

# Emission of ammonia, nitrous oxide, methane and carbon dioxide during composting of deep litter

*Emissions d'ammoniac, de protoxyde d'azote, de méthane et de dioxyde de carbone au cours du compostage de litière.*

**Sven G. Sommer, Preben Dahl, Hans B. Rom and Henrik B. Møller,**  
Research Centre Bygholm Danish Institute of Agricultural Sciences  
Department of Agricultural Engineering  
P.O. Box 536. 8700 Horsens  
E-mail: SvenG.Sommer@agrsci.dk. Telephone: 75602511. Telefax: 75624880

## Abstract

*During storage of solid animal manure, biological transformation of nitrogen and carbon may increase the temperature to 60 to 70°C, i.e. composting. The rise in temperature may cause a substantial loss of ammonia, as the ammonium is transformed to ammonia at high temperatures and because the heat is generating a flow of air through the dung heap. In the present study emission of ammonia, carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) was measured using dynamic chambers covering three heaps of deep litter from a house with dairy cows. The heaps were either mixed after 30 days, compressed or untreated. Compaction of the very porous material enhanced the temperature increase in the heap. Ammonia emission was therefore high from the compacted heap giving a cumulated NH<sub>3</sub> loss of 0.2 kg N ton<sup>-1</sup>. Initially temperature also increased in the heap being turned after 30 days, and in total the NH<sub>3</sub> losses from this heap were similar to losses for the compressed litter. Only, half this amount was lost from the heap in which the temperature did not increase much initially. High amounts of carbon dioxide were emitted during composting of the deep litter, the cumulated losses were 33 kg C, 20 kg C and 17 kg C from the litter being mixed after 30 days, compressed deep litter and untreated deep litter. High nitrous oxide emission were determined when the initial high temperature declined, indicating that nitrification is affected by the high temperatures during composting. Elevated CH<sub>4</sub> emission were observed after a period of 15 to 30 days. Methane and nitrous oxide was emitted at a ratio of 1.6 to 39.9 g CH<sub>4</sub>-C day<sup>-1</sup> tonne<sup>-1</sup> and 0.04 to 10 g N<sub>2</sub>O-N day<sup>-1</sup> tonne<sup>-1</sup>.*

## Résumé

Au cours du stockage de déjections animales solides, les transformations biologiques de l'azote et du carbone aboutissent à une augmentation de la température pouvant aller jusqu'à 60-70°C i.e. compostage. Cette augmentation de température peut entraîner des pertes importantes sous forme d'ammoniac. Dans notre étude, les émissions d'ammoniac, de dioxyde de carbone (CO<sub>2</sub>), de protoxyde d'azote (N<sub>2</sub>O) et de méthane (CH<sub>4</sub>) ont été mesurées à l'aide de

chambres dynamiques couvrant trois tas de litière profonde provenant d'un bâtiment de vaches laitières. Les tas étaient agités après 30 jours, compressés ou non traités. La compaction d'un matériel poreux favorise l'augmentation de température dans le tas. Les émissions d'ammoniac issues du tas compacté étaient alors plus importantes et aboutissent à des pertes cumulées en  $\text{NH}_3$  de 0,2 kg N tonne.

La température initiale augmente également dans le tas retourné ce qui aboutit à des pertes ammoniacales similaires à celles observées avec le tas compacté. Seulement la moitié de cette quantité d' $\text{NH}_3$  était émise dans le cas où la température dans le tas n'augmente pas.

Des quantités importantes de  $\text{CO}_2$  ont été mesurées au cours du compostage de cette litière avec des pertes de 33 kg C, 20 kg C et 17 kg C respectivement à partir de litière agitée après 30 jours, compactée ou non perturbée.

Des pertes importantes en  $\text{N}_2\text{O}$  ont été mesurées lorsque la température initiale élevée commence à décliner, indiquant que les nitrifiants sont inhibés par les températures élevées observées au cours du compostage.

Le méthane et le protoxyde d'azote étaient émis à des taux de l'ordre de 1,6 à 39,9 g C- $\text{CH}_4$  tonne<sup>-1</sup>.jour<sup>-1</sup> et 0,04 à 10 g N- $\text{N}_2\text{O}$  tonne<sup>-1</sup>.jour<sup>-1</sup>.

## 1. Introduction

The policy of the Danish government is to increase the share of organic farms to 10 % of the area under cultivation. Mineral fertilisers are not accepted for plant production within organic farming. Thus, limitation in the amount of nutrients available may contribute to reductions in crop yield and of animal production within organic farming. Nitrogen can be supplied through nitrogen fixation of leguminous plants, and at present, organic farms may import nutrients in roughage (cf. regulation on organic soil production).

A substantial amount of the nutrients needed by the crops in rotation are supplied in animal manure produced by animals feed with imported or produced roughage. The nutrients that are lost from livestock manure are irreplaceable, and losses will therefore reduce plant production on organic farms. Deep bedding and slurry are the two most common types of organic manure at organic farms. In organic farming there is a tradition to transform deep litter into compost. As far as we know, there are few studies of nitrogen losses and transformation of the nutrients in farmyard manure during composting. Traditionally composting processes and gaseous emission of oxidised and reduced nitrogen has been measured in compost of municipal litter and livestock manure being turned frequently, often several times each week (Hellman *et al.* 1997; Martin and Dewes, 1992). In farming systems the deep litter being stored will not be turned at all or in organic farming normally only one time after about 1 month of composting.

Gaseous emission of carbon dioxide, methane and nitrous oxide has been quantified in this study . A movable dynamic chamber was used to determine gaseous losses. Techniques for reducing the losses was tested.

## 2. Methods

Gas emission during composting of deep litter was studied in three pilot scale dung-heaps of deep litter from housing of dairy cows. The litter was stored on a sealed surface (L: 4 m, W: 2 m) with collection of runoff to closed containers buried in the soil. In table one is given the amount and composition of the deep litter used in this experiment. In the experiment starting the 29th of September 1997 the deep litter was mixed by treating the material three times with a manure spreader on the initiation day of the experiment, immediately after this treatment the litter was stored under the following conditions 1) compressed, 2) mixed by turning the litter manually after 3 weeks and 3) untreated.

Treatment	Amount	DM	Ash	Tot-N	NH <sub>4</sub>	NO <sub>3</sub>	P	K	C
	Tonnes	g/kg							
Compressed	0.980	379.35	52.83	7.50	0.63	0.13	1.21	11.95	160.26
		(47.31)	(6.32)	(1.13)	(0.04)	(0.04)	(0.20)	(1.26)	(24.24)
Mixed	0.660	408.55	59.43	8.30	0.60	0.25	1.40	13.67	172.35
		(11.24)	(2.29)	(0.14)	(0.04)	(0.04)	(0.02)	(0.48)	(4.75)
Untreated	0.720	421.65	60.87	8.36	0.54	0.20	1.43	13.54	177.87
		(0.64)	(0.42)	(0.34)	(0.03)	(0.00)	(0.03)	(0.12)	(0.86)

Table 1.

*Amount and composition of the stored deep litter from dairy cow houses. The deep litter was compressed, mixed after 30 days and kept untreated, the volume of the deep litter heaps were 3 m<sup>3</sup>, 3.2 m<sup>3</sup> and 3.6 m<sup>3</sup>, respectively. (In bracket S.D., N=2).*

At the initiation of the experiment 2 samples of organic material each of 2 L, were taken from each dung heap. The samples of organic material were stored at -18°C. For the determination of CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub> and O<sub>2</sub> from the centre of the heap gas samples were collected by modifying the technique of Petersen *et al.* (1998). The two ends of a flexible, but rigid plastic tube (i.d. 10 mm) containing 4 x 2 mm holes per cm length were connected to two 2 m lengths of gas-tight teflon tubes (i.d. 2 mm), the teflon tubes were connected to a diaphragm pump (Model 5002, ASF GmbH, Germany). At initiation of the experiment a silicone tube were inserted into the rigid tube, but no air samples could be collected after 2 to 3 weeks, and at day 30 the silicone tube was removed from the rigid tube in the heap that was mixed after 30 days. A septum for gas sampling was located immediately after the diaphragm pump, continuously circulating air through the tubes during an experiment. Four samples of 55 ml were taken at each sample collection with syringes. The gas samples were transferred to 5 ml glass tubes fitted with butyl rubber septa. When injecting the samples into the glass tubes, a needle was inserted through the rubber seal and the tubes were flushed with 45 ml of the gas in

the syringe, after flushing the tube the 15 ml remaining in the syringe were injected after removing the needle penetrating the septum (Petersen *et al.*, 1998).

### **Dynamic chamber**

The dynamic chamber consists of a mobile chamber covering the storage during measurements, a ventilator for suction of air through the chamber, and equipment for measurements of gas, temperature and air velocity. A field lab placed close to the experimental area provided the supply of electricity (340 Volts) to the ventilators and instruments for measurement of gas emission.

The three movable chambers on wheels had the dimensions, height 1.6 m, width 2 m and length 4 m. The chamber was made of waterproof plywood and mounted on a metal frame, with only one gable closed by plywood, the other end being open for facilitating the chambers to be moved over the heaps, and connected to a stationary gable placed at the end of the sealed surface. The gable on the chambers had an opening for incoming air. A steel tube (L:2 m, D:0.40 m) with a ventilator was connected to the stationary gable. A rectangular metal frame was mounted on the sealed surface perpendicularly to the stationary gable. The dimensions (length: 4 m, width: 2 m) of the frame allowed it to fit closely with the chambers when mounted. Air was drawn through the chamber by the ventilator enabling measurements of the flux of gases to and from the chamber. Before a measurement, the chambers were moved over the dung heap and fixed to the stationary gable.

Air flow through the dynamic chamber was measured with cup anemometers in the steel pipe, the air flow rates could be adjusted from the field-laboratory. Air temperature and the temperature in the dung heap (40 cm) was measured with PT100 and thermocouple sensors (Kontram A/S, DK-Copenhagen). The sensors were connected to a datalogger (Datataker DT200, Data Electronics LTD, Australia).

When measuring emissions of  $\text{NH}_3$  air speed was adjusted to  $3 \text{ m s}^{-1}$ , the air speed was adjusted to  $1.2 \text{ m s}^{-1}$  for measurements of  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and  $\text{CO}_2$  emissions. Ammonia was determined with active denuders. For analysis of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{CO}_2$  four gas samples of 55 ml were taken with syringes both at the inlet of the chamber, and from inside the steel tube 30 cm from the gable at each measuring occasion. The samples were stored as described above for gas samples taken from the dung heap. The emission was calculated as the difference in the flux of gases of the incoming and outgoing gases.

### **Gas Analysis**

*Ammonia* : The concentration of ammonia in the air from the background and from the dynamic chambers was determined by active denuders (Ferm, 1979). An active denuder consists of a glass tube (length 500 mm, inner diameter 7 mm) coated on the inside with oxalic acid, through which air was drawn at a fixed air flow. A diaphragm pump provided suction and a critical orifice adjusted the air flow through

the denuder to exactly  $0.9 \text{ L min}^{-1}$ . All  $\text{NH}_3$  flowing into the tube is absorbed on the oxalic acid. After exposure, the amount of  $\text{NH}_3$  absorbed in the tubes were determined, by dissolving the coating in 5 ml water and analysing  $\text{NH}_3$  concentration using a QuickChem 4200 (Lachat Instruments WI, USA).

The performance of the active denuders were examined in two tests. In test one, air at 1.35-1.45 ppm  $\text{NH}_3$  (v/v) was drawn through the denuders at time intervals from 2-10 min. In test two,  $\text{NH}_3$  concentrations was varied from 4 to 23.5 ppm  $\text{NH}_3$  and the suction time was 10 min. In each test 4 extra tubes were not used for measurements and included as blanks. In each test, two tubes were connected in series to test absorption capacity, one tube was directed to the  $\text{NH}_3$  source and the other was directed towards surroundings, all measurements were replicated. A Brüel and Kjær fotoacoustic gas monitor (DK-Copenhagen) was used to give the  $\text{NH}_3$  concentration of the air through the test runs.

*Methane ( $\text{CH}_4$ )* , *Nitrous oxide ( $\text{N}_2\text{O}$ )* ,  *$\text{CO}_2$  and  $\text{O}_2$* : Nitrous oxide and  $\text{CH}_4$  was measured on a Hewlet Packard (4890, series II) gas chromatograph with a electron capture detector and a flame ionisation detector. It was equipped with a 8 ft x 1/8" column with porapak Q 80/100 for  $\text{N}_2\text{O}$ ,  $\text{N}_2$  was used as a carrier at  $30 \text{ ml min}^{-1}$  and temperatures of injection port, oven and detection were 320, 70 and  $150^\circ\text{C}$ . Methane was isolated with a 6 Ft x 1/8" column with poropak N, He was used as carrier gas and temperatures of injection port, oven and detection were 270, 70 and  $150^\circ\text{C}$ . Oxygen and  $\text{CO}_2$  were measured on a Varian 3700 gas chromatograph with thermal conductivity detector. It was equipped with a 2-m x 1/8" column with a Molecular Sieve was used to isolate  $\text{O}_2$  and a 1-m x 1/8" column with Poropak N for  $\text{CO}_2$ . The carrier gas was He at a flow rate of  $40 \text{ ml min}^{-1}$ , the temperatures of oven and detector were 30 and  $190^\circ\text{C}$ , respectively.

### **Composition of manure**

Before analysis the organic material was thawed to  $0^\circ\text{C}$  and the total sample of 2 L were finely chopped with a cutting machine. Representative subsamples of about 500 g of the chopped material was then cut into small pieces and from this material 100 g was taken for analysis. All manure samples were analysed for dry weight, ash content, total C, Kjeldahl N, TAN (Total Ammoniacal Nitrogen),  $\text{NO}_3^-$ , P and K. TAN and  $\text{NO}_3^-$  in the solid manure was extracted in 1 M KCl for 30 min, filtered before analysis with a QuickChem 4200 flow injection analyser (Lachat Instr. Wisconsin, USA). Dry matter was determined after drying at  $105^\circ\text{C}$  for 24 h, and ash content at  $550^\circ\text{C}$  for 4 h. Total C was determined by dry combustion (Leco model 521-275), K by flame photometry (FLM3, radiometer) after dry ashing and solubilization in acid, and P was measured colorimetrically (Spectronic 1001, Braush & Lomb) after dry ashing and solubilization in acid and a colouring reaction with ammonium molybdate vanadate. Total nitrogen ( $\text{N}_{\text{total}}$ ) was analyzed using the Kjeldahl method and a Kjellfoss 16200 (Copenhagen, DK).

### **Calculations**

The precision of the active denuder was tested by comparing the amount of NH<sub>3</sub> absorbed in the tubes (NH<sub>3,flux</sub>) and the flux of NH<sub>3</sub> flowing through the tube during the exposure period calculated by the following equation :

$$NH_{3,flux}=(NH_3)*F*\Delta t$$

(NH<sub>3</sub>) is the concentration (NH<sub>3</sub>-N mg m<sup>-3</sup>) that was determined with the Brühl and Kjær monitor, airflow F (m<sup>3</sup> min<sup>-1</sup>) and Δt (min) the exposure period. The NH<sub>3,flux</sub> was calculated by subtracting the amount of NH<sub>3</sub> in the blank tubes from the NH<sub>3</sub> being absorbed in the tubes during exposure.

The average NH<sub>3</sub> concentration (C, μg NH<sub>3</sub>-N m<sup>-3</sup>) in the air measured by the tubes was calculated by the following equation :

$$C=(C_1+C_2 -2C_4)*V/(F*\Delta t)$$

where C<sub>1</sub> and C<sub>2</sub> are the concentrations of NH<sub>4</sub><sup>+</sup> (μg NH<sub>4</sub>-N L<sup>-1</sup>) in leachate from the two exposed tubes, C<sub>4</sub> the average concentration of NH<sub>4</sub><sup>+</sup> (μg NH<sub>4</sub>-N L<sup>-1</sup>) in leachate from the four blank tubes, V is the volume of water used to dissolve the NH<sub>4</sub><sup>+</sup> sorbed in the tubes (0.005 l), F is the air flow through the tubes (0.0009 m<sup>3</sup> min<sup>-1</sup>), Δt is the time (min) between the start and conclusion of the measurement.

### 3. Results and discussion

#### Test of denuders

The active denuder was developed for measuring NH<sub>3</sub> at ambient concentrations (Ferm, 1979). The capacity of the denuders for determining NH<sub>3</sub> at high concentrations was therefore tested. The time of suction through the denuder at constant concentration of NH<sub>3</sub> was examined first, showing the precision of the denuders increased by increasing the time of suction (Fig. 1A). In the second test a suction time of 10 minutes was therefore chosen, and the concentrations was varied (Fig 1B). In this test the amount of NH<sub>3</sub> absorbed was highly correlated to the amount of NH<sub>3</sub> flowing into the tube, the correlation coefficient was 0.98 and coefficient of inclination 1 (P= 5%). No increase of ammonia in the second tube

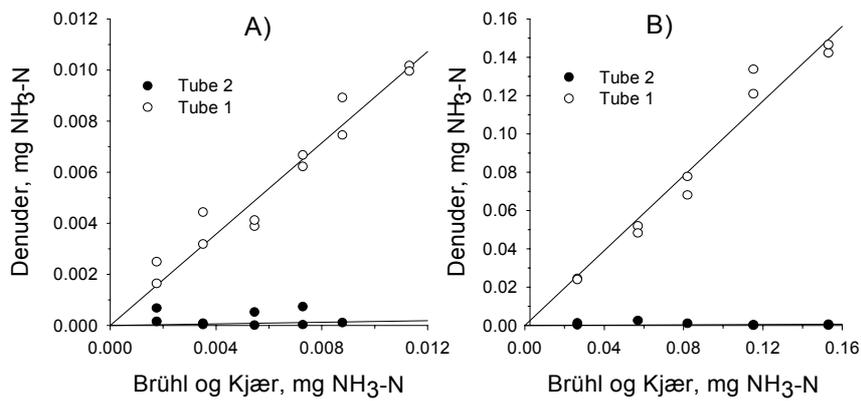
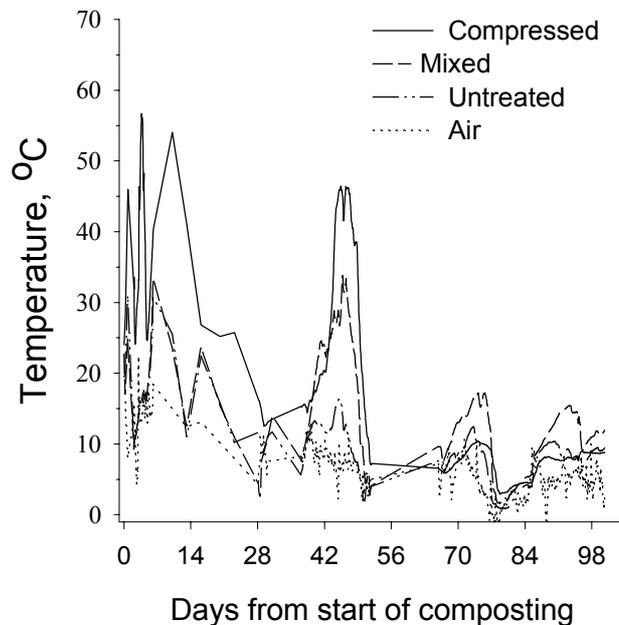


Figure 1

Amount of  $\text{NH}_3$  absorbed in the denuder related to the amount of  $\text{NH}_3$  being sucked into the denuder calculated from measurements of concentrations by Brühl and Kjær fotoacoustic ammonia monitor, flow rate and period of suction. A. 1.35 ppm for 2 to 12 minutes and B) 4 - 24 ppm in 10 minutes.

could be determined, indicating that the ammonia in the air was absorbed in the first tube at  $\text{NH}_3$  concentrations up to 24 ppm, at suction periods of 10 minutes and air flow rate of 0.9 l per minute. The tubes are superior to acid traps (Ryden and McNeill, 1984) when measuring  $\text{NH}_3$  concentrations for short periods, and are easy to handle because they can be stored for long periods both before and after exposure (Sommer *et al.* 1996).



*Figure 2*  
Air temperature and temperature N<sub>2</sub>O in a heap of deep litter, compressed, mixed after 30 days and untreated.

### Temperature and gas concentrations in the compost

At initiation of the experiments wind speeds were high. Therefore the temperature only increased to 20-30°C in the heaps that were not compressed and to 50-60°C in the compressed heap (Fig. 2). The temperature variation measured during the first week was related to changes in wind speed and declined at wind speeds above 15 ms<sup>-1</sup>. After 14 days the temperature declined. Few days after establishing the heap CO<sub>2</sub> concentrations in the compressed heap increased considerably, the variation in concentrations reflected changes in temperature (Fig. 3). Temperature and CO<sub>2</sub> concentrations will be related, because photosynthesis processes are negligible in compost and CO<sub>2</sub> therefore can be regarded as a parameter for microbial activity (Knuth, 1969). After a few weeks no gas could be sampled from inside the heaps. Therefore the sampler in the heap being mixed were changed at mixing. Throughout the experiments oxygen concentrations inside the heaps were near similar to the concentration in the ambient air. After mixing both the temperature and CO<sub>2</sub> concentration increased in the mixed heap, but also in the compressed heap an increase was measured (Fig. 2 and 3). This increase is probably related to growth of actinomyces and fungi's after the temperature decline, the fungi's using cellulose and hemicellose as substrate (Hellman *et al.*, 1997). After 50 days the temperature in the compressed and mixed heap declined to ambient temperature and CO<sub>2</sub> in the mixed heap declined to ambient concentrations.

Nitrous oxide is a by-product of nitrification and denitrification and therefore an indicator of these processes (Hellman *et al.*, 1997). The high N<sub>2</sub>O concentration initially may be an indicator of denitrification of NO<sub>3</sub> present in the deep litter at initiation of the experiment (Fig. 3). Through the period with high temperature N<sub>2</sub>O concentration was low because the number of nitrificants are reduced at high temperatures. After the decline in temperature the N<sub>2</sub>O concentrations increased for a period in the compressed heap and the heap that later was mixed. N<sub>2</sub>O increased again, when the heap was mixed probably because mixing increased composting and thereby created hot spots with low O<sub>2</sub> concentration. Methane were only measured for a period from 30 to 80 days after initiation of the experiment, and in this period no significant increase in CH<sub>4</sub> were determined. Nitrous oxide and CH<sub>4</sub> concentrations were low compared to those measured in the studies of Petersen *et al.* (1998) and Sibbesen and Lind (1993), the open structure of the deep litter probably has facilitated a high convection of air through the organic material and thus reduced N<sub>2</sub>O formation and methanogenesis or induced CH<sub>4</sub> oxidation.

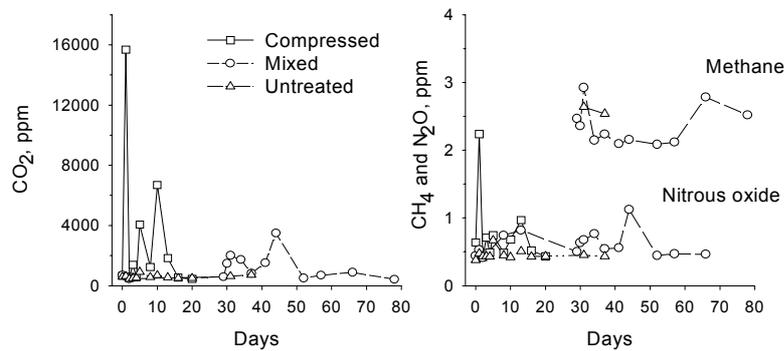


Figure 3.  
Concentration of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in a heap of deep litter, compressed, mixed after 30 days and untreated.

### Emission of gases

Emission of CO<sub>2</sub> were high immediately after establishing the heaps and in the period from 30 to 40 days of composting. Emission of 2 to 3 kg CO<sub>2</sub>-C ton<sup>-1</sup> per day were determined during these periods (Fig. 4). In total CO<sub>2</sub> emissions were 33 kg C, 20 kg C and 17 kg C from the litter being mixed after 30 days, compressed deep litter and untreated deep litter. The emission of CO<sub>2</sub> was significant and reduced the content of C in the compost heaps with 10-19% (Table 2).

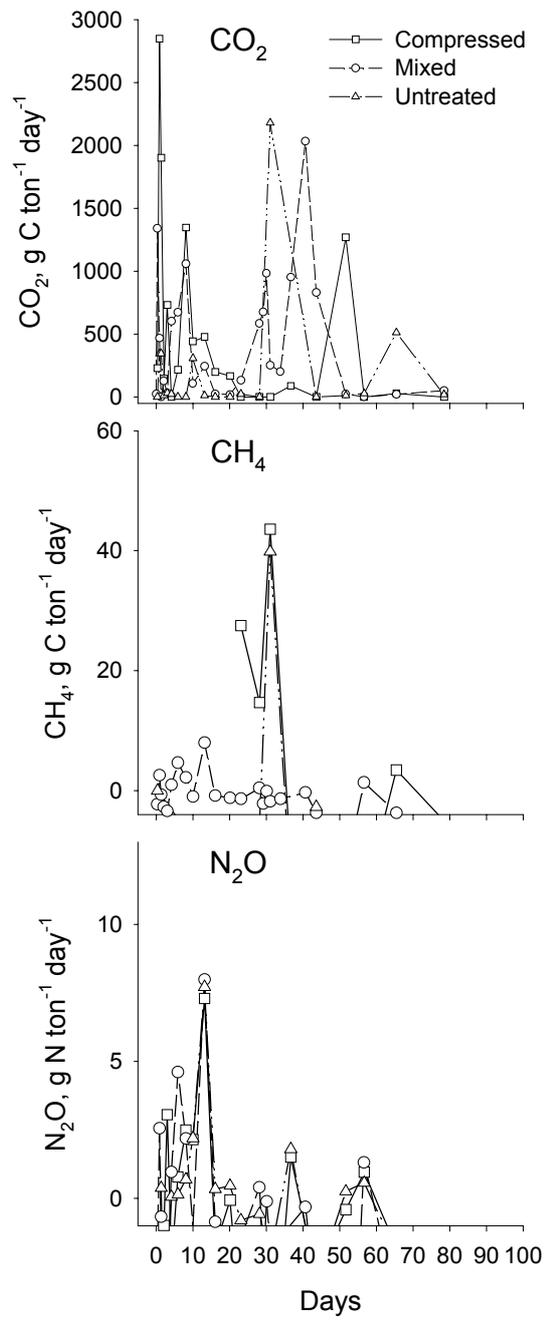
Ammonia	Carbon dioxide	Nitrous oxide
---------	----------------	---------------

	kg N ton <sup>-1</sup>	pct. of N <sub>tot</sub>	kg C ton <sup>-1</sup>	pct. of C	g N ton <sup>-1</sup>	pct. of N <sub>tot</sub>
Compressed	0.23	3.0	19.7	12	0.17	0.0002
Untreated	0.1	1.2	17.1	10	0.388	0.0005
Mixed	0.22	2.6	32.9	19	0.04	0.00005

*Table 2.*  
*Cumulated emission of ammonia carbon dioxide and nitrous oxide*

The highest emission of N<sub>2</sub>O were 10 g N ton<sup>-1</sup> per day (2-3 g N m<sup>-2</sup> per day) were determined from day 10 to 15. In the study of Petersen *et al.* (1998) the highest emissions were observed from 40-50 days after initiation of the experiment, the difference in emission pattern may reflect that the temperature in the experiment of Petersen *et al.* (1998) was high for a longer period than in the present. The emission were low compared to emissions determined by Sibbesen and Lind (1993) and Petersen *et al.* (1998), and the cumulated emission of N<sub>2</sub>O did not cause significant losses of N from the compost (Table 2)

Significant CH<sub>4</sub> emission from the compressed and untreated litter were only observed from 30 to 40 days because data was missing from the first period of the measurements. The highest CH<sub>4</sub> emissions measured was 40 g CH<sub>4</sub>-C ton<sup>-1</sup> per day or approximately 15 g CH<sub>4</sub>-C m<sup>-2</sup> per day, which is similar to the emissions determined by Husted (1994). Cumulated emission of CH<sub>4</sub> were not calculated because data were missing.



**Figure 4**  
*Emission of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in a heap of deep litter, compressed, mixed after 30 days and untreated*

Ammonia was only emitted from the dung heaps during the first 10 days after establishment, and also 2 to 3 days after turning of the heap being mixed (Fig. 5). In the study of  $\text{NH}_3$  volatilisation from solid cattle manure Petersen *et al.* (1998) observed a similar pattern in emission, but the emissions were four times higher due to higher concentrations of TAN in cattle solid manure than in deep litter. In the untreated litter with low temperature during the first five days volatilisation of  $\text{NH}_3$  was also low, indicating that nitrogen losses can be reduced by a treatment reducing the increase in temperature after storage of deep litter. The accumulated  $\text{NH}_3$  volatilisation from the compacted and mixed heaps was similar (Table 2). In this study ammonia volatilization during composting was low compared to losses measured by Petersen *et al.* (1998). The low  $\text{NH}_3$  emission is probably due to transformation of nitrogen in the animal house before storage and a high C:N ratio of the deep litter (=21).

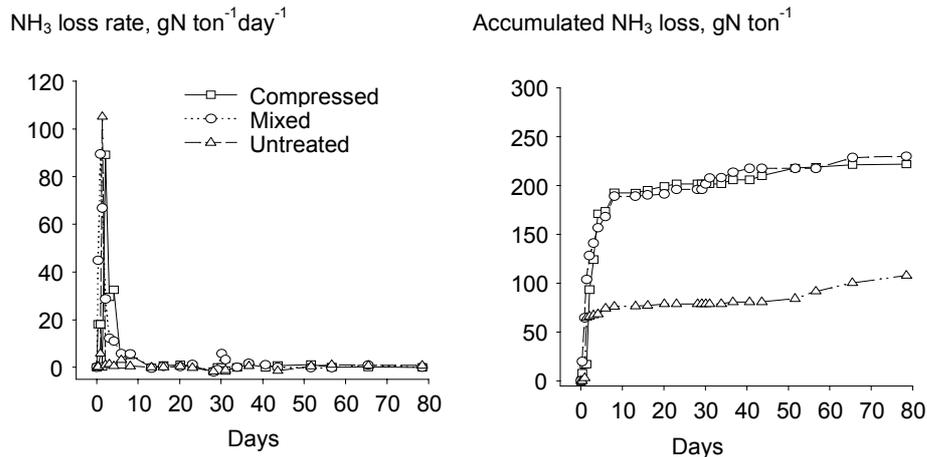


Fig 5.

*Ammonia loss rate and accumulated ammonia volatilization from heaps of composting deep litter, compressed to double density, mixed after 30 days and untreated.*

#### 4. References

**Ferm. M.** 1979. Method for determination of atmospheric ammonia. *Atmos. Environ.* 13, 1385-1393.

**Hellmann. B., Zelles. L., Palojarvi. A. and Bai. Q.** 1997. Emission of climate-relevant trace gases and succession of microbial communities during open-windrow composting. *Appl. Environ. Microbiol.* 63, 10111-10118.

**Husted. S.** 1994. Seasonal variation in methane emission from stored slurry and solid manures. *J. Environ. Qual.* 23, 585-592.

**Knuth. K.** 1969. Nitrogen-cycle ecology of solid waste composting. *Dev. Ind. Microbiol.* 11, 387-395.

**Martin. O. and Dewes. T.** 1992. Loss of nitrogenous compounds during composting of animal wastes. *Biores. Tech.* 42, 103-111.

**Petersen. S.O., Lind. A.-M. and Sommer. S.G.** 1998. Nitrogen and organic matter losses during storage of cattle and pig manure. *J. Agric. Sci. Camb.* 130, 69-79.

**Ryden. H.C. and McNeill. J.E.** 1984. Application of the micrometeorological mass balance method to the determination of ammonia loss from a grazed sward. *J.Sci. Food Agric.* 35, 1297-1310.

**Sibbesen. E. and Lind. A.M.** 1993. Loss of nitrous oxide from animal manure in dungheaps. *Acta. Agric. Scand. Sect. B, Soil Plant Sci.* 43, 16-20.

**Sommer. S.G., Sibbesen. E., Nielsen. T., Schjørring. J.K. and Olesen. J.E.** 1996. A passive flux sampler for measuring ammonia volatilization from manure storage facilities. *J. Environ. Qual.* 25, 241-247.