RESEARCH REPORT

ENVIRONMENT

Title: Meta-Analysis of Greenhouse Gas Emissions from Swine Operations – **NPB #10-104**

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Industry Summary:

Global warming has been linked to Greenhouse Gas (GHG) emissions. Swine operations are important sources of GHG, primarily methane (CH_4) and nitrous oxide (N_2O). The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines for estimating and reporting emissions of GHG. However, the methodology proposed by the IPCC is relatively crude. There is a need to improve the estimates of emissions. A statistical analysis (meta-analysis) on measured GHG emissions in existing studies as well as a literature review was performed to reveal possible bias in estimation of GHG emissions from swine operations and to explore causes of the variation in the reported GHG emissions from swine buildings, manure storage facilities and manure land applications. In total, 96 studies were included in the meta-analysis. The results showed that variation of the measured CH_4 and N_2O emission rates has not been adequately captured by the IPCC approaches. Larger differences between estimated and measured CH_4 emission rates were observed in North American studies than in European studies. In North American studies, the IPCC approaches have a tendency to overestimate CH_4 emissions, especially from lagoons at lower temperatures. For N_2O emissions from swine operations, an overall underestimation of the IPCC approaches was observed in European studies but not in North American studies. The measured GHG emissions from swine operations were significantly affected by types of emission sources, swine categories (stage of production) and geographic regions. Farrowing swine emitted more CH_4 and CO_2 emissions as compared with other swine categories, while gestating swine had greater N_2O emissions. Effects of different manure handling systems, bedding material, manure removal frequency, use of covers on manure storage facilities, temperature and diet crude protein (CP) content were investigated through meta-analysis. For N_2O emissions from swine manure applications, the IPCC default emission factor is within the range of measured values. Factors that can affect the GHG emissions from manure land applications include: temperature, precipitation, soil properties, manure application methods, manure application time, and composition/treatment of manure, etc. The results provided a better understanding on causes of variation in GHG emissions from swine operations. It can help to quantify the emissions more accurately. The knowledge on causes of variation may also be useful for developing cost-effective mitigation strategies.

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Scientific Abstract:

The objective of the project was to provide a systematic review of the literature on GHG emissions from swine operations, which includes both a qualitative review and statistical analysis (meta-analysis) that integrates results of various independent studies. Based on results of the literature review and meta-analysis, variation of the measured CH_4 and N_2O emission rates has not been adequately captured by the Intergovernmental Panel on Climate Change (IPCC) approaches. For CH_4 emissions, the differences between the IPCC estimated emission rates and measured values were significantly influenced by type of emission source, geographic region and measurement methods. Larger differences between estimated and measured CH_4 emission rates were observed in North American studies than in European studies. In North American studies, the results of meta-analysis indicated an overestimation by the IPCC approaches for CH_4 emissions from lagoons (pooled relative difference: -33.9%; 95% CI: -66.8% to -0.01%), and the discrepancy between the IPCC estimated emissions and the measured values mainly occurred at lower temperatures. In European studies, the results indicated an overestimation of the IPCC approaches in swine buildings with pit systems. For N_2O emissions from swine operations, an overall underestimation of the IPCC approaches was observed in European studies but not in North American studies. In European studies, the pooled N_2O emission factors for swine buildings with pit systems was 1.6% (95% CI, 0.6% to 2.7%), while the IPCC default emission factor for pit systems is 0.2%. Lager uncertainties were observed for measured N_2O emissions from bedding systems and from straw flow systems. For N_2O emissions from swine manure applications, the IPCC default emission factor (1%) is within the 95%CI in both North American studies (0.7% to 2.2%) and European studies (-0.3% to 3.5%). The measured GHG emissions from swine operations were significantly different for different emission sources (swine buildings or manure storage facilities), different swine categories (stage of production), and different geographic regions. Swine buildings generated much higher CO_2 emissions than manure storage facilities while CH_4 and N_2O emissions were not significantly different. Farrowing swine emitted more CH_4 and CO_2 emissions as compared with other swine categories, while gestating swine had greater N_2O emissions. North American studies reported significantly higher CH_4 emissions from swine operations than European and Asian studies. In swine buildings, Straw flow systems generated the lowest CH_4 and N_2O emissions of systems compared, while pit systems generated the highest CH_4 emissions and bedding system generated the highest N_2O emissions (no statistical differences). Lagoons generated significantly higher N_2O emissions than slurry storage basin/tanks, while CH_4 and CO_2 emissions are not different. Swine buildings with straw-based bedding resulted in numerically higher CH_4 but lower N_2O emissions as comparing to saw dust based bedding (no statistical differences). An increasing trend was observed for CH_4 emissions as manure removal frequency decreased. Relatively high GHG emissions were observed from deep pits or from pits flushed using lagoon effluent. The CH_4 emissions from slurry storage facilities without covers were significantly higher than from that with covers. Results also showed that the effects of temperature on CH_4 emissions were significant for lagoons or slurry storage facilities (regression slopes were 1.22 and 1.72 kg yr^{-1} hd^{-1} per ^oC respectively). Diet CP was found not a significant factor on GHG emissions from swine operations. The CO_2 emissions from swine operations were positively correlated with CH_4 emissions, especially for emissions from lagoons and slurry storage facilities (R^2= 0.98). Factors that can affect the GHG emissions from manure land applications include: temperature, precipitation, soil properties, manure application methods, manure application time, and composition of manure, etc. Results of meta-analysis showed that the measured cumulative CH_4 emissions increased with increasing average temperature but had a deceasing trend with increasing annual precipitation.

Introduction:

Background

Global warming has been linked to greenhouse gas (GHG) emissions. Official GHG inventories are reported annually by each country to the United Nation Framework Convention on Climate Change (UNFCCC). The Kyoto protocol restricts the total GHG emissions of each signature country and the protocol provides an opportunity for emission trading within signature countries. Within the U.S. there is limited potential for emissions trading at present. High quality emission inventory data are essential for the implementation of emissions trading, for developing cost effective abatement strategies, and as input to climate modeling.

Swine operations are sources of anthropogenic GHG, mostly of CH_4 and N_2O. Emissions of both CH_4 and N_2O from swine operations have large uncertainties. The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines for estimating and reporting emissions of GHG (IPCC, 2006). On April 10, 2009, USEPA published proposed Mandatory Greenhouse Gas Reporting Rules in the Federal Register (EPA, 2009). The proposed rule relied primarily on the 2006 IPCC Guidelines for the method used to calculate GHG emissions from manure storage facilities. The methodology proposed by the IPCC is relatively crude. Estimates of GHG emissions to a large extent are based on expert judgments of the IPCC Expert Group. Consequently, there is a need to improve the estimates of emissions. There are concerns as to whether the IPCC and EPA approaches adequately capture the variation which exists in swine operations practiced in the United States and Canada. Research is needed to assess the validity of the IPCC approaches. There is also a need to better understand the factors influencing the variation of emissions. Climate conditions and national practices may influence emissions in a way that is not captured by the IPCC approaches.

Large volumes of work on GHG emissions from swine operations have been published. However, these data have not been well summarized through a meta-analysis. Meta-analysis is a rapidly expanding area of research that has been relatively underutilized in agricultural fields. It is a quantitative statistical analysis of a large collection of results from individual previous studies for the purpose of integrating the findings. Meta-analysis may serve as a useful tool to help understand and quantify sources of variation in results across studies.

The IPCC guidelines

The IPCC presented guidelines and several methodologies for the evaluation of CH_4 and N_2O emissions arising from enteric fermentation and manure management during livestock production (IPCC, 2006).

Methane is produced through anaerobic biochemical decomposition of feed within an animal's digestive system as well as manure during its collection, storage, or treatment. In the IPCC guidelines, CH_4 emissions from enteric fermentation and from manure management are estimated separately. The IPCC "Tier 1" approach default CH_4 enteric fermentation emission factors is 1.5 kg CH_4 yr^{-1} $head^{-1}$ for swine production in developed countries. The more detailed "Tier 2" approach requires specific data on nutrient requirements, feed intake and CH_4 conversion rates for specific feed types to estimate CH_4 emissions from enteric fermentation.

To estimate CH_4 emission from manure management, the IPCC "Tier 2" approach requires detailed information on animal characteristics and the manner in which manure is managed. The manure management CH_4 emission factor can be developed using the following equation:

$$EF = VS \cdot 365\ \text{days/yr} \cdot B_0 \cdot 0.67\ \text{kg/m}^3 \cdot MCF$$

Where: EF = manure management CH_4 emission factor, kg CH_4 yr^{-1} hd^{-1}; VS = daily excreted volatile solid, kg d hd^{-1}; B_0 = maximum CH_4 producing capacity from manure produced, m^3 per kg of VS; MCF = CH_4 conversion factors that reflects the percentage of VS actually converted to CH_4 compared to B_0, %. The factor 0.67 kg m^{-3} is conversion factor of m^3 CH_4 to kg CH_4. The default values of VS, B_0 and MCFs for swine are provided in IPCC (2006).

The direct N_2O emission from manure management is estimated from N excretion rate and an emission factor. Default emission factors for direct N_2O emission from the manure management system are provided in IPCC "Tier 1" and "Tier 2" approaches. In the "Tier 2" approach, country-specific N excretion rates are used. The IPCC (2006) default emission factor for direct N_2O emission from managed soil is 1% (0.01kgN_2O-N per kg applied N).

Objectives:

The objective of the project was to provide a systematic review of the literature on GHG emissions from swine operations, which includes both a qualitative review and statistical analysis (meta-analysis) that integrates results of various independent studies. The project aims to reveal the bias and improve the accuracy in estimation of GHG emissions, to identify knowledge gaps in the research literature, and to provide a clearer picture and a solid foundation for the next generation of research in the field. The specific activities include: compare the measured values of GHG emissions from swine operations in the literature to the estimated values using the IPCC and EPA approaches to assess the validity of these approaches; identify and evaluate the causes of the variation in the reported GHG emissions from swine operations; explore sources of heterogeneity in the studies and possible new hypotheses; provide recommendations for directions of future research activities related to GHG emissions from swine operations based on the results of the meta-analysis and systematic review.

Materials & Methods:

Literature search

Multiple strategies will be undertaken to identify potentially eligible studies to be included in the meta-analysis and qualitative analysis. The literature search included the following 12 electronic bibliographic databases: AGRICOLA, AGRIS, Biological & Agricultural Index, Biological Abstracts, CAB Abstracts, CAB Reviews, Pig News and Information, Environment Complete, Pollution Abstracts, Conference Papers Index, Web of Science, and Google Scholar. The searches in each of the databases were started with combinations of the following key words: swine, pig, greenhouse gas, CH_4, and N_2O. In each database, an iterative process was used to refine the search strategy through testing of several search terms and incorporation of new search terms as new relevant studies are identified. A manual search was carried out for references that were cited in the identified studies and reviews. The following inclusion criteria were used to identify studies: Studies must report measurement data of CH_4 or N_2O emission from swine building or manure storage facilities; studies are reported in English; studies were conducted between 1970 and 2011; inclusion would not be restricted by study size or publication type. Efforts were made to check our own data and consult with experts in the field to identify unpublished studies. Two individuals independently conducted the search processes and screened the studies by reading the title and abstract of each study to select studies for full review according to the inclusion criteria. For each identified study either an abstract or full article was obtained and entered into an electronic database. Studies within the United States and Canada were separated from studies conducted in other countries for comparison analysis.

Data extraction

The included studies were distributed to four reviewers for quality assessment and data extraction. Standard data extraction sheets were developed for data extraction. For each study (each data source), data were extracted in the following categories: (1) information on the paper (author, year, title); (2) information on emission source (location, swine category, size of operation, diet, manure handling system, manure storage type, treatment, average temperature, etc.; (3) information on measurement methods; (4) average emission data and standard deviation (CH_4, N_2O, CO_2); (5) main conclusion of the paper (factors that influence emissions, research gaps, etc.). For the purpose of analyses, data are categorized into several emission sources (swine buildings, lagoon and slurry storage facilities, and swine manure land application sites). Each study was reviewed in duplicate by two independent reviewers. Data extraction reports from four reviewers were synthesized, and disagreements were resolved by consensus between the reviewers. With the results from the data review and extraction processes, a meta-analysis database was created. The process and outcomes of data extraction and synthesis were reviewed by independent expert reviewers. A full list of included studies and the completed data extraction sheet are available to allow for independent scrutiny of the process.

Various units of emission data have been used in literature. In order to perform statistical analysis and to compare the measured values with the IPCC estimated values, the units of measured emission data from swine operations were all converted to kg yr^{-1} hd^{-1} using the calculating method presented in Table 1. When performing unit conversion, pig weight, pig number, area of lagoon/storage tank, and other needed information were first extracted from the original studies. If pig weight was not available from the original studies, default values were used (In North American studies, market: 46 kg, farrowing: 180 kg, gestation: 150 kg, nursery: 18 kg). When unit conversion is not possible due to lack of key information, the original emission data was excluded from statistical analysis.

Table 1. Unit conversion of emission data in literature

Original units	Calculation of unit conversion to kg yr^{-1} hd^{-1}
g d^{-1} AU^{-1}	× pig weight (kg) / 500 (kg) × 365 (d) / 1000
g d^{-1} kg^{-1}	× pig weight (kg) × 365 (d) / 1000
g $hd^{-1}d^{-1}$	× 365 (d) / 1000
g d^{-1}	× 365 (d) / pig number / 1000
L CH_4 d^{-1} pig^{-1}	× 0.67 (kg m^{-3}) × 365 (d) / 1000
Kg CO_2e d^{-1} kg^{-1}	× 365 (d) / GWP × pig weight (kg)
kg $site^{-1}d^{-1}$	× 365 (d) / pig number
kg $m^{-2}yr^{-1}$	× area (m^2) / pig number
kg $ha^{-1}d^{-1}$	× 365 (d) × area (ha) / pig number
g $m^{-2}d^{-1}$	× 365 (d) × area (m^2) / pig number / 1000
g $m^{-3}d^{-1}$	× 365 (d) × volume (m^3) /pig number / 1000
mg $m^{-2}s^{-1}$	× 365 (d) × 24 (h) × 3600 (s) ×area (m^2) / pig number/ 1000000
L CH_4 kg^{-1} VS	× 0.67 (kg m^{-3}) × VS (kg d^{-1} hd^{-1}) × 365 (d) /1000
m^3 CH_4 $m^{-3}d^{-1}$	× 0.67 (kg m^{-3}) × volume (m^3) × 365 (d) /pig number

Comparison of the measured CH_4 and N_2O emissions with the IPCC estimated values

The measured CH_4 and N_2O emissions from swine operations or swine manure land application were compared with the IPCC estimated values. The CH_4 emissions from manure storage facilities were estimated using the IPCC "Tier 2" approach as described in section 2. Default values of VS, B_0 and MCFs for swine in corresponding geographic regions (IPCC, 2006) were used. The CH_4 emissions from a swine building were estimated by adding emissions from enteric fermentation (using the "Tier 1" approach as suggested by IPCC for swine) and that from manure management systems in a swine building (using the IPCC "Tier 2" approach). The N_2O emissions from swine buildings and manure storage facilities were estimated using the IPCC "Tier 2" approach. For CH_4 emissions from swine operations, the percentage relative difference between the measured and IPCC/EPA estimated values [(measured values – IPCC values) / (measured values + IPCC values)] were calculated and adopted as the effect size metric. For N_2O emissions from swine operations or from swine manure land application, the measured emission factors for direct N_2O emissions were used as the effect size metric and were compared with the IPCC default emission factors. The indirect N_2O emissions (i.e., emissions result from volatile N losses that occur primarily in the forms of NH_3) are not addressed as part of this study. The pooled effect estimate represents a weighted average effect size metric of all studies included in the meta-analysis with a greater weight being given to larger studies and less weight to smaller studies. Considering the many sources of heterogeneity between studies, a random-effect model will be used in the meta-analysis. For each category of emission sources (swine buildings, manure storage facilities, and manure land application), graphical summaries (Forest plot) were presented to illustrate the difference between the measured and the estimated values in eligible studies, and summary statistics with confidence interval were calculated to determine the overall direction and significance of the differences. Weighted paired t-tests were performed to compare the measured CH_4 and N_2O emissions with the corresponding IPCC estimated values for each group of emission sources. Significant differences were declared for the comparison at $P < 0.05$.

Analysis of variation in GHG emissions from swine operations

Data were analyzed statistically by ANOVA using the MIXED model procedure of SAS (SAS for Windows, Version 9.1.3, SAS Institute, Cary, NC). All or part of the following variables (factors) were treated as a fixed effect in the analyses, which include, geographic region, emission source, source conditions (e.g., manure removal frequency, bedding material, etc.), swine category (or stage of production), average temperature, size of operation, diet crude protein (CP) content, methods of measurement, etc. Study (or each publication) was treated as a random effect. The ratios of emission rate over standard deviation were used as weighting variables, so that data points that have relative small standard deviation were given more weight in the comparison. For data points without information of standard deviation, lowest weights in the same group of emission sources were assigned. Tukey's test was applied in comparing emissions for various effects. Significant difference was declared for the comparison when $P<0.05$. A qualitative review was also performed to evaluate causes of variation in GHG emissions that has been identified in literature.

Results:

Literature search results

The literature search and review efforts yielded a total of 53 studies (publications) that provided GHG emission data from swine operations with units of emission data that could be converted into kg yr^{-1} hd^{-1}, and 43 studies that provided cumulative GHG emission data from swine manure land application with units that could be converted into kg ha^{-1} (Table 2). Some studies provided emission data under different settings/treatments, therefore in these cases more than one data point was extracted from the studies.

Table 2. Results of literature search

Emission source	Geographic region	Number of studies (data points)	Author, year
Swine building	North America	12 (32)	Ball and Mohn, 2003; Desutter and Ham, 2005; Kai et al.,2006; Lague et al., 2003; Li et al., 2011; Ni et al., 2008; Pepple et al., 2010; Powers et al., 2008; Sharpe and Harper, 2001; Zahn et al., 2001; Zhang, et al., 2007; Unpublished study at MSU.
	Europe	20 (78)	Amon et al.,2007; Blanes-Vidal et al., 2008; Cabaraux et al., 2009; Christensen and Thorbek, 1987; Costa and Guarino, 2008; Costa and Guarino, 2009; Dourmad et al., 2009; Groenestein et al., 1996; Guarino et al., 2008; Haeussermann et al., 2006; Jelinek et al., 2007; Jensen and Jørgensen, 1994; Nick et al., 2004; Nick et al., 2005; Osada et al., 1998; Palkovicova et al., 2009; Philippe et al., 2007a, 2007b, 2009, 2010;
	Asia	3 (6)	Dong et al., 2007a, 2007b, 2009.
	Oceania	0 (0)	-
Manure storage facilities	North America	16 (32)	Clark et al., 2005; Desutter and Ham, 2005; Hamilton et al., 2005; Harper et al., 2000; Harper et al., 2004; Kaharabata et al., 1998; Lague et al., 2005; Masse et al., 2003; Park et al. 2006; Park et al. 2010; Pelletier et al., 2004; Sharpe and Harper, 1999; Sharper et al., 2002; Shores et al., 2005; Zahn et al., 2001; Zhang et al., 2007.
	Europe	3 (4)	Loyon et al., 2007; Husted et al., 1993; Rodhe et al., 2010
	Asia	1 (3)	Su et al., 2003.
	Oceania	1 (1)	Craggs et el., 2008.
Land application	North America	16 (62)	Bender and Wood, 2007; Chan and Parkin, 2001; Chantigny et al., 2001; Chantigny et al., 2007; Chantigny et al., 2010; Hermandez-Ramirez et al., 2009; Jarecki and Lal, 2006; Jarecki et al., 2008; Jarecki et al., 2009; Mkhabela et al., 2009; Parkin et al., 2006; Rochette et al., 2004; Sharpe and Harper, 1997;

			Sharpe and Harper, 2002; Sistani et al., 2010; Sullivan et al., 2005.
	Europe	20 (59)	Arcara et al., 1999; Boeckx et al., 2001; Cardenas, et al., 2007; Chadwick et al., 1998; Chadwick et al., 2000; Chirinda et al., 2010; Dambreville et al., 2006; Dambreville et al., 2007; Ferm et al., 1999; Lo´pez-Ferna´ndez et al., 2007; Meijide et al, 2007; Meijide et al, 2009; Misselbrook et al., 1998; Petersen, 1999; Sanchez-Martı´n et al., 2010; Thomsen et al., 2010; Vallejo et al., 2005; Vallejo et al., 2006; Velthof et al., 2003; Webb et al., 2004; Weslien et al., 1998.
	Asia	4 (6)	Akiyama and Tsuruta, 2003; Wang et al., 2000; Watanabe et al., 1997; Lu et al., 2000.
	Oceania	3 (3)	Sherlock et al., 2002; Sommer et al., 1996; Bhandral et al., 2007, Bertora et al., 2008.

The database

Databases of GHG emissions from swine operations and manure land applications were obtained as one of the results of the data extraction processes for the purpose of statistical analysis. The emission rates of CH_4, N_2O and CO_2 from swine operations were provided in units of kg yr^{-1} hd^{-1}. In order to investigate the factors that may affect GHG emissions, the following variables were included in the database: geographic regions (North America, Europe, Asia, Oceania), average temperature, emission source type (swine buildings were classified into pit systems, deep bedding systems and straw flow systems; manure storage facilities were classified into lagoon and slurry storage), source conditions (for pit systems, considering manure removal frequency; for deep bedding systems, considering different bedding material; for lagoon or slurry storage, considering with/without cover), swine category (finishing, farrow to finish, farrowing, gestating, and nursery), size of operation (number of animals), diet CP content, and methods of measurement (traditional methods [chamber methods, emission rate was calculated as concentration multiplying ventilation rate, etc.], FTIR [open-path Fourier transform infrared spectrometry], MMB [Micrometeorological mass balance], and SF_6 [sulfur hexafluoride as a tracer]. The database for GHG emissions from swine operations and swine manure land applications are provided in Appendix 1-4.

Average GHG emissions by geographic region

Average GHG emissions from swine operations and swine manure land applications in literature are listed in Tables 3 and 4. The average CH_4 and CO_2 emissions from manure storage facilities in Asian studies are remarkably low because only one study from Taiwan was included (Su et al., 2003) and in the study manure was diluted before being treated with a solid/liquid separator and an anaerobic wastewater treatment system. The measured CH_4 and N_2O emissions from swine buildings, manure storage facilities, and land applications in North American studies are presented in Appendix 1 to 3.

Table 3. Average GHG emissions from swine operations in different geographic regions

Emission source	**Geographic region**	**Emission rates (kg yr^{-1} hd^{-1})**					
		CH_4		**N_2O**		**CO_2**	
		Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Swine buildings	North America	8.4	11.0	0.01	0.01	1182	890
	Europe	3.5	2.8	0.31	0.47	678	559
	Asia	1.5	0.5	0.08	0.04	779	373
	Oceania	-	-	-	-	-	-
Manure storage facilities	North America	17.5	19.5	0.011	0.026	62.5	138.6
	Europe	32.9	36.7	0.000	0.000	143.5	34.6
	Asia	0.8	0.5	0.001	0.000	0.7	0.5
	Oceania	17.1	4.1	-	-	-	-

Table 4. Average GHG emissions from swine manure land applications in different geographic regions

Emission source	Geographic region	Cumulative emission (kg ha^{-1})					
		CH_4		N_2O		CO_2	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Swine manure land applications	North America	3.5	7.7	5.3	4.5	17715	21759
	Europe	1.6	2.4	10.8	56.3	-	-
	Asia	319	152	1.0	-	-	-
	Oceania	0.7	1.0	4.5	6.4	-	-

Comparison of the measured CH_4 and N_2O emissions from swine operations with the IPCC estimated values

(1) Overall comparison and heterogeneity of the differences

Results of weighted paired t-test for CH_4 and N_2O emissions using all available data points are presented in Table 5. Overall, the measured CH_4 emissions from swine operations were not significantly different from the IPCC estimated values, while the measured N_2O emissions were significantly higher than the IPCC estimated values the measured values. The R^2 values between the measured and the IPCC estimated emission rates for CH_4 and N_2O were only 0.26 and 0.11 respectively, which indicates that variation of the emission rates has not been adequately captured by the IPCC approaches.

Table 5. Results of weighted paired t-test for comparison between the measured CH_4 and N_2O emissions with the IPCC estimated values using all available data

Difference (kg yr^{-1} hd^{-1}): IPCC estimated emission rates – measured values							
	n	Lower CL Mean	Mean	Upper CL Mean	Std Dev	t value	P value
CH_4	122	-1.76	-0.08	1.61	23.25	-0.09	0.93
N_2O	75	-0.15	-0.12	-0.08	0.25	-5.83	<0.01

The P values of main effects on the differences between the IPCC estimated emission rates and measured values are presented in Table 6. For CH_4 emissions, the differences were significantly influenced by type of emission source, geographic region and measurement methods, while for N_2O emissions none of the factors were significant.

Table 6. P values of main effects on the differences between the IPCC estimated emission rates and measured values

Factors	CH_4	N_2O
Emission source	<0.01	0.30
Swine category	0.50	0.73
Geographic region	0.02	0.57
Method	<0.01	-
Temperature	0.77	0.44
Size of operation	0.36	0.79

Effects of measurement method on the difference between IPCC estimated CH_4 emission rates and measured values are presented in Table 7. When CH_4 emissions were measured using the FTIR method or the SF_6 method, the differences were much larger than when emissions were measured using the traditional method or the MMB method. In the database, there is only one study (Shore et al., 2005) that used the FTIR method and one study (Kaharabata et al., 1998) that used the SF_6 method. Study numbers contributed to larger uncertainties in these two studies and a possible overestimation of CH_4 emission rates associated with the FTIR method and the SF_6 method. In the study by Kaharabata et al. (1998), the measured CH_4 emission rate was 5.8 times of the IPCC estimated value. The authors have attributed the discrepancy to two reasons. First, they assumed 70% of the animal population was serviced by the manure storage facilities due to lack of detailed information on the types, quantity, and capacity of the facilities. Second, they assumed observations around midday were representative of emission for the whole day, which could lead to an overestimation because nighttime emissions can be lower. The two studies were excluded in the following analysis.

Table 7. Effects of measurement method on the differences between the IPCC estimated CH_4 emission rates and measured values

Difference ($kg\ yr^{-1}\ hd^{-1}$): IPCC estimated emission rates – measured values				
Measurement method	Traditional	MMB	FTIR	SF_6
Main effect mean	3.3[a]	15.9[a]	-12.1[b]	-60.4[c]
SEM[1]	2.3	8.3	3.6	10.5

[a,b,c] Values within the same section differ significantly if without common letter (P < 0.05).
[1]: Standard error of the mean.

Larger differences between estimated and measured CH_4 emission rates were observed in North American studies than in European studies. Comparisons of the measured emissions with the IPCC estimated values were performed in subgroups of geographic regions and emission sources in the following analysis.

(2) Comparison in North American studies

Figure 1 presents the Forest plot for CH_4 emissions from swine operations in North American studies. The pooled relative differences for swine buildings (pit system) and for slurry storage facilities were -10.3% (95% CI, -34.3% to 13.6%, p=0.36) and -10.3% (95% CI, -26.2% to 5.6%, p=0.17) respectively, suggesting that the IPCC estimated CH_4 emissions from swine buildings and from slurry storage facilities were not significantly different from the measured values. However, the pooled relative difference for lagoons was -33.9% (95% CI, -66.8% to -0.01%, p=0.04), suggesting an overestimation by the IPCC approaches for emissions from lagoons. The overall pooled relative difference between measured and IPCC estimated CH_4 emission rates in North American studies using a random effect model was -16.0% (95% CI, -29.3% to -2.7%, p=0.02), suggesting an overall overestimation using the IPCC approaches.

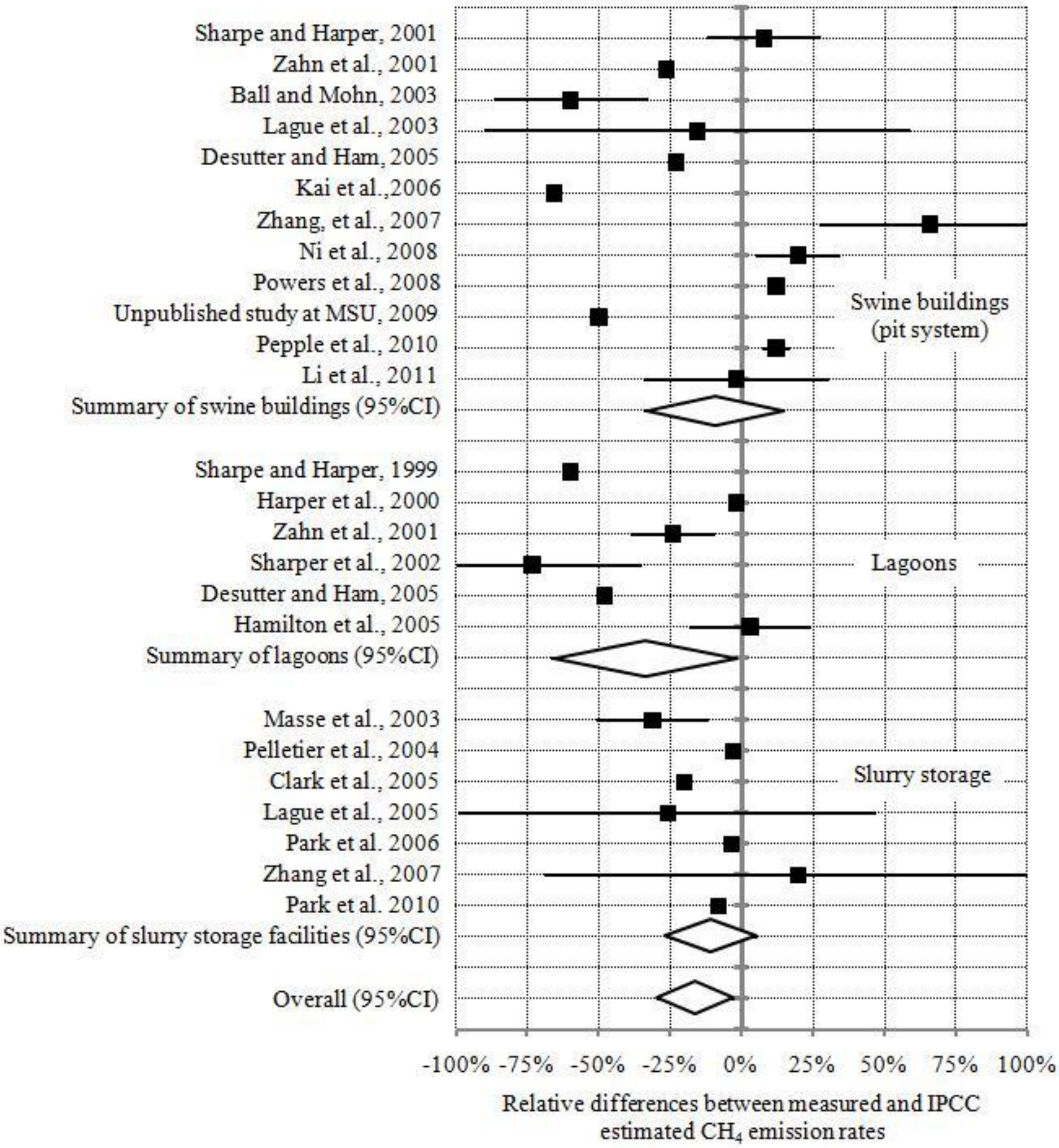

Figure 1. Forest plot for CH_4 emissions from swine operations in North American studies

Figure 2 presents the Forest plot for N_2O emissions from swine operations in North American studies. The pooled N_2O emission factors for swine buildings (pit system) were 0.06% (95% CI, -0.08% to 0.20%, p=0.24), while the IPCC default emission factor for these systems is 0.2% (0.002 kg N_2O-N per kg excreted N). The IPCC default emission factor is on the upper limit of the 95%CI of measured values. The pooled N_2O emission factors for lagoons and for slurry storage facilities were 0.35% (95% CI, -2.82% to 3.53%, p=0.39) and 0.01% (95% CI, -0.02% to 0.04%, p=0.04), respectively, while the IPCC default emission factor for lagoons and for slurry storage facilities is 0. The large variation in measured N_2O emissions from lagoons comes from the study of Harper et al. (2004) that reported relatively high emissions of N_2O. The overall pooled N_2O emission factors in North American studies was -0.08% (95% CI, -0.03% to 0.20%, p=0.14).

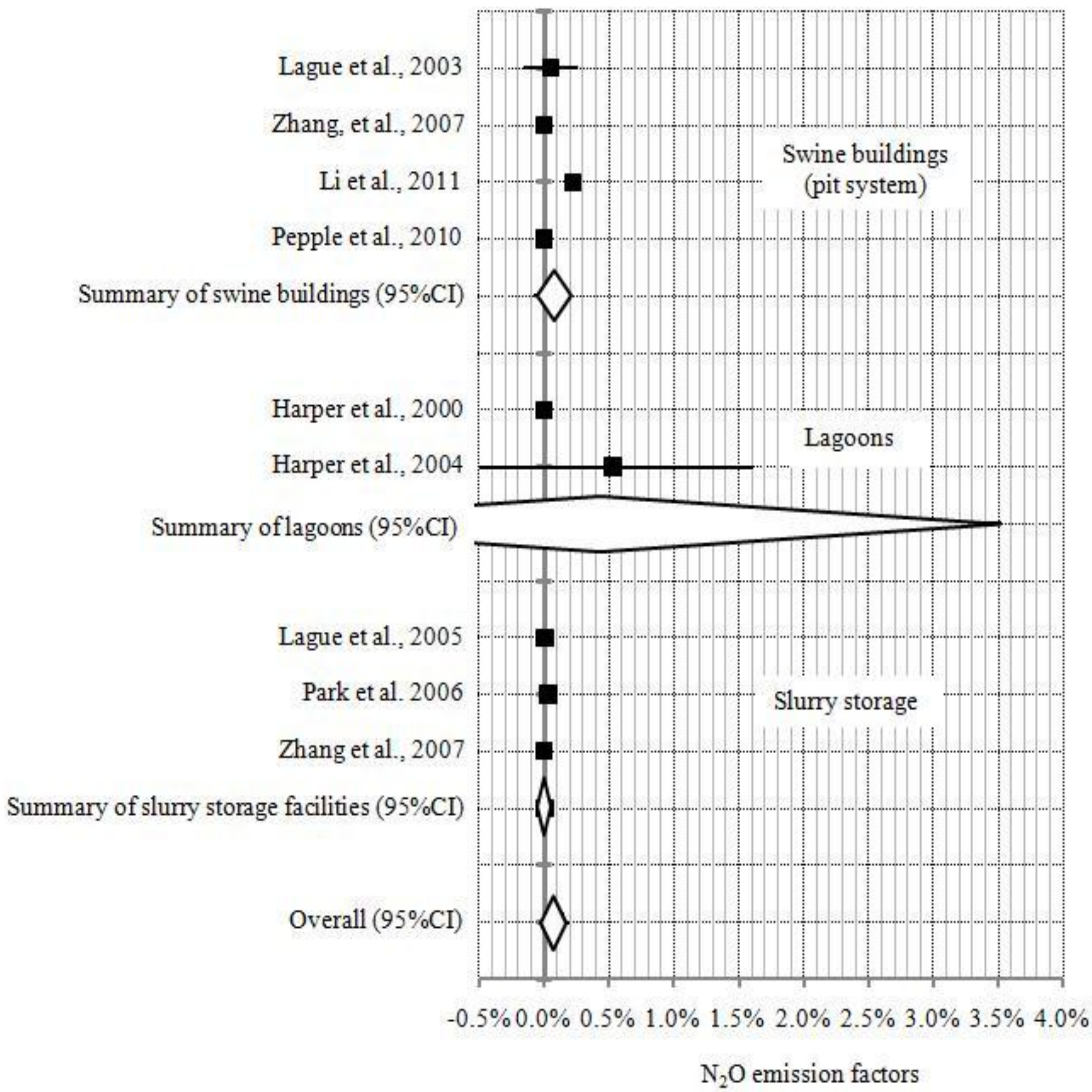

Figure 2. Forest plot for N_2O emissions from swine operations in North American studies

Results of weighted paired t-test for comparison between the measured CH_4 and N_2O emissions and the IPCC estimated values in subgroups of emission sources in North American studies are presented in Table 8. For lagoons, the IPCC estimated CH_4 emission rates were significantly higher than the measured values. For swine buildings with pit systems, the IPCC estimated N_2O emission rates were significantly higher than the measured values, because 13 out of 18 data points in the literature reported negligible N_2O emissions.

Table 8. Results of weighted paired t-test for comparison between the measured CH_4 and N_2O emissions with the IPCC estimated values in North American studies

Difference (kg yr^{-1} hd^{-1}): IPCC estimated emission rates – measured values

	Emission sources	n	Lower CL Mean	Mean	Upper CL Mean	Std Dev	t value	P value
CH_4	Lagoons	10	1.58	8.46	15.34	9.58	2.78	0.02
	Slurry storage	14	-3.91	0.75	5.40	11.84	0.35	0.73
	Swine buildings (pit system)	32	-3.33	-1.52	0.28	13.11	-1.72	0.10
N_2O	Lagoons	3	-0.138	-0.034	0.070	0.042	-1.42	0.29
	Slurry storage	7	-0.002	-0.000	0.001	0.001	-1.29	0.24
	Swine buildings (pit system)	18	0.012	0.023	0.034	0.022	4.53	<0.01

Approximately 25% of the swine facilities in the US use anaerobic lagoons/wash systems (Eklund and LaCosse, 1995). For lagoons, the R^2 between the measured and the IPCC estimated CH_4 emission rates was 0.75; while in 80% of data points, the IPCC estimated emissions were higher than the measured values. Temperature has been identified as an important factor that influences MCF for lagoons in the IPCC approaches. The estimated MCF from measurements were compared with the IPCC provided MCF at various temperatures for lagoons in North American studies (Figure 3). It was observed that the discrepancy between the IPCC estimated emissions and the measured values mainly occurred at lower temperatures. When temperatures were at 15 ^oC, the average estimated MCF from measurements were only 38% of the IPCC provided MCF. When temperatures were at 12 ^oC, the estimated MCF from measurements were only 25% of the IPCC provided MCF.

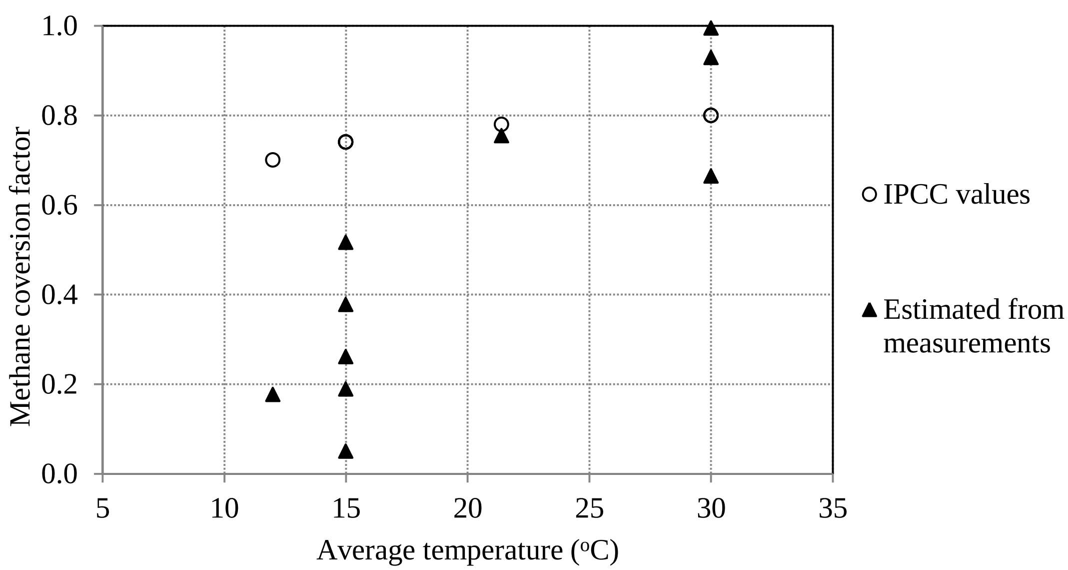

Figure 3. Comparison of estimated MCF from measurements and the IPCC provided MCF for lagoon in North American studies

For slurry storage facilities, the R^2 between the measured and the IPCC estimated CH_4 emission rates was 0.45; while in 93% of data points, the IPCC estimated emissions were higher than the measured values. The estimated MCF from measurements were compared with the IPCC provided MCF at various temperatures for slurry storage facilities in North

American studies (Figure 4). The estimated MCF from measurements and the IPCC provided MCF followed a similar increasing trend with increasing temperature.

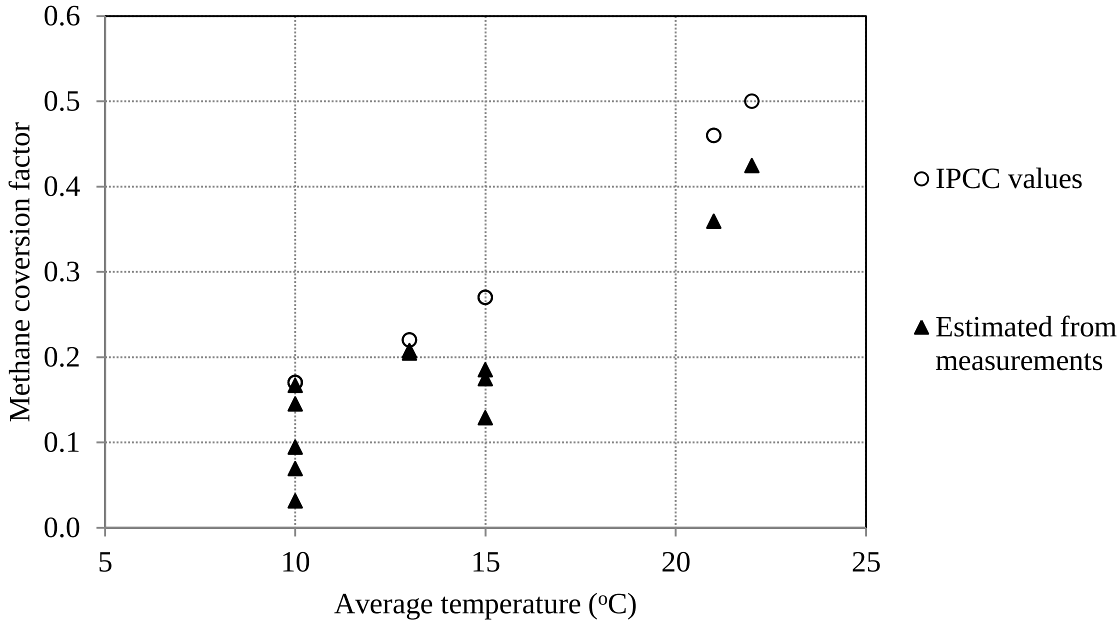

Figure 4. Comparison of estimated MCF from measurements and the IPCC provided MCF for slurry storage facilities North American studies

For swine buildings with pit systems, the R^2 between the measured and the IPCC estimated CH_4 emission rates was only 0.12, which indicates large uncertainties and unaccounted factors that have significant impacts on emissions from these systems.

(3) Comparison in European studies

Figure 5 presents the Forest plot for CH_4 emissions from swine operations in European studies. The pooled relative difference for swine buildings with pit systems was -21.1% (95% CI, -38.8% to -3.4%, p=0.02), suggesting an overestimation of the IPCC approaches in these systems. The pooled relative difference for swine buildings with bedding systems, for swine building with straw flow systems and for slurry storage facilities were 10.5% (95% CI, -20.7% to 41.7%, p=0.45), -19.2% (95% CI, -424% to 386%, p=0.65), and -19.4% (95% CI, -212% to 173%, p=0.71) respectively, suggesting that the IPCC approaches showed no significant bias from measured CH_4 emissions from these systems. Large uncertainties were observed for measured CH_4 emissions from swine building with straw flow systems and from slurry storage facilities. The overall pooled relative difference between measured and IPCC estimated CH_4 emission rates in European studies using a random effect model was -14.4% (95% CI, -28.9% to -0.2%, p=0.05), suggesting an overall overestimation of the IPCC approaches.

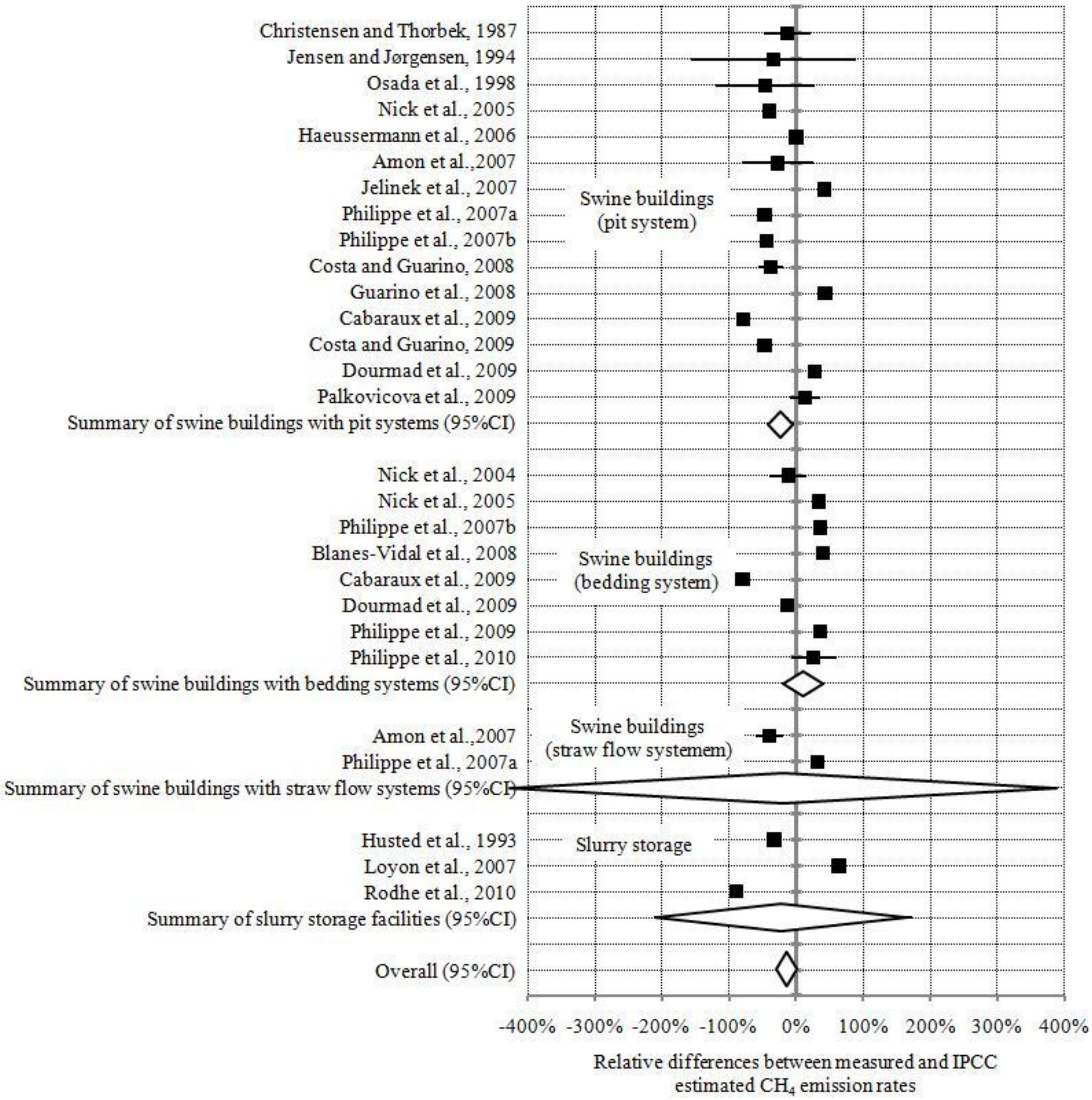

Figure 5. Forest plot for CH_4 emissions from swine operations in European studies

Figure 6 presents the Forest plot for N_2O emissions from swine operations in European studies. The pooled N_2O emission factors for swine buildings with pit systems was 1.6% (95% CI, 0.6% to 2.7%, p=0.01), while the IPCC default emission factor for pit systems is 0.2%. The pooled N_2O emission factors for swine buildings with bedding systems and that with straw flow systems were 4.8% (95% CI, -0.2% to 9.8%, p=0.06) and 0.5% (95% CI, -7.0% to 8.1%, p=0.54) respectively, while the IPCC default emission factors for solid storage systems is 0.5%. The measured N_2O emissions were significantly higher than IPCC estimated values in pit systems, and lager uncertainties were observed for measured N_2O emissions from bedding systems and from straw flow systems. The overall pooled N_2O emission factors in European studies was 2.2% (95% CI, 0.8% to 3.6%, p<0.01), suggesting an overall underestimation of the IPCC approaches.

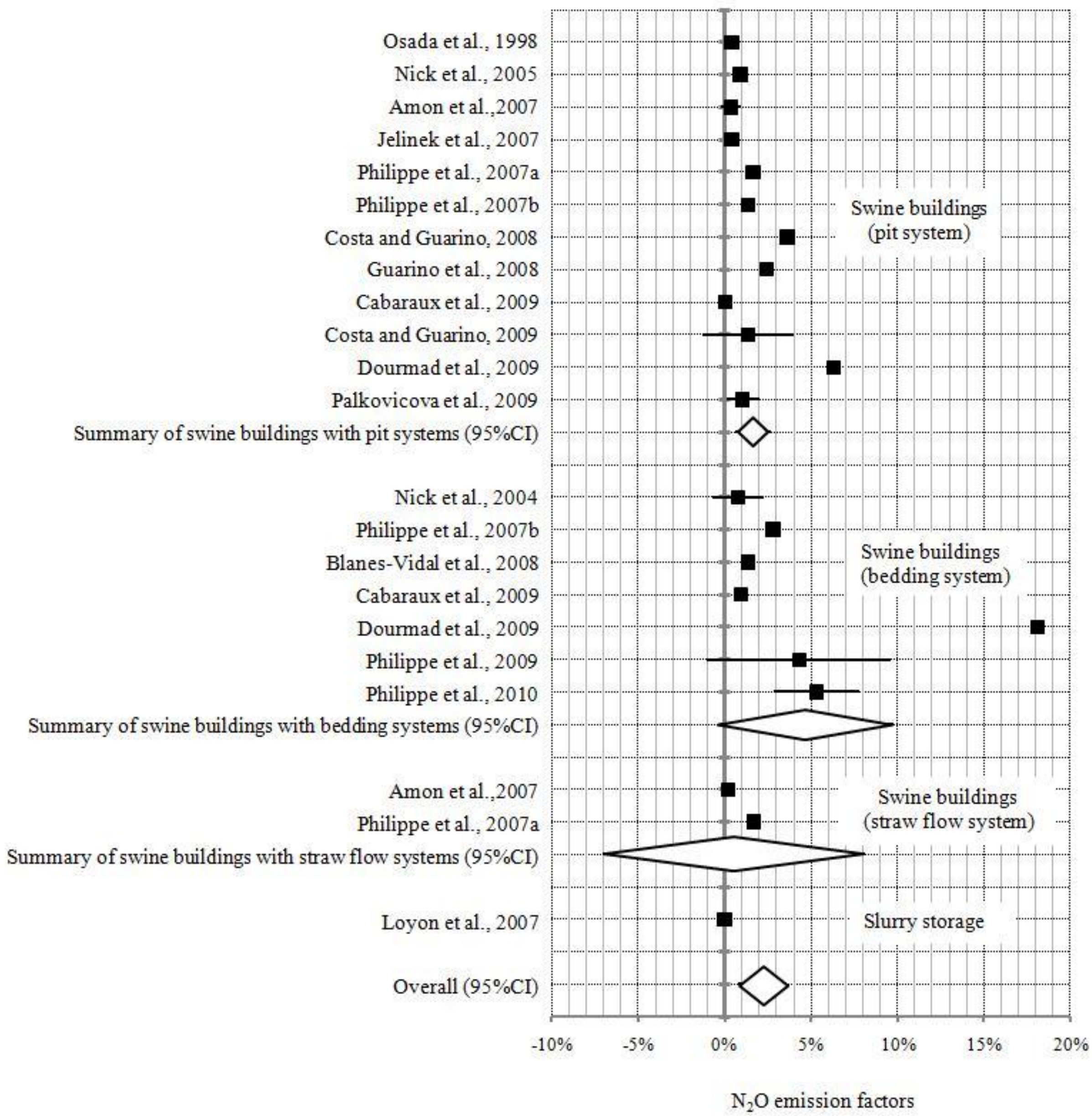

Figure 6. Forest plot for N_2O emissions from swine operations in European studies

Results of weighted paired t test for comparison between the measured CH_4 and N_2O emissions with the IPCC estimated values in subgroups of emission sources in European studies are presented in Table 9. For swine buildings with pit systems, the IPCC estimated CH_4 emission rates were significantly higher than the measured values, conversely, the IPCC estimated N_2O emission rates were significantly lower than the measured values. For swine buildings with bedding systems, the IPCC estimated CH_4 emission rates were significantly lower than the measured values.

Table 9 Results of weighted paired t-test for comparison between the measured CH_4 and N_2O emissions with the IPCC estimated values in European studies

Difference (kg yr^{-1} hd^{-1}): IPCC estimated CH_4 emission rates – measured values								
	Emission sources	n	Lower CL Mean	Mean	Upper CL Mean	Std Dev	t value	P value
CH_4	Slurry storage	4	-74.17	-22.97	28.22	129.14	-1.43	0.25
	Swine building (pit system)	22	2.82	4.86	6.91	14.96	4.94	<0.01
	Swine building (bedding system)	12	-2.87	-1.46	-0.06	7.41	-2.29	0.04
	Swine building (straw flow system)	5	-1.61	0.08	1.77	2.73	0.13	0.90
N_2O	Slurry storage	2	0	0	0	0	.	.
	Swine building (pit system)	20	-0.14	-0.10	-0.07	0.10	-6.72	<0.01
	Swine building (bedding system)	10	-0.48	-0.22	0.04	0.69	-1.88	0.09
	Swine building (straw flow system)	5	-0.07	0.02	0.11	0.11	0.72	0.51

Comparison of the measured N_2O emissions from swine manure land applications with the IPCC estimated values

Figure 7 and 8 present the Forest plots for N_2O emissions from swine manure land applications in North American studies and in European studies. The pooled N_2O emission factors in North American studies and in European studies were 1.4% (95% CI, 0.7% to 2.2%, p<0.01) and 1.6% (95% CI, -0.3% to 3.5%, p<0.01) respectively. The IPCC default emission factor for managed soil is 1% (0.01 kg N_2O-N per kg applied N), which is within the 95%CI in both North American and European studies.

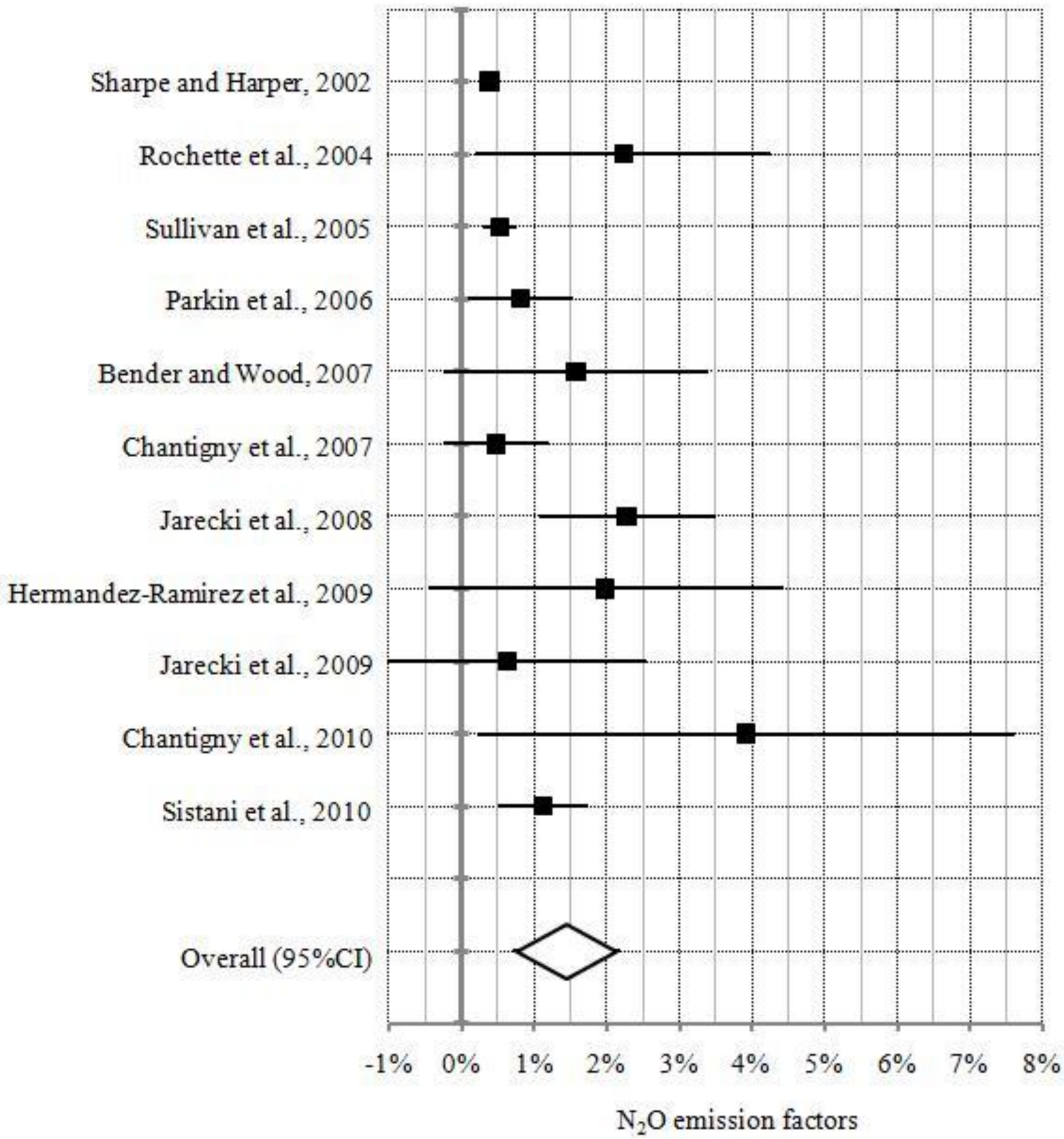

Figure 7. Forest plot for N_2O emissions from swine manure land applications in North American studies

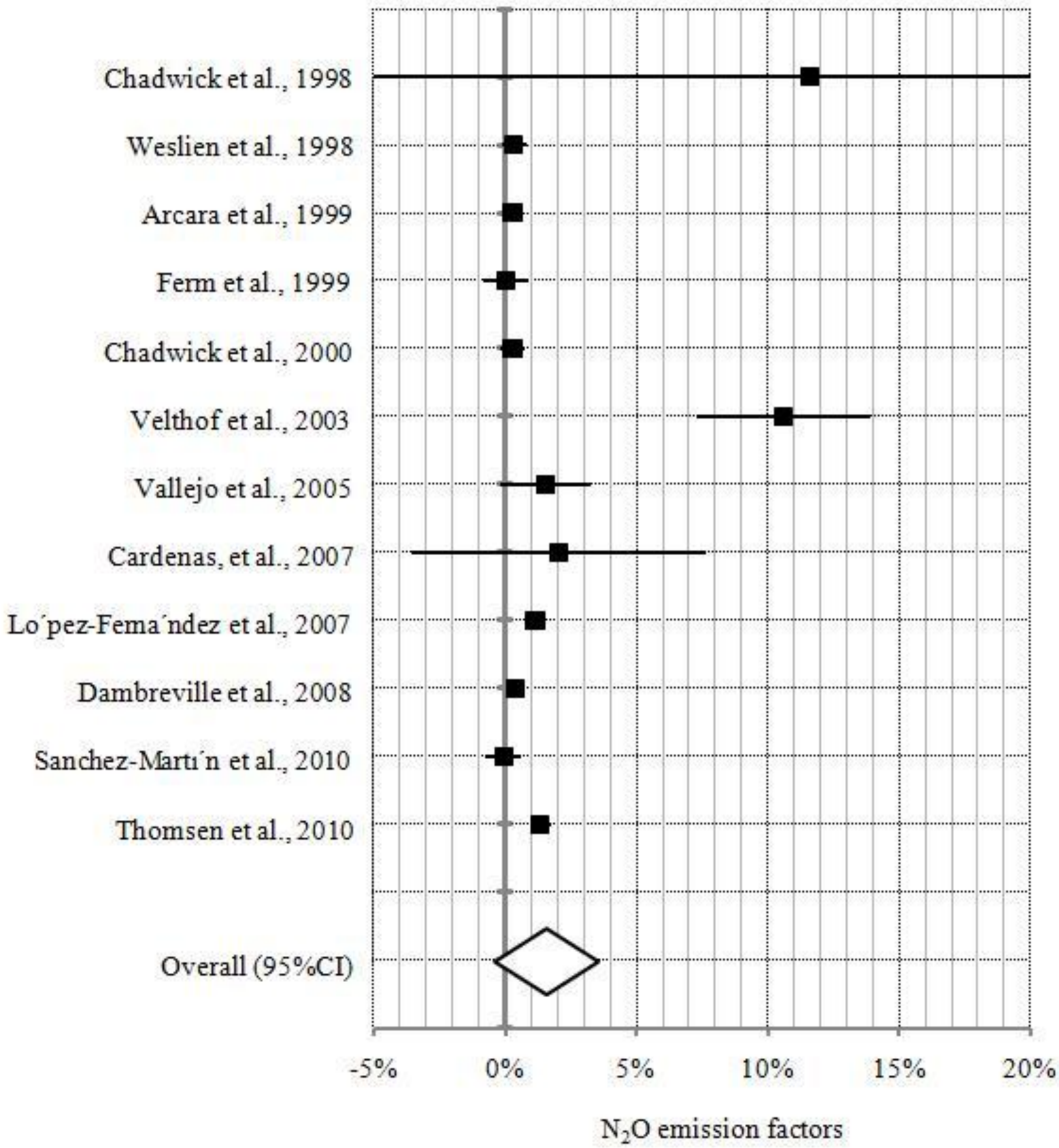

Figure 8. Forest plot for N_2O emissions from swine manure land applications in European studies

Causes of variation in GHG emissions from swine operation

(1) Overall analysis

The P values of main effects on GHG emissions from swine operations in the overall analysis are presented in Table 10. Type of emission source (swine buildings or manure storage facilities) was significant for CO_2 emissions, but was not significant for CH_4 and N_2O emissions. Swine category (stage of production) was significant for all of the three GHG gases. Geographic region of swine operations was significant for CH_4 and N_2O emissions, but was not significant for CO_2 emissions. Neither temperature nor size of operation was significant in the overall analysis.

Table 10. P values of main effects on GHG emissions from swine operations

Cause of variation	CH_4 (n=76)	N_2O (n=53)	CO_2 (n=40)
Emission source	0.94	0.93	<0.01
Swine category	0.05	<0.01	<0.01
Geographic region	0.04	0.02	0.85
Temperature	0.20	0.95	0.83
Size of operation	0.89	0.24	0.67

(2) Effect of emission source

Main effect means of GHG emissions from different emission source are presented in Table 11. The CH_4 and N_2O emissions from swine buildings were not significantly different compare to that from manure storage facilities. However, swine buildings generated much higher CO_2 emissions than manure storage facilities. In swine buildings, CO_2 emissions were 18 to 1032 times higher than CH_4 emissions, and therefore in most cases CO_2 is the larger contributor to total GHG emissions from swine building given that the global warming potential of CH_4 is 21 times higher than CO_2. For manure storage facilities, CO_2 emissions were much lower, indicating that CH_4 is the larger contributor to total GHG emissions from manure storage facilities.

Table 11. Main effect means of GHG emissions from different emission source (kg yr^{-1} hd^{-1})

Emission source	CH_4		N_2O		CO_2	
	Main effect mean	SEM[1]	Main effect mean	SEM[1]	Main effect mean	SEM[1]
Swine buildings	4.8	1.8	0.16	0.18	855[b]	94
Manure storage facilities	4.6	3.0	0.21	0.44	-63[a]	260
P value	0.94		0.93		<0.01	

[a,b]: Values within the same section differ significantly if without common letter ($P < 0.05$).

[1]: Standard error of the mean.

Within the subgroup of swine buildings, three manure handling systems were compared with each other. Cabaraux et al. (2009) and Dourmad et al. (2009) reported that CH_4 and N_2O emissions decreased in a sawdust bedding system as compared to a fully slatted floor/pit system. Philippe et al. (2007b) reported that straw bedding systems produce more NH_3 and N_2O than keeping pigs on slatted floors but CH_4 emissions are not different. The results of one way ANOVA meta-analysis (Table 12) showed that swine buildings with straw flow systems generated the lowest CH_4 and N_2O emissions of systems compared, while pit systems generated the highest CH_4 emissions and bedding system generated the highest N_2O emissions (no statistical differences). Within the subgroup of manure storage facilities, emissions from lagoons and slurry storage basin/tanks were compared. The results (Table 12) showed that lagoons generated significantly higher N_2O emissions than slurry storage basin/tanks, while CH_4 and CO_2 emissions are not different.

Table 12. Effect of different manure handling systems on GHG emissions from swine operations (kg yr^{-1} hd^{-1})

Emission source	Different systems	CH_4		N_2O		CO_2	
		Main effect mean	SEM[1]	Main effect mean	SEM[1]	Main effect mean	SEM[1]
Swine buildings	Pit system	5.5	1.1	0.41	0.16	859	144
	Bedding system	4.8	1.3	0.49	0.16	801	186
	Straw flow system	2.9	2.1	0.38	0.17	916	232
P value		0.36		0.09		0.91	
Manure storage	Lagoons	16.2	5.9	0.034[b]	0.011	39	78

facilities	Slurry storage	12.2	5.1	0.001[a]	0.006	90	50
P value		0.58		0.04		0.60	

[a,b]: Values within the same section differ significantly if without common letter ($P < 0.05$).
[1]: Standard error of the mean.

The effect of bedding material on CH_4 emissions has been investigated. Masse et al. (2008) stated that MCF is dependent on bedding content. Nicks et al. (2003, 2004) reported that pig houses with saw dust based litter emitted 33% less CH_4 than straw-based litter systems. The results of one way ANOVA meta-analysis (Table 13) showed that straw-based bedding resulted in numerically higher CH_4 but lower N_2O emissions (no statistical differences).

Table 13. Effect of bedding material on CH_4 emissions from swine buildings (kg yr^{-1} hd^{-1})

Bedding material	CH_4		N_2O	
	Main effect means	SEM[1]	Main effect means	SEM[1]
Straw	4.1	0.7	0.26	0.11
Saw dust	3.6	0.8	0.72	0.41
Corn stalk	2.4	2.1	-	-
P value	0.52		0.39	

[1]: Standard error of the mean.

Ni et al. (2008) claimed that the design of swine barns and the management of the stored manure have an apparent effect on CH_4 emissions. Long term manure storage in deep-pit pig barns may result in greater gas emissions from the building because of the larger quantity of manure in the barns. Sharpe and Harper (2001) claimed that the longer retention time would allow for greater waste decomposition inside the house before being pumped into the lagoon. Kai et al. (2006) suggested that complete removal of manure from the pig house, e.g., by flushing or manure conveyor belts, contributes to low CH_4 emissions from pig housing. Data points in the subgroup of swine buildings with pit systems were used to analyze the effect of manure removal frequency on GHG emissions. Although showing no statistically significant differences, an increasing trend was observed for CH_4 emissions as manure removal frequency decreased (Figure 9, $P = 0.13$). Two outlying data points were identified from Zhang et al. (2007), in which high emissions were observed when manure was removed every 3 wks in a farrowing operation. Deep pits and pits flushed using lagoon effluent also generated relatively high CH_4 emissions. Results for N_2O and CO_2 emissions showed very high uncertainties (Figure 10, $P = 0.49$; Figure 11, $P = 0.74$). Deep pits and pits with manure removed every 3 or 4 months had relatively higher N_2O emissions. For CO_2 emissions, manure removal frequency was not a significant factor; relatively higher CO_2 emissions were observed from pits flushed using lagoon effluent.

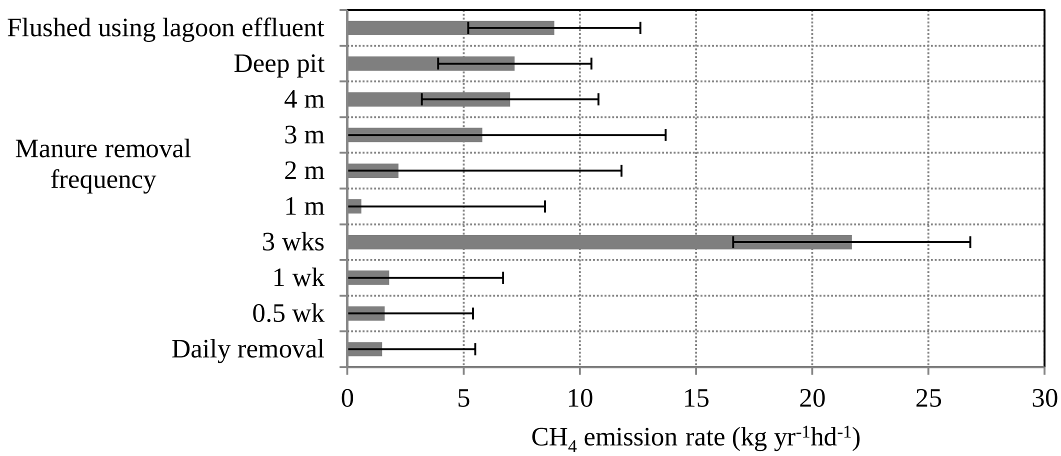

Figure 9. Effect of manure removal frequency on CH_4 emissions from swine buildings

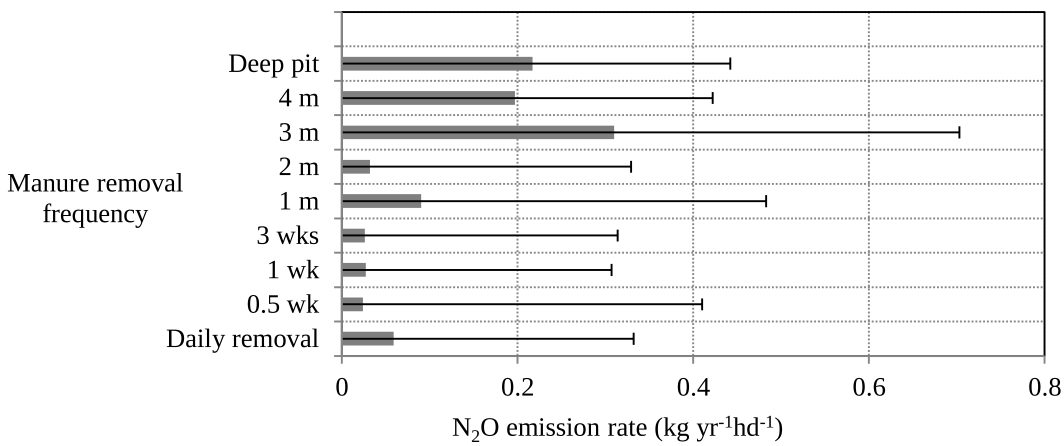

Figure 10. Effect of manure removal frequency on N_2O emissions from swine buildings

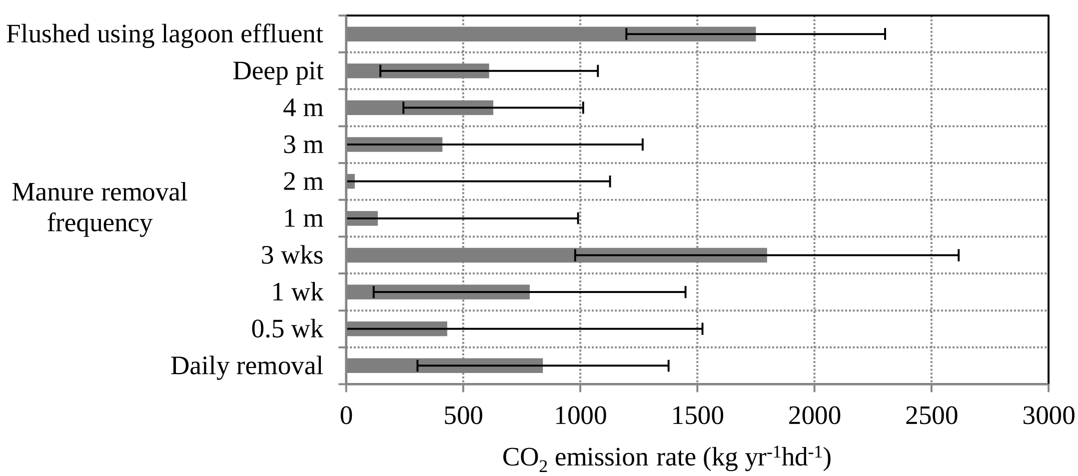

Figure 11. Effect of manure removal frequency on CO_2 emissions from swine buildings

The use of covers has been proposed to reduce CH_4 and CO_2 emissions from manure storage facilities. Lague et al. (2003) observed that the presence of a blown chopped straw cover on manure storage facilities did reduce GHG emissions. Amon et al. (2007) also demonstrated that a solid cover was effective in mitigating GHG and NH_3 emissions from pig slurry during storage. Safley and Westerman (1988) found that CH_4 emission rates may vary depending on the areas of lagoon covered. Hansen et al. (2006) reported that covers reduced CH_4 emission by 88%. However, it was observed that straw covers on manure storages can increase CH_4 emissions, and either straw or swelled-clay covers on manure storages can increase N_2O emissions (Lague et al., 2005). Zhang et al. (2007) reported that a negative air pressure cover did not result in any significant reduction in CH_4 emissions in comparison with the open earthen manure storage. Guarino et al. (2006) evaluated the effectiveness of five simple floating covers for reducing emissions from pig and cattle slurry. They found higher reduction efficiencies were achieved for NH_3, odor and CO_2 by all the tested covers at the greater thickness, but no statistically significant reductions in CH_4 emission from pig slurry were found (Guarino et al, 2006). Data points in the subgroup of slurry storage facilities were used to analyze the effect of covers on CH_4 emissions (Table 14). The CH_4 emissions from slurry storage facilities without covers were significantly higher than from that without covers. In 7 out of 9 data points that reported N_2O emissions from manure storage facilities, N_2O emissions were negligible. There was no enough data to evaluate the effect of cover on N_2O emissions from manure storage facilities through meta-analysis.

Table 14. Effect of covering on CH_4 emissions from slurry storage facilities (kg yr^{-1} hd^{-1})

Slurry storage facilities	Main effect means	SEM[1]	P-value
With cover	-2.8^{a}	9.5	0.05
Without cover	14.2^{b}	6.7	

[a,b]: Values within the same section differ significantly if without common letter (P < 0.05).
[1]: Standard error of the mean.

Zahn et al. (2001) indicated that manure management environment, and specifically loading rate, may significantly influence the flux rate of CH_4 from stored swine manure. Su et al. (2003) reported that solid/liquid separation immediately after washing pig houses (preventing manure from becoming slurry) can reduce biogas production by 62% and also prevent CH_4 production. However, Dinuccio et al. (2008) showed that the solid liquid separation of the pig slurry reduced NH_3 losses, but increased CH_4 emissions by 3% and CO_2 emissions by 10% compared with the storage of the rough slurry. Lague et al. (2003) reported that CH_4 production rate was higher with the fully slatted floor room than with the partially slatted floor room. The larger contact area between the manure and the air likely promotes higher CH_4 emissions (Lague et al., 2003). Steed and Hashimoto (1994) observed contrary results in that they found higher MCF values in closed systems than in systems that were open to the atmosphere, and attributed this to inhibition of methanogenesis by oxygen. The degree of anaerobic bacteria fermentation and therefore the amount of CH_4 emissions depend furthermore on pH value, slurry temperature, retention time, and the presence of inhibiting compounds (Zeeman, 1991; Huther et al., 1997).

Several studies have evaluated the GHG credits and debits of composting and it has been concluded that manure composting has the potential to reduce GHG (Boldrin et al. 2009; Brown et al., 2008; Zeman et al., 2002). Fukumoto et al. (2003) demonstrated that there is a possibility of changing CH_4 and N_2O emission rates during swine manure composting simply by changing the scale of the compost pile. An aerobic-anoxic manure treatment system and a biofilter manure treatment system have been used to reduce GHG emission successfully from liquid swine manure (Pelletier et al., 2004). The CH_4 production from slurry can be reduced by addition of inhibiting compounds and acids (Berg and Pazsiczki, 2003; Amon et al., 2004). Costa and Guarino (2008) and Guarino et al. (2008) demonstrated that photocatalytic treatment with TiO_2 coating and UA-A light can reduce CH_4 emissions from swine buildings.

(3) Effect of swine category

The emissions of GHG from swine may depend on the species and category due to differences in diets and digestive systems. Main effect means of GHG emissions from different swine categories (stage of production) are presented in Table 15. The highest CH_4 and CO_2 emissions were from farrowing swine, and they were significantly higher than that from finishing and nursery swine. The gestating swine had significantly lower CH_4 emissions but similar CO_2 emissions as compared with farrowing swine. The highest N_2O emissions were from gestating swine and they were significantly higher than that from finishing swine. Zhang et al. (2007) also reported that CO_2 emissions from farrowing rooms were significantly higher than that from gestation rooms.

Table 15. Main effect means of GHG emissions from different swine categories (kg yr^{-1} hd^{-1})

Swine category	CH_4		N_2O		CO_2	
	Main effect mean	SEM[1]	Main effect mean	SEM[1]	Main effect mean	SEM[1]
Farrowing	9.3[b]	2.0	0.26[a,b]	0.15	811[b]	148
Farrow to finish	5.0[a,b]	2.5	0.10[a,b]	0.81	-	-
Finishing	2.6[a]	2.1	-0.04[a]	0.18	28[a]	147
Gestating	3.0[a]	2.9	0.41[b]	0.19	609[b]	175
Nursery	3.5[a]	5.2	0.20[a,b]	-	137[a]	179
P value	0.05		<0.01		<0.01	

[a,b]: Values within the same section differ significantly if without common letter ($P < 0.05$).

[1]: Standard error of the mean.

(4) Effect of geographic region

Main effect means of GHG emissions from different geographic regions are presented in Table 16. North American studies reported significantly higher CH_4 emissions from swine operations than European and Asian studies. This is probably due to the different prevailing manure handling systems and different manure handling practices in different regions.

Table 16. Main effect means of GHG emissions from different geographic regions (kg yr^{-1} hd^{-1})

Geographic region	CH_4		N_2O		CO_2	
	Main effect mean	SEM[1]	Main effect mean	SEM[1]	Main effect mean	SEM[1]
North America	9.5[b]	2.3	0.21[a,b]	0.21	481	207
Europe	5.0[a]	2.1	0.36[b]	0.21	398	171
Asia	-0.4[a]	3.7	-0.01[a]	0.24	310	229
P value	0.04		0.02		0.85	

[a,b]: Values within the same section differ significantly if without common letter ($P < 0.05$).

[1]: Standard error of the mean.

(5) Effect of temperature

Many researchers have identified temperature as an important factor for CH_4 emissions from manure storage facilities. Low temperatures can suppress microbial activities and metabolism, and therefore production of CH_4. Cullimore et al. (1985) found that CH_4 production from pig manure linearly increased with increasing effluent temperature ($T < 26^{o}C$) in a laboratory study. Husted et al. (1994) reported that production rate of CH_4 is highly dependent on the temperature range and CH_4 emissions from solid pig manure peaked at 35 to 45°C. Sharpe and Harper (1999) observed that CH_4 fluxes from an anaerobic swine lagoon were linearly related to lagoon water temperature below 22^{o}C (R^2=0.87); and at higher temperatures, CH_4 fluxes were related to air and effluent temperature (R^2=0.47) as well as wind speed (R^2=0.52). Masse et al. (2003) observed that as storage temperature increased from 10 to 15 ^{o}C, CH_4 emissions increased, and the effect of temperature on CH_4 production was more important for swine manure than for dairy cow manure. Lague et al. (2003) reported that CH_4 emissions from manure storage facilities were lower between the hours of 10:00 and 18:00 than during the rest of the day, and CH_4 emissions were higher during the summer and lower during the spring seasons. Moller et al. (2004) found that the effect of temperature on CH_4 and CO_2 production from manure was dependent on storage duration.

During 90 d storage, there was a strong influence of temperature on the MCF for pig manure, where the MCF increased from 5.3 % at the low temperature to 31.3 % at the high temperature (Moller et al., 2004). Desutter and Ham (2005) observed that biogas production was dependent on lagoon temperature. Biogas steadily increased when temperatures in the bottom sludge layer reached between 10 and 15^oC (Desutter and Ham, 2005). Amon et al. (2007) reported higher CH_4 emissions from manure storage in a warm period than in a cold period.

Temperature can also influence GHG emissions from swine buildings. High temperature induced high ventilation rates. High ventilation rates diluted CH_4 concentrations but were correlated to high CH_4 emissions (Ni et al., 2008). Blanes-Vidal et al. (2008) reported that the correlation between averaged ventilation flow and CH_4 emission on an hourly basis was 0.79. Zhang et al. (2007) reported that CH_4 emissions from swine buildings were significantly ($P<0.05$) higher in June, July, and August than September. Dong et al. (2009) observed that CH_4 emissions from a swine barn were higher in summer than in spring, presumably resulting from the combined effects of warmer microenvironment and elevated building ventilation rate. Ni et al. (2008) claimed that temperature is an important factor for both CH_4 and CO_2 emissions from swine buildings. Haeussermann et al (2006) reported a clear influence of the indoor temperature on CH_4 emissions from swine buildings but only for mean daily temperatures above 25 ^oC. Monteny et al. (2001) claimed that slurry cooling as well as lowered indoor temperatures and a reduced air exchange rate were proactive methods to reduce CH_4 emissions.

In the overall meta-analysis, effect of temperature was not significant (Table 10). This is probably due to the complex situation in swine buildings. When only considering a subgroup of contributors to emissions from lagoons or slurry storage facilities, the effect of temperature become significant. Regression analysis was performed for CH_4 emissions from lagoons, manure storage facilities and swine buildings individually (Table 17). As expected, for both lagoons and manure storage facilities, CH_4 emissions increased with increasing temperature. For swine buildings, temperature was not a significant factor.

Table 17. Regressions of CH_4 emissions from lagoons and manure storage facilities vs. temperature

Emission source type	Intercept ($kg\ yr^{-1}\ hd^{-1}$)	Slope ($kg\ yr^{-1}\ hd^{-1}$ per ^oC)	P value
Lagoons	-7.4	1.22	0.02
Slurry storage facilities	-15.7	1.72	0.01
Swine buildings	4.0	0.06	0.65

Guarino et al. (2008) reported that N_2O emissions from swine buildings were negatively affected by room temperature. There is no enough data to perform regression analysis on N_2O emissions through meta-analysis.

(6) Effect of diet

Matching dietary nutrients with the requirements of the pig reduces the excretion of excess nutrients, such as nitrogen and carbon. Lower nutrient availability, in turn, has the potential to reduce GHG emissions from manure. Therefore, diet modification has been proposed as an appropriate strategy for the abatement of GHGs produced during the biodegradation of excreted nutrients in pig manure (Lague, 2003). Ball et al. (2003) showed that low protein diets can reduce GHG emissions from growing pigs by 25 to 30% and from sows by 10-15%. Atakora et al. (2003) reported a reduction of CH_4 emissions by 27.3% and CO_2 by 3.8% emissions when pigs were fed 16% CP (supplemented with AA) diets compared to 19.0% CP diets. Atakora et al. (2004) reported that the CO2-e emitted by finisher pigs and sows fed wheat-barley-canola diets were reduced by 14.3% to 16.5% when feeding the reduced CP, amino acid supplemented diets, and were similar for finishing pigs and sows. Only a 7.5% reduction was observed when feeding the corn-soybean reduced CP diet. The total reduction in GHG emissions was 10% for every 10% relative dietary protein reductions. In another study (Atakora et al., 2005), twelve gilts (80 kg) were fed ad libitum on either a control diet (16.8% CP) based on wheat, barley, canola and soybean meal, or a low CP diet (11.2% CP) containing only barley (94% of the diet), supplemented with synthetic lysine, methionine, threonine, tryptophan, isoleucine and valine, in a cross-over design. The GHG production by pigs, in CO_2-e, tended to be lower for the low CP (3020 g/d) than for the control (3334 g/d); P = 0.057). Velthof et al. (2005) and Misslbrook et al. (1998) also observed that CH_4 emissions during storage were smaller at a low than at a high dietary CP content. The emission of CH_4 was significantly related to content of dry matter, total C, and volatile fatty acids (VFA) in the manure. Misslbrook et al. (1998) claimed that the 50% of the reduction in CH_4 emission from the slurry observed when pigs were fed the lower CP diet was probably the result of the reduced VFA content of the slurry, and CH_4 emission was more closely related to VFA content than to total C content. Velthof et al. (2005) claimed that decreasing the CP content has the largest potential to simultaneously decrease NH_3 and CH_4 emissions during manure storage and N_2O emission from soil. However, Clark et al. (2005) observed that mean CO_2 and CH_4 emissions increased with lower dietary CP ($P< 0.05$), thereby not supporting the use of dietary CP reduction to reduce GHG emissions from stored swine manure.

Data points (n=32) in the subgroup of studies that included diet CP information were used to analyze the effect of diet CP on GHG emissions (Table 18). Three factors (diet CP, geographic region, and swine category) were considered in the regression analysis. Diet CP was not a significant factor. The regression slope was positive for CO_2 and CH_4 emissions, indicating that CO_2 and CH_4 emissions may increase with increasing diet CP. It had been expected that lower CP diet may result in lower N excretion, and thus has possibility to reduce N_2O emissions from manure. However, this was not supported by the results of the meta-analysis.

Table 18. Regressions of GHG emissions vs. diet CP

	Slope (kg yr^{-1} hd^{-1} per 1% diet CP)	**P value**
CH_4	0.37	0.16
N_2O	-0.02	0.79
CO_2	215	0.43

Powers et al. (2008) observed that inclusion of distillers dried grains with solubles (DDGS) in a corn diet resulted in lower CH_4 emissions from swine housing. Corn diets were intermediate in CH_4 production and diets based on corn germ meal or dehulled, degermed corn diets resulted in the greatest CH_4 production ($P<0.05$). However, Li et al. (2010) reported that feeding 20% DDGS to grow/finish pigs resulted in increased CH_4 emissions. Pepple et al. (2010) reported that DDGS has no effect on GHG from manure storage.

There seems to be a close relationship between fermentable carbohydrates in the diet and CH_4 production (Aarnink and Verstegen, 2007). Increasing fermentable carbohydrate level in the diet to lower the pH of faeces and manure and consequently NH_3 emission, will, at the same time, increase CH_4 production (Aarnink and Verstegen, 2007). The pH also influences CH_4 production. Kim et al. (2004) found a reduction of CH_4 emissions by 14% when ideal pH was reduced one unit through addition of acidogenic Ca and P sources to pig diets.

Ball et al. (2003) found that CH_4 production was greater for the barley-based diets than for the corn-based diets. It was found that by reducing the protein content of the barley-based diet, the CH_4 production decreased by 57% (Ball et al., 2003). Reducing the protein content of the corn-based diets did not affect CH_4 production, probably due to the lower content of non-starch polysaccharides in these diets compared to barley based diets. Jensen and Jørgensen (1994) found that high fiber in diets increased the CH_4 emissions. Jørgensen (2007) claimed that the production of CH_4 depended on fiber origin; however high variation was observed between animals. Growing pigs fed diets varying in total fiber content (2.8–40%) had a CH_4 production equivalent to 0.1 to 1.3% of digested energy. Christensen and Thorbek (1987) reported that flatus production may not only be reduced by changing the composition of the dietary carbohydrates, but also by inclusion of a polyunsaturated oil in the diet of simple-stomached animals and humans.

(7) Effect of wind speed

Sharpe and Harper (1999) reported that CH_4 emissions from lagoons are related to wind speed. Sharpe et al. (2002) related CH_4 emissions to wind speed, effluent temperature and concentration of VS and observed an R^2 value of 0.65. Husted (1993) reported that a strong dependence between CH_4 emission rates and air flow through the chamber was found for pig solid manure, but not for pig slurry.

(8) Uncertainties from measurement method

Ni et al. (2008) claimed that characteristics of the measurement instruments and their maintenance may also cause differences in measured data. Osada et al. (1998) employed an infrared photoacoustic detection instrument to measure gas emissions in pig units but admitted that this instrument tended to overestimate. Future comparison of different methodologies and technologies will help to increase the accuracy and comparability of measurement data in this field. Zahn et al. (2001) reported that Harper and Sharpe (1997) explained the discrepancies between emission values by differences in measurement methods or due to atypical flux event periods.

Table 7 depicted that, when emissions were measured using the FTIR method or the SF_6 method, the differences between estimated and measured values were much larger than that when emissions were measured using the traditional method or the MMB method. Larger uncertainties and a possible overestimation of emission rates may be associated with the FTIR method and the SF_6 method.

(9) Correlation between CO_2 emissions and CH_4 emissions

The CO_2 emissions were positively correlated with CH_4 emissions, particularly for emissions from lagoon and slurry storage facilities (for swine building, R^2= 0.27; for lagoon and slurry storage facilities, R^2= 0.98). Correlation between CO_2 emissions and CH_4 emissions from lagoon or slurry storage facilities were plotted in Figure 12 (n=15). One data point from Zhang et al. (2007) was not included in the correlation analysis, where an extraordinarily high CO_2 emission rate was reported (475 kg yr^{-1} hd^{-1}) with relatively low CH_4 emission rates (46 kg yr^{-1} hd^{-1}) from a farrowing operation storage facility.

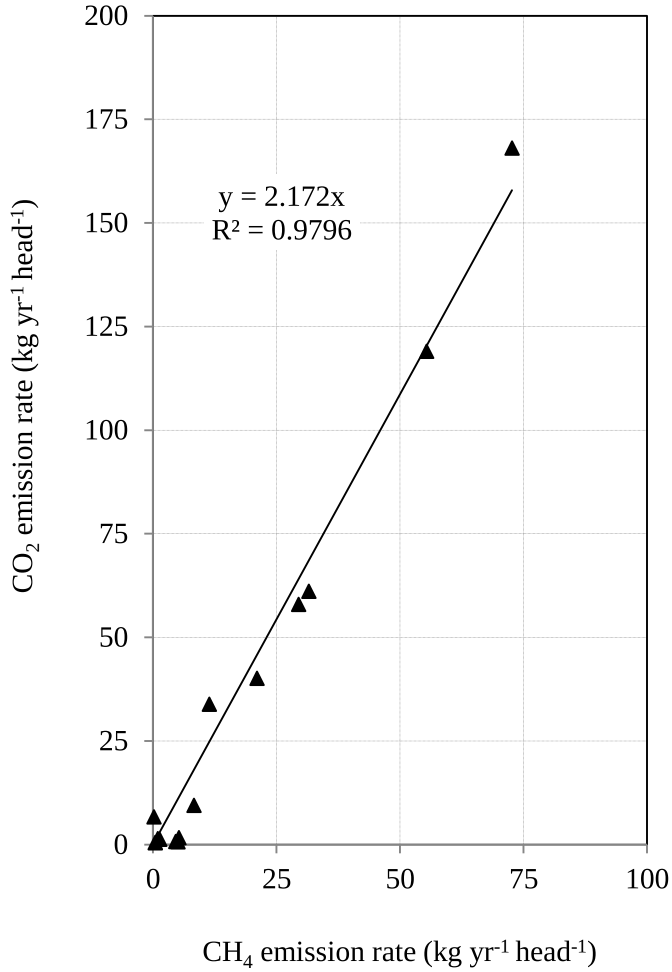

Figure 12. Correlation between CO_2 emissions and CH_4 emissions from lagoons or slurry storage facilities

Causes of variation in GHG emissions from swine manure land applications

Swine manures provide soluble C and N for microbial respiration and denitrification (Granli and Bockman, 1994), therefore manure that been applied on soil is a net source of N_2O and CH_4 emissions. While most natural agricultural soils were consuming CH_4 (Chan and Parkin, 2001, Topp and Pattey, 1997), manure application modified CH_4 balance of agricultural soils not only by causing post-application emissions but also by decreasing the net uptake rates (Rochette et al., 2000). Hiitsch et al. (1993) showed that NH_4^+-N additions result in a decrease in the capacity of a soil to act as a sink for CH_4, which would result in greater emissions. According to literature review, factors that can affect the GHG emissions from manure land applications include: temperature, precipitation, soil properties, manure application methods, manure application time, and composition/treatment of manure, etc. Effects of average temperature and annual precipitation on GHG emissions from land applications were investigated through meta-analysis. Results showed that average temperature and annual precipitation were both significant factors that influence cumulative CH_4 emissions, while no effects on N_2O and CO_2 emissions were observed (Table 19).

Table 19. P values of main effects on GHG emissions from land applications

Cause of variation	CH_4 (n=6)	N_2O (n=39)	CO_2 (n=5)
Average temperature	0.01	0.93	0.89
Annual precipitation	0.01	0.97	-

(1) Temperature:

Hermandez-Ramirez et al. (2009) reported that both N_2O and CO_2 fluxes from land correlated with soil temperature. Chirinda et al. (2010) also reported positive relationship between N_2O fluxes and soil temperature. In the other hand, Akiyama and Tsuruta (2003) observed no clear seasonal temperature effect on N_2O fluxes. Jarecki and Lal (2006) found CO_2 fluxes from soil were strongly correlated to temperature, but CH_4 fluxes were not correlated with temperature or fluxes of other GHG. Results of meta-analysis showed that average temperature had effects on cumulative emissions of CH_4 but not N_2O and CO_2. This is not in agreement with studies of Hermandez-Ramirez et al. (2009) and Jarecki and Lal (2006), which indicate that the effect of temperature on GHG fluxes in short term may not be expanded to long term cumulative emissions. According to results of meta-analysis, the measured cumulative CH_4 emissions increased with increasing average temperature (Figures 13).

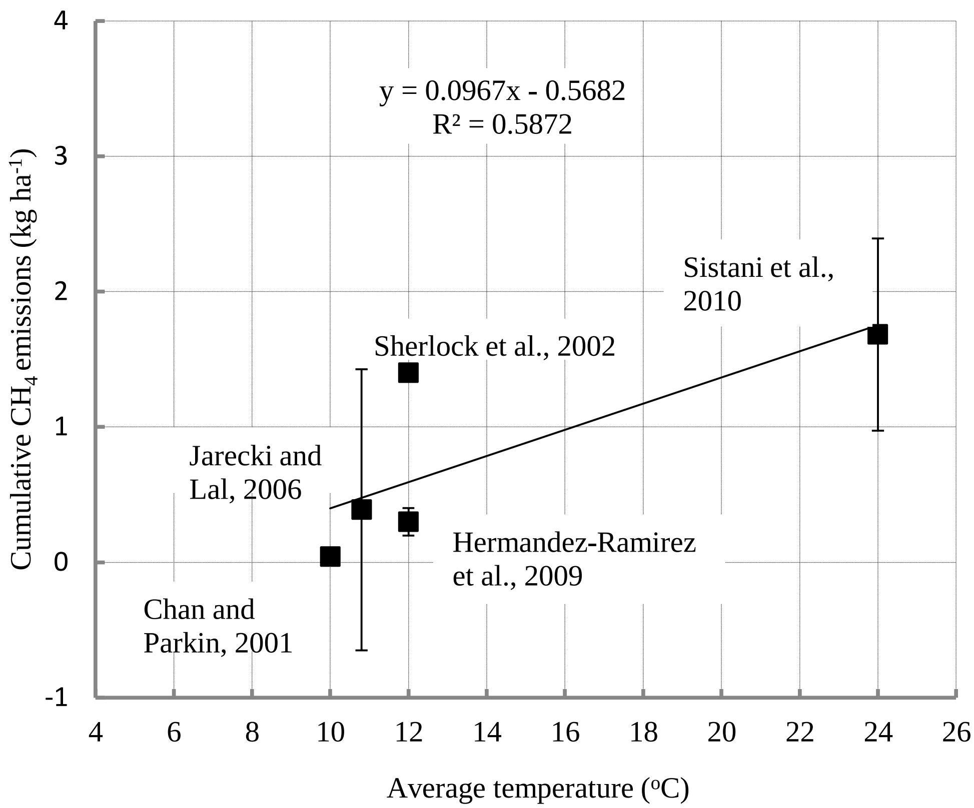

Figure 13. Correlation between land application CH_4 emissions and average temperature

(2) Precipitation

Akiyama and Tsuruta (2003) claimed that rainfall events can affect N_2O emissions by increasing water-filled pore space. Jarecki and Lal (2006) reported that daily N_2O but not CH_4 fluxes were correlated with precipitation, while Mkhabela et al. (2009) observed daily N_2O fluxes were not affected ($P > 0.05$) by soil water status and simulated rainfall. Results of meta-analysis showed that annual precipitation had effects on CH_4 but not N_2O and CO_2. This is not in agreement with studies of Jarecki and Lal (2006), which indicate that the effect of precipitation on GHG fluxes in short term may not be expanded to long term cumulative emissions. According to results of meta-analysis, the measured cumulative CH_4 emissions had a deceasing trend with increasing annual precipitation (Figures 14).

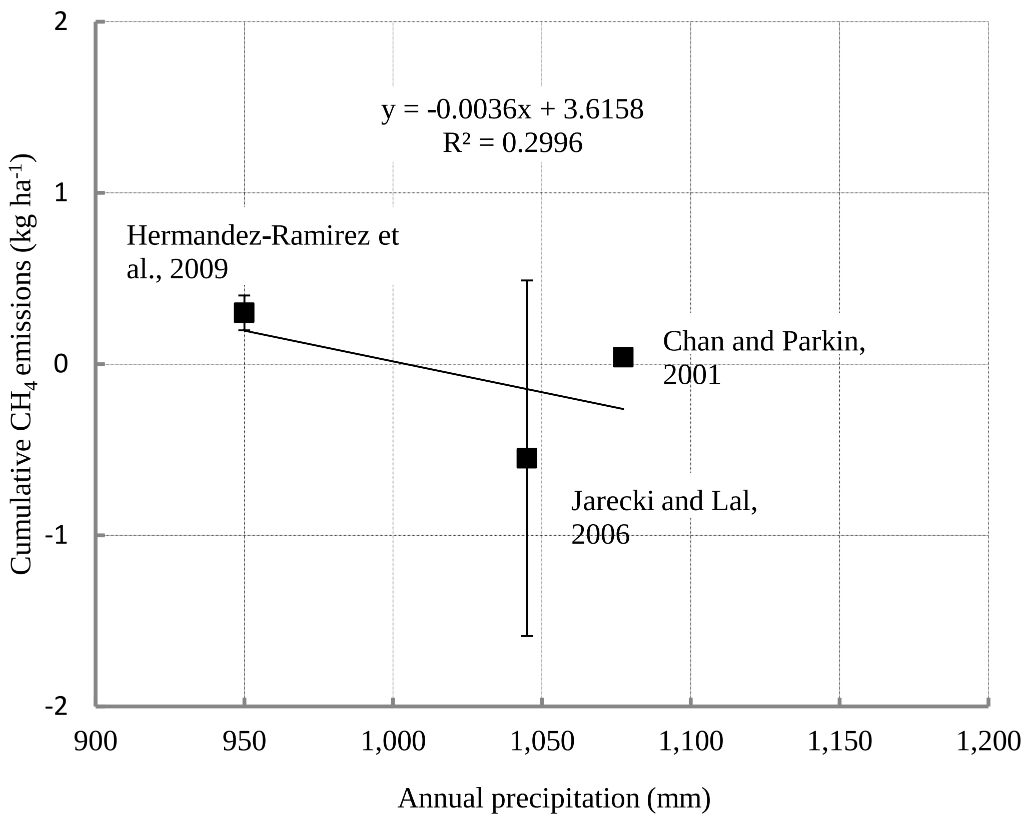

Figure 14. Correlation between land application CH_4 emissions and annual precipitation

(3) Soil properties

Jarecki et al. (2008) found that manure additions to the sandy loam soil significantly increased CH_4 emissions, and a significant soil effect on cumulative N_2O emissions was also observed. It is thought that the major differences between the different soils controlling both N_2O and CH_4 emissions were cation exchange capacity and percent water-filled pore space (Jarecki et al., 2008).

Tenuta et al. (2010) claimed that Soil moisture and NO_3^- concentration were the main determinants of both the type and quantity of GHG emitted. Mkhabela et al. (2006) reported that soil type had a significant effect on N_2O, and when soils are generally wet, a significant amount of N_2O may be emitted. Hermandez-Ramirez et al. (2009b) found that manured soils at high water contents registered shorter duration peaks but with higher overall N_2O production rates than those observed at moderate water content. Fischer and Whalen (2005) concluded that moisture levels near or above field capacity were necessary to support strong N_2O and total gaseous N production in these soils. However, Sharpe and Harper (1997) reported that N_2O did not appear to be directly related to soil water content. Chantigny et al. (2010) observed large N_2O emission coefficients measured in many treatments, and the contradicting responses among N sources depending on soil type, indicate that that site specific factors, such as soil properties (e.g., texture, organic matter content) and drainage conditions have a differential influence on emissions depending on N source.

The net CH_4 uptake by soils in natural ecosystems has been shown to decrease with increasing water content (Lessard et al. 1994; Dunfield et al. 1995, Rochette et al. 2000). Tenuta et al. (2010) observed that grassland soils with seasonally high water tables can be significant sources of CH_4 and emissions of CH_4 increased with hog slurry application in the soil.

Chadwick D.R. and B.F. Pain (1997) found that CH_4 emissions were influenced by soil type only when the slurries applied had low dry matter contents and most of the CH_4 emitted was derived from the slurry itself and not from the soil.

Jarecki and Lal (2006) observed that daily CO_2 fluxes negatively correlated with soil-moisture content. Arcara et al. (1999) also found that emissions of soil CO_2 were influenced by the water content of soil and CO_2 emissions were almost insignificant due to the high water content of the soil.

(4) Manure application time

Hermandez-Ramirez et al. (2009) reported that manure application timing clearly showed a strong impact on N_2O emissions because spring application resulted in 1.8- and 3.4-fold greater emissions when compared with fall application. Rochette et al. (2004) observed 1.9 times greater N_2O emissions with spring versus fall land application of pig slurry and they attributed lower N_2O emissions with fall application to limited nitrification reflecting cold and wet soils. Tenuta et al. (2010) showed that split application of hog slurry to grassland has the potential to reduce emission of GHGs, in particular N_2O, compared to applying all manure in spring. Smith and Owens (2010) suggested that, in order to minimize GHG emissions from manure applications, producers should consider applying manure during drier periods of the year, when rainfall is not expected to occur for 1 week following the application. This information complements recommendations that suggest applying manures during drier periods to avoid nutrient losses to surface waters through runoff. Rochette et al. (2004) claimed that the impacts of the timing of animal manure application on N_2O emissions cannot be generalized, but will likely vary between years in response to interactions between crop, climatic, and soil factors.

(5) Manure application method

Sistani et al. (2010) showed that manure application method for no-till corn grain production can have a significant influence on GHG emissions after application. They observed that the injection of effluent reduced the N_2O emission by 34% compared to surface and aeration applications, and aeration or injection application increased CH_4 emissions compared to surface application (Sistani et al., 2010). Velthof et al. (2003) reported that N_2O emissions from pig manure placed in a row at 5 cm depth was significantly higher than from surface-application and other techniques in which manure was incorporated in the soil. Lovanh et al. (2010) compared GHG emissions using Aerway injection (aeration) method, surface spray method, and row injection method, and observed that the Aerway injection method resulted the highest initial N_2O and CH_4 concentrations inside the monitored chambers, while the surface spray method produced the highest gas fluxes followed by Aerway injection method and row injection method. These results indicated that modification of application techniques may be tools to mitigate GHG emission from manure land application.

(6) Composition/treatment of manure

Cardenas et al. (2007) underlines the key role of livestock diet in slurry composition and consequently in N_2O and CH_4 emissions from soils. They observed that reducing the $NH_4^+$and soluble organic C added with the slurry allows mitigating the N_2O emission. It has been pointed that since estimated indirect N_2O emissions (i.e., emissions result from volatile N losses that occur primarily in the forms of NH_3) were generally higher than direct N_2O emissions, more emphasis should be directed towards reducing NH_3 emissions following manure land applications (Mkhabela et al., 2009).

Bertora et al. (2008) claimed that the solid/liquid separation tends to globally restrain the emission of N_2O. They observed that the IPCC default emission factor for N_2O emissions underestimated for both the non-treated pig slurry and its liquid fraction (digested or not), but overestimated for the separated solid fraction and urea. Ferm et al. (1999) suggested that a combined treatment, acidification followed by solid/ liquid separation, appears as an efficient solution to mitigate N_2O and CO_2 emissions after soil application. Since acidification has a low impact on the solid fraction, it may be profitable for farmers to acidify only the liquid fraction obtained after solid–liquid separation and conserve the solid fraction to be used in raw or after composting (Ferm et al., 1999). Anaerobic digestion of pig slurry can also reduce N_2O emissions with respect to untreated pig slurry (Meijide et al., 2007). Vallejo et al. (2006) stated that anaerobic digestion and separation improved the quality of pig slurry as fertilizer and is an option to mitigate denitrification losses and N_2O emissions. Composting liquid pig manure before land application with either straw or yard waste was also found to be effective in reducing CO_2 and N_2O emissions as it stabilized the manure C (Yang et al. 2002; Yang et al., 2003).

Addition of barley straw can markedly reduced N_2O production from soil (Chantigny et al. 2001). Parkin et al. (2006) reported that there was a significant reduction in N_2O emissions in the presence of the rye cover crop. However, in the field measurements, introduction of rye/oat cover crop to soybean–corn cropping system did not reduce N_2O emission from swine manure application (Jarecki et al., 2009), despite of the observed significant reduction in N_2O emissions in the presence of the rye cover crop in laboratory experiments.

Discussion

Large volumes of work on GHG emissions from swine operations have been published. Hundreds of studies were reviewed and 96 studies were included in the meta-analysis. Based on results of the literature review and meta-analysis, variation of the measured CH_4 and N_2O emission rates has not been adequately captured by the IPCC approaches. For CH_4 emissions, the differences between the IPCC estimated emission rates and measured values were significantly influenced by type of emission source, geographic region and measurement methods.

Larger differences between estimated and measured CH_4 emission rates were observed in North American studies than in European studies. In North American studies, swine buildings usually handle manure using pit storage systems. The pooled relative differences between the measured CH_4 emissions with the IPCC estimated values for swine buildings (pit system) and for slurry storage facilities were -10.3% (95% CI, -34.3% to 13.6%) and -10.3% (95% CI, -26.2% to 5.6%) respectively, suggesting that the IPCC estimated CH_4 emissions from swine buildings and from slurry storage facilities were not significantly different from the measured values. For lagoons, the R^2 between the measured and the IPCC estimated CH_4 emission rates was 0.75; while in 80% of data points, the IPCC estimated emissions were higher than the measured values. The pooled relative difference between the measured CH_4 emissions with the IPCC estimated values for lagoons was -33.9% (95% CI, -66.8% to -0.01%), suggesting an overestimation by the IPCC approaches for CH_4 emissions from lagoons. It was observed that the discrepancy between the IPCC estimated emissions and the measured values mainly occurred at lower temperatures. In European studies, pit systems, bedding systems or straw flow systems are used in swine buildings to handle manure. The pooled relative difference for swine buildings with pit systems was -21.1% (95% CI, -38.8% to -3.4%), suggesting an overestimation of the IPCC approaches in these systems. The pooled relative difference for swine buildings with bedding systems, for swine building with straw flow systems and for slurry storage facilities were 10.5% (95% CI, -20.7% to 41.7%), -19.2% (95% CI, -424% to 386%), and -19.4% (95% CI, -212% to 173%) respectively, suggesting that the IPCC approaches showed no significant bias from measured CH_4 emissions from these systems.

For N_2O emissions from swine operations, an overall underestimation of the IPCC approaches was observed in European studies but not in North American studies. In North American studies, the IPCC default N_2O emission factors for swine building with pit systems (0.2%) and for lagoons and slurry storage facilities (0%) were all within the range of the 95%CI of measured values in North American studies (For swine building with pit systems: -0.08% to 0.20%; for lagoons: -2.82% to 3.53%; for slurry storage facilities: -0.02% to 0.04%). In European studies, there was an overall underestimation of the IPCC approaches. The measured N_2O emissions were significantly higher than IPCC estimated values in pit systems, and lager uncertainties were observed for measured N_2O emissions from bedding systems and from straw flow systems. The pooled N_2O emission factors for swine buildings with pit systems was 1.6% (95% CI, 0.6% to 2.7%), while the IPCC default emission factor for pit systems is 0.2%. The pooled N_2O emission factors for swine buildings with bedding systems and that with straw flow systems were 4.8% (95% CI, -0.2% to 9.8%) and 0.5% (95% CI, -7.0% to 8.1%) respectively, while the IPCC default emission factors for solid storage systems is 0.5%.

The measured GHG emissions from swine operations were significantly different for different emission sources (swine buildings or manure storage facilities), different swine categories (stage of production), and different geographic regions. Swine buildings generated much higher CO_2 emissions than manure storage facilities while CH_4 and N_2O emissions were not significantly different. For swine buildings, CO_2 is the larger contributor to total GHG emissions; for manure storage facilities, CH_4 is the larger contributor to total GHG emissions. Within the subgroup of swine buildings, the results of meta-analysis showed that straw flow systems generated the lowest CH_4 and N_2O emissions of systems compared, while pit systems generated the highest CH_4 emissions and bedding system generated the highest N_2O emissions (no statistical differences). Within the subgroup of manure storage facilities, the results showed that lagoons generated significantly higher N_2O emissions than slurry storage basin/tanks, while CH_4 and CO_2 emissions are not different. Within the subgroup of bedding systems, the results showed that swine buildings with straw-based bedding resulted in numerically higher CH_4 but lower N_2O emissions as comparing to saw dust based bedding (no statistical differences). Large variations were observed for GHG emissions from swine buildings with pit systems. But an increasing trend can still be observed for CH_4 emissions as manure removal frequency decreased. Relatively high GHG emissions were observed from deep pits or from pits flushed using lagoon effluent. The use of covers has been proposed to reduce GHG emissions from manure storage facilities, but the effectiveness was not consistent in literature. Results of mate-analysis showed that CH_4 emissions from slurry storage facilities without covers were significantly higher than from that with covers. There was no enough data to evaluate the effect of cover on N_2O emissions from manure storage facilities through meta-analysis.

The emissions of GHG from swine may depend on the species and category due to differences in diets and digestive systems. Results of meta-analysis showed that farrowing swine emitted more CH_4 and CO_2 emissions as compared with other swine categories, while gestating swine had greater N_2O emissions. The differences in GHG emissions among different swine categories (stage of production) have not been adequately reflected by the IPCC approaches.

Results of meta-analysis showed that North American studies reported significantly higher CH_4 emissions from swine operations than European and Asian studies. This is probably due to the different prevailing manure handling systems and different manure handling practices in different geographic regions.

Many researchers have identified temperature as an important factor for CH_4 emissions from manure storage facilities. Results of meta-analysis showed that the effects of temperature on CH_4 emissions were significant for lagoons or slurry storage facilities. The regression slope of CH_4 emission over temperature for lagoons or slurry storage facilities were 1.22 and 1.72 kg yr^{-1} hd^{-1} per ^{o}C respectively. But for swine buildings, temperature was not a significant factor. Diet CP was found not a significant factor on GHG emissions from swine operations. It had been expected that lower CP diet may result in lower N excretion, and thus has possibility to reduce N_2O emissions from manure. However, this was not supported by the results of the meta-analysis. Differences in measurement methods may also cause differences in measured data. When emissions were measured using the FTIR method or the SF_6 method, the differences between estimated and measured values were much larger than that when emissions were measured using the traditional method or the MMB method. This indicates larger uncertainties and possible overestimation of emission rates associated with the FTIR method and the SF_6 method. The CO_2 emissions from swine operations were positively correlated with CH_4 emissions, especially for emissions from lagoons and slurry storage facilities (R^2= 0.98). For lagoons or slurry storage facilities, CO_2 emissions were approximately 2 times greater than CH_4 emissions.

For N_2O emissions from swine manure applications, the IPCC default emission factor (1%) is within the 95%CI in both North American studies (0.7% to 2.2%) and European studies (-0.3% to 3.5%). According to literature review, factors that can affect the GHG emissions from manure land applications include: temperature, precipitation, soil properties, manure application methods, manure application time, and composition/treatment of manure, etc. Effects of average temperature and annual precipitation on GHG emissions from land applications were investigated through meta-analysis. Results showed that average temperature and annual precipitation were both significant factors that influence cumulative CH_4 emissions, the measured cumulative CH_4 emissions increased with increasing average temperature but had a deceasing trend with increasing annual precipitation. No effects on N_2O and CO_2 emissions were observed.

Results of this study provided a better understanding on causes of variation in GHG emissions from swine operations. It can help to quantify the emissions more accurately. The knowledge on causes of variation may also be useful for developing cost-effective mitigation strategies.

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Appendix 1. CH_4 and N_2O emissions from swine production buildings in North American studies

Ref*	Emission rates in original units			Emission rates in kg yr^{-1} hd^{-1}		IPCC estimated emission rates in kg yr^{-1} hd^{-1}		Conditions
	Original units	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	
1	g d^{-1}	15.0±1.1	-	0.46	-	1.8	-	Finishing, barley-based diets
		21.6±1.4	-	0.66	-	1.8	-	Non pregnant sow, barley-based diets
		8.8±1.4	-	0.27	-	1.8	-	Non pregnant sow, corn-based diets
2	kg yr^{-1} hd^{-1}	1.5	-	1.5	-	2.4	-	Finishing, slatted floor with under-floor pits, drained every 5-7 d
3	g d^{-1} AU^{-1}	14	-	0.5	-	2.4	-	Grower pig, slatted floor and recharge pit
4	g d^{-1} kg^{-1} pig	0.63	Neg.	41.4	0	11.5	0.049	Farrowing, liquid manure management
		0.27	Neg.	14.8	0	11.5	0.041	Gestating, liquid manure management
		1.96	Neg.	12.9	0	11.5	0.004	Nursery, liquid manure management
		0.14	0.002	2.4	0.034	6.9	0.022	Grower-finisher, liquid manure management
		0.1	Neg.	6.6	0	11.5	0.049	Farrowing, liquid manure management
		0.07	Neg.	3.8	0	11.5	0.041	Gestating, liquid manure management
		0.39	Neg.	2.6	0	11.5	0.004	Nursery, liquid manure management
		0.24	Neg.	4	0	6.9	0.022	Grower-finisher, liquid manure management, partially slatted floor
		0.43	0.001	7.2	0.017	6.9	0.022	Grower-finisher, liquid manure management, fully slatted floor
5	g d^{-1} hd^{-1}	3.2±0.3	0.8±0.2	1.2	0.024	1.8	0.022	Grow-finish, manure cleaned twice weekly, corn control diet
		5.3±0.3	0.8±0.2	1.9	0.024	1.8	0.022	Grow-finish, manure cleaned twice weekly, diet containing 20% DDGS and inorganic trace minerals
		6.2±0.3	0.8±0.2	2.3	0.024	1.8	0.022	Grow-finish, manure cleaned twice weekly, 2 diet containing 20% DDGS with organic trace minerals
6	g d^{-1} AU^{-1}	36.2±2.0	-	4	-	2.4	-	Finishing barn with shallow manure flushing system
		28.8±1.8	-	3.2	-	2.4	-	Finishing barn with shallow manure flushing system
7	g d^{-1} hd^{-1}	25±1.7	Neg.	9.1	0	6.9	0.022	Wean to finish, deep pit, non-DDGS
		23.4±1.6	Neg.	8.5	0	6.9	0.022	Wean to finish, deep pit, DDGS
8	g d^{-1} hd^{-1}	6.2	-	2.3	-	1.8	-	Grow-finish, manure cleaned twice weekly
9	g d^{-1} hd^{-1}	6.9±3.4	-	10.6	-	11	-	Farrow to finish, pits beneath slatted floor flushed every 8 h, winter
		29.2±6.7	-	13.6	-	11	-	Farrow to finish, flushing pits beneath slatted floor flushed every 8 h, summer
		37.2±1.4	-	2.5	-	2.4	-	Farrow to finish, flushing pits beneath slatted floor flushed every 8 h, summer
		46.2±2.8	-	16.9	-	11	-	Farrow to wean, pull-plug system beneath slatted floor flushed every 7-8 d, summer
10	kg d^{-1} $site^{-1}$	52.8	-	1.4	-	2.4	-	Feeder to finish, confinement buildings with under-slat storage
11	g d^{-1} AU^{-1}	184±170	Neg.	24.2	0	3.3	0.049	Farrowing, liquid manure stored in under-floor shallow gutters and removed every 3 wks
		351±204	Neg.	46.1	0	3.3	0.049	Farrowing, liquid manure stored in under-floor shallow gutters and removed every 3 wks
		118±119	Neg.	12.9	0	3.3	0.041	Gestating, liquid manure stored in under-floor shallow gutters and removed every wk
		73±51	Neg.	8	0	3.3	0.041	Gestating, liquid manure stored in under-floor shallow gutters and removed every wk
12	g d^{-1} hd^{-1}	1.75±0.01	-	0.6	-	1.8	-	Grow-finish, manure cleaned twice weekly

*References: 1. Ball and Mohn, 2003; 2. Desutter and Ham, 2005; 3. Kai et al.,2006; 4. Lague et al., 2003; 5. Li et al., 2010; 6. Ni et al., 2008; 7. Pepple et al., 2010; 8. Powers et al., 2008; 9. Sharpe and Harper, 2001; 10. Zahn et al., 2001; 11. Zhang, et al., 2007; 12. Unpublished study at MSU, 2009.

Appendix 2. CH_4 and N_2O emissions from swine manure storage facilities in North American studies

Ref*	Emission rates in original units			Emission rates in kg yr^{-1} hd^{-1}		IPCC estimated emission rates in kg yr^{-1} hd^{-1}		Conditions
	Original units	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	
1	g d^{-1} m^{-3}	42	Neg.	0.2	0	0.3	0	Liquid swine manure storage vessel
2	kg yr^{-1} hd^{-1}	8.3	-	8.3	-	23.5	-	Finishing, anaerobic lagoon
3	kg d^{-1} ha^{-1}	200	-	21.1	-	25.4	-	Corn-soybean diet, simulated anaerobic lagoon, August
		280	-	29.5	-	25.4	-	Corn-soybean diet, simulated anaerobic lagoon, July
		300	-	31.6	-	25.4	-	Corn-soybean diet, simulated anaerobic lagoon, June
4	kg d^{-1} ha^{-1}	125.8	Neg.	23.99	0	24.8	0	Anaerobic lagoon
5	kg N d^{-1} ha^{-1}	-	0.3	-	0.022	-	0	Anaerobic swine lagoon
		-	0.4	-	0.081	-	0	Anaerobic swine lagoon
6	kg yr^{-1} m^{-2}	56.5±11.3	-	78.3	-	13.4	-	Sow, hog and piglet, cereal grain and corn diet, above-surface open manure-slurry tank
7	g CO_2e d^{-1} kg^{-1} pig	5.8	Neg.	4.6	0	5.4	0	Swine uncovered concrete tank
		6.62	0.02	5.3	0.001	5.4	0	Swine uncovered earthen manure basin
		1.25	Neg.	1	0	5.4	0	Swine covered earthen manure basin
8	L kg^{-1} VS	34.1±6.9	-	2.2	-	5.4	-	Swine manure storage barrels, storage 180 d, 10ºC
		62.6±15.9	-	4.1	-	8.6	-	Swine manure storage barrels, storage 180 d, 15ºC
		45.8±8.6	-	3	-	5.4	-	Swine manure storage barrels, storage 272 d, 10ºC
		89.5±25.6	-	5.9	-	8.6	-	Swine manure storage barrels, storage272 d, 15ºC
9	kg yr^{-1} hd^{-1}	6.7	3.6	6.7	0.004	7.2	0	Liquid swine manure storage tank in cold climate
10	mg s^{-1} m^{-2}	1.75	-	14.1	.	16.6	-	Liquid swine manure storage tank
11	g CO_2e d^{-1} kg^{-1} pig	6.4	-	5.1	.	5.4	-	Liquid swine manure storage tank
12	kg yr^{-1} hd^{-1}	5.6	-	5.6	-	22.2	-	Anaerobic swine lagoon
13	kg yr^{-1} hd^{-1}	6.0	-	6	-	23.5	-	Anaerobic swine lagoon
		1.6	-	1.6	-	23.5	-	Anaerobic swine lagoon
14	kg d^{-1} ha^{-1}	223.9	-	25	-	25.4	-	Anaerobic swine lagoon
		447.31	-	49.9	-	24.8	-	Anaerobic swine lagoon
		209.23	-	23.4	-	21	-	Anaerobic swine lagoon
		118.08	-	13.2	-	25.1	-	Anaerobic swine lagoon
		580.75	-	64.8	-	25.4	-	Anaerobic swine lagoon
15	kg d^{-1} $site^{-1}$	466.1	-	12	-	23.5	-	Feeder to finish, lagoon systems without anoxic photosynthetic blooms
		831.0	-	16.4	-	23.5	-	Farrow to feeder, lagoon systems with anoxic photosynthetic blooms
		122.7	-	5.5	-	8.5	-	Farroww to finish, earthen, concrete, or steel-lined manure storage basins
16	g d^{-1} m^{-2}	44±27	Neg.	45.9	0	14.6	0	Farrowing operation, earthen manure storage
		30±25	Neg.	11.4	0	14.6	0	Farrowing operation, earthen manure storage with negative air pressure covered

*References: 1. Clark et al., 2005; 2. Desutter and Ham, 2005; 3. Hamilton et al., 2005; 4. Harper et al., 2000; 5. Harper et al., 2004; 6. Kaharabata et al., 1998; 7. Lague et al., 2005; 8. Masse et al., 2003; 9. Park et al. 2006; 10. Park et al. 2010; 11. Pelletier et al., 2004; 12. Sharpe and Harper, 1999; 13. Sharper et al., 2002; 14. Shores et al., 2005; 15. Zahn et al., 2001; 16. Zhang et al., 2007.

Appendix 3 CH_4 and N_2O emissions from swine manure land application in North American studies

Ref*	T (°C)	Annual precipitation (mm)	Soil type	Application methods / conditions	Amount of application	Cumulative emissions in kg ha^{-1}		N_2O EF (%)
						CH_4	N_2O	
1	-	-	Black belt	Effluent	112 kg N ha^{-1}	13.93	1.93	0.85
1	-	-	Coastal plain	Effluent	112 kg N ha^{-1}	19.31	5.50	2.63
1	-	-	Appalachian	Effluent	112 kg N ha^{-1}	30.51	3.19	1.26
2	10	1077.3	-	Injected	-	0.04		0.00
3	20	-	-	Pig slurry	60 m^3 ha^{-1}	-	0.26	0.00
3	20	-	-	Pig slurry +barley straw	60 m^3 ha^{-1}	-	0.15	0.00
4	4	1100	Loam	Raw liquid swine manure	140 kg N ha^{-1}	-	2.34	0.94
4	4	1100	Loam	Clarified fraction of LSM after natural settling of solids at the bottom of a storage tank	140 kg N ha^{-1}	-	1.82	0.70
4	4	1100	Loam	Drain through a bed of wood shavings and saw dust (50:50,v/v)	140 kg N ha^{-1}	-	2.75	1.12
4	4	1100	Loam	Anaerobically digested LSM	140 kg N ha^{-1}	-	0.88	0.27
4	4	1100	Loam	Pumped to a tank where coagulant and pressurized air were injected, then remove the floating material	140 kg N ha^{-1}	-	2.05	0.80
4	4	1100	Sandy loam	Raw liquid swine manure	140 kg N ha^{-1}	-	0.65	0.25
4	4	1100	Sandy loam	Clarified fraction after natural settling of solids at the bottom of a storage tank	140 kg N ha^{-1}	-	0.69	0.27
4	4	1100	Sandy loam	Drain through a bed of wood shavings and saw dust (50:50,v/v)	140 kg N ha^{-1}	-	0.54	0.21
4	4	1100	Sandy loam	Anaerobically digested LSM	140 kg N ha^{-1}	-	0.31	0.10
4	4	1100	Sandy loam	Pumped to a tank where coagulant and pressurized air were injected, then remove the floating material	140 kg N ha^{-1}	-	0.41	0.15
5	4	1100	Clay	Raw liquid swine manure	100 kg N ha^{-1}	-	11.16	4.47
5	4	1100	Clay	Clarified fraction of LSM after natural settling of solids at the bottom of a storage tank	100 kg N ha^{-1}	-	11.68	4.80
5	4	1100	Clay	Drain through a bed of wood shavings and saw dust (50:50,v/v)	100 kg N ha^{-1}		15.27	7.09
5	4	1100	Clay	Anaerobically digested LSM	100 kg N ha^{-1}	-	12.05	5.04
5	4	1100	Clay	Pumped to a tank where coagulant and pressurized air were injected, then remove the floating material	100 kg N ha^{-1}	-	13.94	6.24
5	4	1100	Loam	Raw liquid swine manure	100 kg N ha^{-1}	-	7.21	3.15
5	4	1100	Loam	Clarified fraction after natural settling of solids at the bottom of a storage tank	100 kg N ha^{-1}	-	5.85	2.28
5	4	1100	Loam	Drain through a bed of wood shavings and saw dust (50:50,v/v)	100 kg N ha^{-1}	-	5.89	2.31
5	4	1100	Loam	Anaerobically digested	100 kg N ha^{-1}	-	5.69	2.18
5	4	1100	Loam	Pumped to a tank where coagulant and pressurized air were injected, then remove the floating material	100 kg N ha^{-1}	-	4.82	1.63
6	12	950	-	Summer	255 kg N ha^{-1}	0.44	12.84	3.20
6	12	950	-	Summer	255 kg N ha^{-1}	0.31	11.42	2.85
6	12	950	-	Fall	255 kg N ha^{-1}	0.21	5.17	1.29
6	12	950	-	Fall	255 kg N ha^{-1}	0.23	2.36	0.59
7	10.8	1045	-	Compost	-	-0.55	15.97	0.00
8	17	-	Sandy loam	5cm x 5cm trench in soil, poured in 684 mL slurry, covered with soil	200 kg N ha^{-1}	1.51	9.87	2.71
8	17	-	Clay soil	5cm x 5cm trench in soil, poured in 684 mL slurry, covered with soil	200 kg N ha^{-1}	0.20	6.24	1.84
9	8.7	835	Silty clay loam	Injected, no cover crop	224 kg N ha^{-1}	-	11.94	0.09
9	8.7	835	Silty clay loam	Injected, cover crop	112 kg N ha^{-1}	-	7.86	0.00
9	8.7	835	Silty clay loam	Injected, cover crop	224 kg N ha^{-1}	-	12.89	0.36
9	8.7	835	Silty clay loam	Injected, cover crop	336 kg N ha^{-1}	-	18.86	2.08
10	16	-	-	-	-	-	2.87	0.00
11	17	-	-	Rye+high manure	19.5 gN m^{-2}	-	3.65	0.65

11	17	-	-	Rye+low manure	7.53 gN m^{-2}	-	2.07	0.35
11	17	-	-	Fallow+high manure	19.1 gN m^{-2}	-	5.78	1.45
11	17	-	-	Fallow+low manure	7. gN m^{-2}	-	2.36	0.79
11	17	-	-	Rye+high manure	17.9 gN m^{-2}	-	2.47	0.66
11	17	-	-	Rye+low manure	2.99 gN m^{-2}	-	0.80	0.43
11	17	-	-	Fallow+high manure	17.8 gN m^{-2}	-	3.30	1.06
11	17	-	-	Fallow+low manure	2.99 gN m^{-2}	-	0.85	1.10
12	3.5	1174	-	-	219 kg N ha^{-1}	-	9.43	2.74
12	3.5	1174	-	-	186 kg N ha^{-1}	-	5.03	1.72
13	18	-	Oat field	Solid set sprinkle irrigation - from lagoon	45 kg N ha^{-1}	-	2.70	3.80
14	25	-	-	-	274.5 kg N ha^{-1}	-	2.35	0.38
15	24	-	Corn field	No-tillage	200 kg N ha^{-1}	1.20	7.30	1.56
15	24	-	Corn field	Aeration	200 kg N ha^{-1}	2.10	6.90	1.43
15	24	-	Corn field	Injector	200 kg N ha^{-1}	2.60	4.70	0.73
15	24	-	Corn field	No-tillage	200 kg N ha^{-1}	1.10	3.60	1.08
15	24		Corn field	Aeration	200 kg N ha^{-1}	0.90	3.60	1.08
15	24	-	Corn field	injector	200 kg N ha^{-1}	2.20	3.00	0.89
16	-	-	-	Supplement with NH_4NO_3	112 kg N ha^{-1}		7.07	0.00
16	-	-	-	Supplement with NH_4NO_3	112 kg N ha^{-1}		3.14	0.00
16	-	-	-	Supplement with NH_4NO_3	112 kg N ha^{-1}		2.67	0.00
16	-	-	-	Supplement with fertilizer	112 kg N ha^{-1}		3.14	0.60
16	-	-	-	Supplement with fertilizer	112 kg N ha^{-1}		2.04	0.40
16	-	-	-	Supplement with fertilizer	112 kg N ha^{-1}		3.14	0.60

*References: 1. Bender and Wood, 2007; 2. Chan and Parkin, 2001; 3. Chantigny et al., 2001; 4. Chantigny et al., 2007; 5. Chantigny et al., 2010; 6. Hermandez-Ramirez et al., 2009; 7. Jarecki and Lal, 2006;8. Jarecki et al., 2008; 8. Jarecki et al., 2009; 9. Jarecki et al., 2009; 10. Mkhabela et al., 2009; 11. Parkin et al., 2006; 12. Rochette et al., 2004; 13. Sharpe and Harper, 1997; 14. Sharpe and Harper, 2002; 15. Sistani et al., 2010; 16. Sullivan et al., 2005.

Appendix 4 Database of GHG emissions from swine operations for analysis of variation

Ref[1]	Region[2]	T (°C)	Source[3]	Source condition[4]	Diet CP	Size of operation (heads)	Swine category[5]	Measurement method	CH_4		N_2O		CO_2	
									Mean[6]	Std[6]	Mean[6]	Std[6]	Mean[6]	Std[6]
1	EU	23	BP	Pit1d	.	160	FN	traditional	2.10	0.37	0.080	0.034	.	.
	EU	20	BP	Pit1d	.	160	FN	traditional	0.90	0.18	0.020	0.011	.	.
	EU	23	BS	BS	.	160	FN	traditional	0.80	0.39	0.060	0.044	.	.
	EU	20	BS	BS	.	160	FN	traditional	0.60	0.14	0.010	0.004	.	.
	EU	24	BS	BS	.	160	FN	traditional	1.00	0.37	0.040	0.012	.	.
	EU	20	BS	BS	.	160	FN	traditional	0.60	0.15	0.020	0.006	.	.
2	NA	.	BP	.	19.3%	12	FA	traditional	0.66	0.04	.	.	96.83	.
	NA	.	BP	.	19.3%	12	FA	traditional	0.27	0.04	.	.	92.66	.
	NA	.	BP	.	19.3%	12	FN	traditional	0.46	0.03	.	.	68.36	.
3	EU	20	BB	BST	.	40	FN	traditional	5.06	1.71	0.200	0.036	.	.
4	EU	16	BB	BSW	.	38	FN	traditional	0.20	0.01	0.184	0.046	155.90	2.61
	EU	24	BB	BST	17.5%	40	FN	traditional	0.30	0.04	0.099	0.033	121.90	7.19
	EU	27	BP	Pit	17.5%	40	FN	traditional	0.30	0.03	0.000	.	110.60	7.19
	EU	23	BP	Pit	17.5%	38	FN	traditional	0.30	0.01	0.006	0.048	.	.
5	EU	20	.	.	16.5%	14	FN	traditional	1.20	0.35	.	.	.	.
	EU	20	.	.	16.5%	14	FN	traditional	0.90	0.27	.	.	.	.
	EU	20	.	.	18.3%	14	FN	traditional	2.10	0.09	.	.	.	.
	EU	20	.	.	18.3%	14	FN	traditional	1.60	0.09	.	.	.	.
6	NA	.	SS	SSN	.	12	FN	traditional	0.20	.	0.000	.	6.67	.
7	EU	26	BP	PitDp	.	391	FN	traditional	5.90	.	0.520	.	739.00	.
	EU	26	BP	PitDp	.	391	FN	traditional	4.30	.	0.530	.	772.00	.
8	EU	23	BP	Pit1m	.	355	FA	traditional	0.62	.	0.090	.	168.00	.
	EU	25	BP	Pit1m	.	350	FN	traditional	0.63	.	0.090	.	101.00	.
	EU	24	BP	Pit3m	.	350	FN	traditional	6.90	.	0.130	.	498.00	.
	EU	16	BP	Pit3m	.	42	GE	traditional	4.80	.	0.490	.	323.00	.
9	OE	15	LA	LA	.	8000	.	traditional	17.10	4.14	.	.	.	.
10	NA	15	BP	Pit1wk	.	10500	FN	traditional	1.50	.	.	.	610.00	.
	NA	15	LA	LA	.	10500	FN	traditional	8.30	.	.	.	9.40	.
11	AS	21	BB	BCN	.	98	FN	traditional	2.40	.	.	.	731.00	.
12	AS	26.5	BS	BS	.	24	FA	traditional	1.41	0.52	0.080	0.022	1091.00	15.72
13	AS	25	BS	BS	19.3%	24	FA	traditional	1.40	0.53	0.080	0.022	1094.00	16.07
	AS	25	BS	BS	18.7%	192	FN	traditional	1.50	0.55	0.060	0.052	244.00	15.46
	AS	25	BS	BS	15.4%	60	GE	traditional	1.75	0.35	0.140	0.105	1080.00	80.27
	AS	28	BS	BS	20.9%	220	NU	traditional	0.80	0.30	0.020	0.006	433.00	15.91
14	EU	24	BB	BSW	.	100	FN	traditional	2.15	.	2.640	.	.	.
	EU	24	BP	Pit	.	100	FN	traditional	4.42	.	0.920	.	.	.
15	EU	2.5	BB	BSW	.	18	.	traditional	.	.	4.130	.	.	.
	EU	2.5	BB	BSW	.	18	.	traditional	.	.	2.750	.	.	.
16	EU	24	BP	Pit	.	165	FA	traditional	6.83	.	0.360	.	2291.00	.
	EU	24	BP	Pit	.	165	FA	traditional	5.80	.	0.340	.	2050.00	.
17	EU	14	BP	Pit3wk	.	54	FN	traditional	2.60	.	.	.	.	.
	EU	14	BP	Pit3wk	.	54	FN	traditional	2.40	.	.	.	.	.
18	NA	30	LA	LA	.	.	.	traditional	21.10	.	.	.	40.09	.
	NA	30	LA	LA	.	.	.	traditional	29.50	.	.	.	57.95	.
	NA	30	LA	LA	.	.	.	traditional	31.60	.	.	.	61.09	.

19	NA	21.4	LA	LA	.	12000	.	MMB	23.99	.	0.000	.	.	.
20	NA	.	LA	LA	.	4300	FA	MMB	.	.	0.081	.	.	.
	NA	.	LA	LA	.	13700	FF	MMB	.	.	0.022	.	.	.
21	EU	11	SS	SSN	.	200	FA	traditional	3.20	0.20	.	.	.	.
22	EU	.	.	.	.	.	FN	traditional	6.20	3.60	0.060	0.090	605.00	223.05
23	EU	.	.	.	.	4	FN	traditional	0.30	.	.	.	.	.
	EU	.	.	.	.	4	FN	traditional	3.10	.	.	.	.	.
24	NA	.	SS	SSN	.	510	FA	SF6	78.30	25.70	.	.	.	.
25	NA	25	BP	Pit	16.0%	.	FN	traditional	0.50	.	.	.	.	.
26	NA	5	BP	Pit	.	.	FA	traditional	41.40	.	0.000	.	3233.14	.
	NA	5	BP	Pit	.	.	FA	traditional	6.60	.	0.000	.	2428.80	.
	NA	5	BP	Pit	.	.	FN	traditional	2.40	.	0.034	.	2477.14	.
	NA	5	BP	Pit	.	.	FN	traditional	4.00	.	0.000	.	1508.33	.
	NA	5	BP	Pit	.	.	FN	traditional	7.20	.	0.017	.	1545.49	.
	NA	5	BP	Pit	.	.	GE	traditional	14.80	.	0.000	.	1151.11	.
	NA	5	BP	Pit	.	.	GE	traditional	3.80	.	0.000	.	1460.29	.
	NA	5	BP	Pit	.	.	NU	traditional	12.90	.	0.000	.	585.77	.
	NA	5	BP	Pit	.	.	NU	traditional	2.60	.	0.000	.	202.67	.
27	NA	10	SS	SSC	.	.	.	traditional	1.00	.	0.000	.	1.38	.
	NA	10	SS	SSN	.	.	.	traditional	4.60	.	0.000	.	0.67	.
	NA	10	SS	SSN	.	.	.	traditional	5.30	.	0.001	.	1.61	.
28	NA	20	BP	Pit0.5wk	18.5%	12	FN	traditional	1.20	0.11	0.024	0.006	.	.
	NA	20	BP	Pit0.5wk	20.1%	12	FN	traditional	1.90	0.11	0.024	0.006	.	.
	NA	20	BP	Pit0.5wk	20.9%	12	FN	traditional	2.30	0.11	0.024	0.006	.	.
29	EU	.	SS	SSN	.	200	FA	traditional	55.40	.	0.000	.	119.00	.
	EU	.	SS	SSN	.	200	FA	traditional	72.70	.	0.000	.	168.00	.
30	NA	10	SS	SSN	.	.	.	traditional	2.20	0.45	.	.	.	.
	NA	15	SS	SSN	.	.	.	traditional	4.10	1.04	.	.	.	.
	NA	10	SS	SSN	.	.	.	traditional	3.00	0.56	.	.	.	.
	NA	15	SS	SSN	.	.	.	traditional	5.90	1.69	.	.	.	.
31	NA	.	BP	PitEff	.	1100	FN	traditional	4.00	0.22	.	.	1933.70	88.40
	NA	.	BP	PitEff	.	1100	FN	traditional	3.20	0.20	.	.	1577.78	66.67
32	EU	21.2	BB	BST	17.8%	16	FN	traditional	5.60	0.08	0.190	0.004		.
	EU	20.5	BP	PitDp	17.8%	16	FN	traditional	6.60	0.08	0.130	0.004		.
33	EU	19.1	BB	BSW	17.6%	18	FN	traditional	1.80	.	.	.		.
	EU	20	BB	BST	17.6%	18	FN	traditional	2.70	.	0.036	.		.
34	EU	17	BP	Pit1wk	.	40	FN	traditional	1.70	.	0.055	.		.
	EU	17	BP	Pit2m	.	40	FN	traditional	2.00	.	0.059	.	36.10	.
35	EU	15	BP	Pit4m	.	348	FN	traditional	11.60	.	0.100	.	601.00	.
	EU	0	BP	Pit4m	.	348	FN	traditional	11.10	.	0.200	.	814.00	.
36	NA	13	SS	SSN	.	1672	FF	MMB	6.70	.	0.004	.	.	.
37	NA	22	SS	SSN	.	1000	FN	traditional	14.10	.	.	.	.	.
38	NA	13	SS	SSN	.	940	FN	traditional	5.10	.	.	.	0.59	.
39	NA	8.8	BP	PitDp	.	1300	FN	traditional	9.10	0.62	0.000	.	579.49	28.39
	NA	8.8	BP	PitDp	.	1300	FN	traditional	8.50	0.58	0.000	.	526.71	19.98
40	EU	18.6	BB	BST	13.2%	5	GE	traditional	5.55	2.95	0.910	0.411	880.00	94.94
	EU	18.8	BB	BST	12.9%	5	GE	traditional	6.28	1.83	0.350	0.080	1095.00	94.90
41	EU	18.5	BB	BST	13.2%	10	GE	traditional	3.70	1.09	0.650	0.256	774.00	131.43
	EU	18.6	BB	BST	13.2%	10	GE	traditional	5.60	2.97	0.910	0.411	880.00	94.94
42	EU	20.5	BP	Pit4m	17.0%	16	FN	traditional	5.55	0.94	0.240	0.201	588.00	21.91

	EU	19.1	BS	BS	17.0%	16	FN	traditional	3.24	0.45	0.250	0.246	646.00	40.15
43	EU	20.6	BB	BST	16.8%	16	FN	traditional	5.85	0.49	0.410	0.362	719.00	21.90
	EU	20.5	BP	Pit4m	16.8%	16	FN	traditional	5.96	0.87	0.200	0.163	635.00	69.34
44	NA	20	BP	Pit0.5wk	20.3%	12	FN	traditional	2.30	.	.	.	.	.
45	EU	8	SS	SSN	.	.	FN	traditional	0.31	.	.	.	.	.
46	NA	12	LA	LA	.	12000	FF	MMB	5.60	.	.	.	.	.
47	NA	29	BP	PitEff	.	1200	FA	traditional	16.90	1.02	.	.	.	.
	NA	29	BP	PitEff	.	873	FF	traditional	10.60	2.43	.	.	.	.
	NA	29	BP	PitEff	.	904	FF	traditional	13.60	0.51	.	.	.	.
	NA	8	BP	PitEff	.	873	FF	traditional	2.50	1.23	.	.	.	.
48	NA	15	LA	LA	.	4300	FA	MMB	1.60	.	.	.	.	.
	NA	15	LA	LA	.	13700	FF	MMB	6.00	.	.	.	.	.
49	NA	29	LA	LA	.	980	FN	FTIR	25.00	1.47	.	.	.	.
	NA	22	LA	LA	.	980	FN	FTIR	49.90	4.83	.	.	.	.
	NA	9	LA	LA	.	980	FN	FTIR	23.40	8.49	.	.	.	.
	NA	25	LA	LA	.	980	FN	FTIR	13.20	.	.	.	.	.
	NA	27	LA	LA	.	980	FN	FTIR	64.80	5.51	.	.	.	.
50	AS	17.5	SS	SST	.	.	FN	traditional	1.39	0.17	0.002	.	1.28	0.21
	AS	22	SS	SST	.	.	FN	traditional	0.46	0.05	0.001	.	0.44	0.08
	AS	28	SS	SST	.	.	FN	traditional	0.45	0.05	0.001	.	0.42	0.08
51	NA	20	BP	Pit0.5wk	20.1%	12	FN	traditional	0.60	0.16	.	.	431.31	.
52	NA	15	LA	LA	.	14170	.	traditional	12.00	.	.	.	.	.
	NA	15	LA	LA	.	18500	.	traditional	16.40	.	.	.	.	.
	NA	15	SS	SSN	.	8200	.	traditional	5.50	.	.	.	.	.
	NA	15	BP	Pit	.	13680	FN	traditional	1.40	.	.	.	.	.
53	NA	20	BP	Pit3wk	.	3000	FA	traditional	24.20	22.36	0.000	.	2181.68	1443.71
	NA	20	BP	Pit3wk	.	3000	FA	traditional	46.10	26.79	0.000	.	1520.38	928.96
	NA	21	SS	SSC	.	3000	FA	traditional	11.40	9.50	0.000	.	33.82	24.70
	NA	21	SS	SSN	.	3000	FA	traditional	45.90	28.17	0.000	.	474.65	343.21
	NA	20	BP	Pit1wk	.	3000	GE	traditional	12.90	13.01	0.000	.	1258.73	812.15
	NA	20	BP	Pit1wk	.	3000	GE	traditional	8.00	5.59	0.000	.	526.90	328.33

[1] References: 1. Amon et al.,2007; 2. Ball and Mohn, 2003; 3. Blanes-Vidal et al., 2008; 4. Cabaraux et al., 2009; 5. Christensen and Thorbek, 1987; 6. Clark et al., 2005; 7. Costa and Guarino, 2008; 8. Costa and Guarino, 2009; 9. Craggs et el., 2008; 10. Desutter and Ham, 2005; 11. Dong et al., 2009; 12. Dong et al., 2007a; 13. Dong et al., 2007b; 14. Dourmad et al., 2009; 15. Groenestein et al., 1996; 16. Guarino et al., 2008; 17. Haeussermann et al., 2006; 18. Hamilton et al., 2005; 19. Harper et al., 2000; 20. Harper et al., 2004; 21. Husted et al., 1993; 22. Jelinek et al., 2007; 23. Jensen and Jørgensen, 1994; 24. Kaharabata et al., 1998; 25. Kai et al.,2006; 26. Lague et al., 2003; 27. Lague et al., 2005; 28. Li et al., 2011; 29. Loyon et al., 2007; 30. Masse et al., 2003; 31. Ni et al., 2008; 32. Nick et al., 2005; 33. Nick et al., 2004; 34. Osada et al., 1998; 35. Palkovicova et al., 2009; 36. Park et al. 2006; 37. Park et al. 2010; 38. Pelletier et al., 2004; 39. Pepple et al., 2010; 40. Philippe et al., 2009, 41. Philippe et al., 2010; 42. Philippe et al., 2007a, 43. Philippe et al., 2007b; 44. Powers et al., 2008; 45. Rodhe et al., 2010; 46. Sharpe and Harper, 1999; 47. Sharpe and Harper 2001; 48. Sharper et al., 2002; 49. Shores et al., 2005; 50. Su et al., 2003; 51. Unpublished study at MSU; 52. Zahn et al., 2001; 53. Zhang, et al., 2007.

[2] Region: NA=North America; EU=Europe; AS=Asia; OE=Qceania.

[3] Source: LA=Lagoon; SS=Slurry storage facilities; BP=Swine building with pit system; BB=Swine building with bedding system; BS=Swine building with straw flow system.

[4] Source condition: LA=Lagoon; SSC= Slurry storage facilities with cover; SSN= Slurry storage facilities without cover; SST= Slurry storage facilities with treatment; BST=Straw bedding; BSW=Sawdust bedding; BCN=Corn stalk bedding; BS= Swine building with straw flow system; PitDp=deep pit; PitEff=pit flushed using lagoon effluent; Pit1d, Pit0.5wk, Pit1wk, Pit3wk, Pit1m, Pit2m, Pit3m, Pit4m=pit with corresponding manure removal frequency.

[5] Swine category: FA=Farrowing; FF=Farrow to finish; FN=Finishing; GE=Gestating; NU=Nursery.

[6] Unit of mean emission rate and standard deviation: kg yr^{-1} hd^{-1}.