Batch 1.

Table 5 Averaged CH_4 and N_2O fluxes measured with the small chambers for each channel according to different aeration regimes

Batch	CH_4/μg m^{-2} s^{-1}			N_2O/μg m^{-2} s^{-1}		
	High	Medium	Low	High	Medium	Low
1	148.2*a**(14, 62)	182.5*b*(14, 86.8)	147.0*a*(14, 71.3)	0.507*a*(14, 0.103)	1.039*c*(14, 0.206)	0.640*b*(14, 0.124)
2	72.2*a*(16, 19.5)	170.3*c*(16, 55.6)	133.0*b*(16, 58.4)	1.722*c*(14, 0.289)	1.038*a*(14, 0.172)	1.394*b*(16, 0.286)

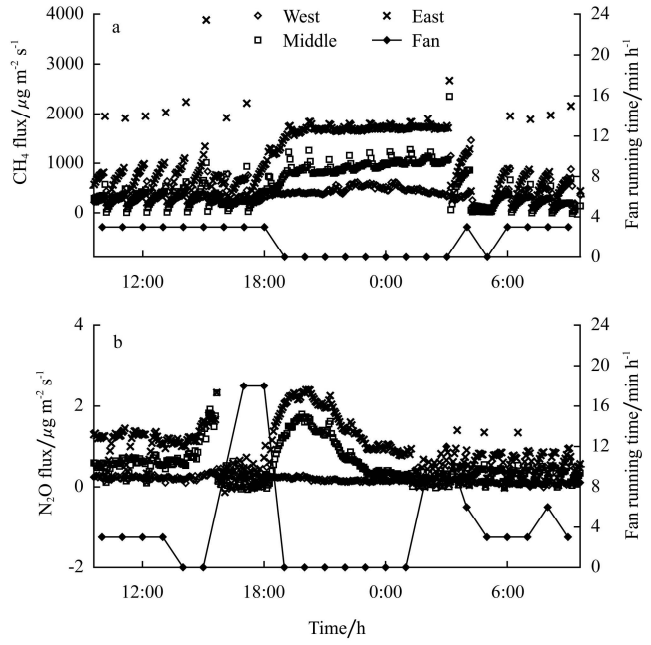
Note: Means followed by the same letter within each batch were not significantly different at 0.05 level. Values in brackets are the number daily observations and standard error of the mean. Aeration regimes for channels 1, 2, and 3 were 3-minutes per hour when composting temperature was below 66°C. When the composting temperature exceeded 66°C, the aeration regimes were 2-minutes (Low), 3-minutes (Medium), and 4-minutes (High) per 10 minutes, respectively.

Different aeration rates had been set for each channel to be activated when any of the six temperature probes in each channel recorded temperature above 66°C. Due to a combination of power supply failure to individual aeration fans and malfunction of some temperature probes, the total recorded time over the entire in-vessel composting phase when aeration fans were active for low, medium, and high aeration regimes, respectively, were 1,274, 1,245, and 672 minutes for Batch 1, and 1,530, 1,023, and 1,148 minutes for Batch 2. The aeration time was considered to be a better measure of total aeration rather than the aeration rate. The correlation of CH_4 fluxes with total aeration time was insignificant (r = -0.097). However, N_2O fluxes showed a positive correlation with the total aeration time (r = 0.556).

Despite the negligible response of mean CH_4 fluxes to total aeration time, an immediate increase in fluxes was observed when the aeration fans were turned off for a few hours, followed by decreased fluxes when the fans were turned on, as observed by the high temporal resolution data (Figure 4a). Regarding N_2O, when a short period of high aeration rate was followed by no aeration, fluxes increased sharply, peaked, but then decreased gradually while aeration was still off (19:00 to 1:00 h, Figure 4b). A closer inspection of Figure 4 indicated large variations of fluxes in the short term (< 1 h) when the fans were operating. This effect is detailed for CH_4 and N_2O fluxes for a period of 3 h (Figures 5 and 6). Generally, a sharp increase in CH_4 flux was observed shortly after aeration took place, followed by a steep drop to a minimum flux, and then a gradual increase until the next aeration (Figure 5). Interestingly, the temporal patterns in CH_4 fluxes observed using the small and mega chambers methods were similar, but the mega chamber showed maximum CH_4 fluxes about four minutes later. In addition, the drop in CH_4 flux was less steep for the mega chamber as compared to the small chambers. This was most likely due to differences in the time to exchange the chamber head space volume: 12 minutes for the mega chamber and two minutes for the small chambers.

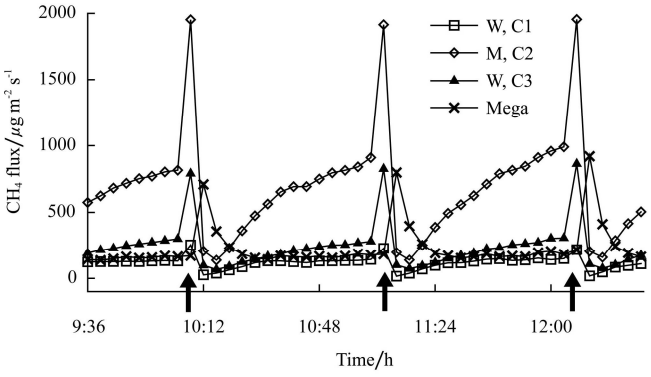
The lack in response of CH_4 fluxes to the total aeration time was surprising as an increased supply of oxygen should have had an inhibiting effect on methanogens and consequently, CH_4 production, as seen over a short-period in Figure 4. However, as discussed, CH_4 fluxes peaked shortly after fan operation, which was probably due to purging of CH_4 stored in the compost (Figure 5). It appears that this purging effect

counteracted the inhibiting effect that increased aeration would have had on CH_4 production (Chan et al., 2011). Purging of stored CH_4 is also common during compost mixing (Andersen et al., 2010b; Park et al., 2011), when aeration is expected to be high. This effect partially explains the lack of decreased CH_4 fluxes with increased aeration time observed.



Note: Lack of aeration effect on 4-minutes CH_4 (a) and N_2O (b) fluxes for a selected 1-day period in Batch 2 (day 266 and 259, respectively), measured using three small chambers positioned at west end, middle, and east end of channel 2. The fan running time is shown to indicate times when fan was operating. Different days were selected for (a) and (b) because high CH_4 and N_2O fluxes occurred at different times, that is, middle and early stages of the in-vessel composting phase, respectively.

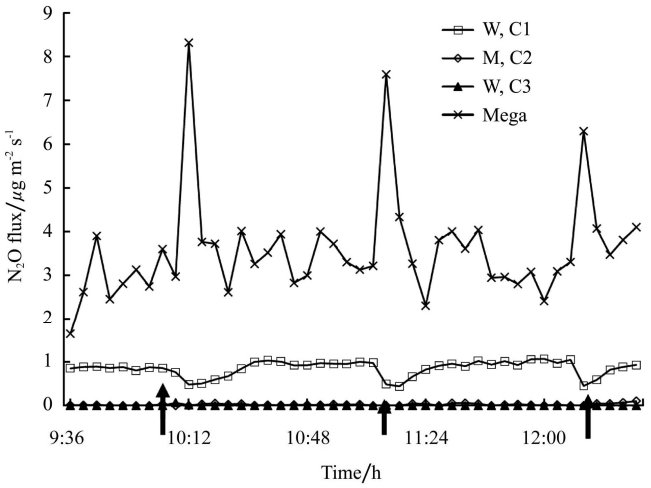
Figure 4 Lack of aeration effect on CH_4 and N_2O fluxes during composting



Note: Short-term aeration effect on 4-minutes CH_4 fluxes from 9:36 to 12:28 h on day 266 during in-vessel composting in Batch 2, measured with small chambers at west end of channel 1 (W, C1), middle chamber on channel 2 (M, C2), west chamber on channel 3 (W, C3), and mega chamber. Arrows indicate when aeration was active.

Figure 5 Short-term aeration effect on CH_4 flux during composting

In the case of N_2O, the purging effect of stored N_2O was not as prominent as for CH_4 due partially to the relatively lower N_2O fluxes that were measured (Figure 6). Intermittent aeration would enhance aerobic and anaerobic microhabitats, which would result in N_2O generation by coupled nitrification-denitrification (Wrage et al., 2001). That is, denitrifier produced N_2O from NO_3^- generated by neighboring nitrifiers in aerobic conditions. In addition to coupled nitrification-denitrification, abundant oxygen from aeration would cause increased N_2O fluxes as N_2O reductase is inhibited by oxygen (Knowles, 1982). Hence, the purging effect of stored N_2O probably was combined with a stimulation of N_2O production due to added oxygen, resulting in the positive correlation between N_2O flux and total aeration time observed.



Note: Short-term aeration effect on 4-minutes N_2O fluxes from 9:36 to 12:28 h on day 266 during in-vessel composting in Batch 2, measured with small chambers at west end of channel 1 (W, C1), middle chamber on channel 2 (M, C2), west chamber on channel 3 (W, C3), and mega chamber. Arrows indicate when aeration was active.

Figure 6 Short-term aeration effect on N_2O flux during composting

4 Conclusions

According to the measurements using small chambers and a mega chamber during composting, temporal variation patterns in CH_4 and N_2O fluxes were observed to be similar for the small and mega chambers methods including periods with active aeration. However, large spatial variations were observed in the mean fluxes from the small chambers. Mean CH_4 fluxes from all the small

chambers and the mega chamber were comparable for one batch but significantly higher for the small chambers in another batch. On the other hand, mean N_2O fluxes were significantly lower for the small chambers as compared to the mega chamber. This difference was attributed to the potentially higher N_2O emissions on the drier edges of the compost, where small chambers were not placed due to space restrictions. Our results suggested that a mega chamber that covers a larger emitting surface area can avoid biases in flux estimates due to spatial variability of the source.

When only small chambers are used for flux measurements, a large number should be strategically positioned to cover different areas of the emitting surface so as to capture a representative flux. On the other hand, if a few small chambers are used, they should be moved frequently to different locations on the emitting surface.

Total aeration time did not have a significant effect on CH_4 fluxes, but affected N_2O fluxes. This could be related to the flushing of stored CH_4 at the onset of aeration, which promoted fluxes, as opposed to the expected decrease with high aeration time. The purging of stored N_2O enhanced the expected stimulation of N_2O production at higher aeration times, resulting in the positive trend observed for N_2O fluxes.

Further research using long term and several repeated measurements with stratified chamber positioning are needed to support the findings in this study. In addition, a better simulation of the effect of chambers on environmental conditions would improve our understanding of the relationship between chamber size and measured flux.

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Nomenclature

A	Compost surface area (m^2)
C/N	Carbon-to-nitrogen ratio
E	East end chamber location
F_c	Flux ($\mu g\ m^{-2}\ s^{-1}$)
H	High aeration regime
L	Low aeration regime
M	Middle chamber location
N	Medium aeration regime
Q	Air flow rate ($m^3\ s^{-1}$)
TS	Total solids
TKN	Total Kjeldahl nitrogen
TC	Total carbon
W	West end chamber location
Δc:	Difference in gas density ($\mu g\ m^{-3}$)

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