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Report 627

Monitoring methane and nitrous oxide reduction by manure treatment

August 2012

LIVESTOCK RESEARCH
WAGENINGEN UR

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Abstract
Reduction of greenhouse gas emissions (CH_4 and N_2O) by manure treatment should be accounted for in the National Inventory Report (NIR). At the moment reliable activity data and emission factors from manure treatment are hardly available. This is the outcome of a national and international literature review. It is recommended to use a model approach to estimate greenhouse gas emissions from manure treatment.

Keywords
Manure treatment, greenhouse gas, methane, nitrous oxide, emission

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Summary

In the in-country review 2011 of UNFCCC it was strongly recommended to include in the Dutch National Inventary Report (NIR) the effects of manure treatment on the emissions of greenhouse gasses e.g. methane (CH_4) and nitrous oxide (N_2O). However, at this moment not all necessary data are available to record manure treatment in NIR. Wageningen UR Livestock Research (WLR) carried out a desk study to evaluate the available data and propose a plan how to make missing data available.

To quantify the impact of manure treatment on CH_4 and N_2O emissions data on the amount of manure treated and data on the amount, composition and management of the end products from manure treatment are required. The main manure treatment technologies that have impact on greenhouse gas emissions were identified, based on the actual and expected amount of manure treated. Available information on activity data was obtained from a review of Dutch literature, data on emission factors was obtained from a review of international literature.

The evaluation of activity data showed that reliable data on the amount and composition of manure treated by nitrification/denitrification and incineration are available. Data on the amount and composition of the manure treated by flotation and ultra filtration is available but was qualified as unreliable. Table I gives an overview of the main treatment technologies and the availability and reliability of activity data for the whole manure chain which comprises manure treatment as one of the links.

Tabel I Availability and reliability of activity data for the whole manure chain comprising selected manure treatment technologies.

Treatment, as part of manure chain	*Activity data*			
	Amount		*Composition*	
	Availability	*Reliability*	*Availability*	*Reliability*
Anaerobic digestion	-	-	-	-
Nitrification/denitrification	+	+	+	+
Incineration	+	+	+	+
Composting/drying/pelleting	-	-	-	-
Production of mineral concentrates				
Flotation	+	-	+	-
Ultra filtration	+	-	+	-
Solid/liquid separation	-	-	-	-

Furthermore, the evaluation of emission factors showed that reliable emission factors for CH_4 and N_2O from the main treatment processes are not sufficiently available. The emissions that were measured in past research showed a large variation. These measurements need to be further underpinned before they can be used for defining general emission factors. An extensive and costly measurement program will have to be performed to provide reliable emission factors.

An alternative (recommended) approach would be to estimate emissions from the whole manure treatment chain by using average emission factors for each link of the chain. This approach was chosen in a study in which the whole manure chain was described as a number of sequential unit operations, each having its own conversion or production factor for CO_2, CH_4 and N_2O. Using reliable activity data (amount and composition of the manure) as model input, the total greenhouse gas emission can thus be calculated. The emission factors used in the model were based on literature and expert judgement. If the use of this model is being considered as a suitable approach for establishing emission factors for the NIR framework, the conversion and emission factors used in the model should be improved and validated. Without going through a further analysis of the model first, currently it is not possible to define a measurement program in detail or to estimate the costs to improve the emission factors.

Contents

1 Introduction

The Reduction Plan on non-CO_2 Greenhouse gasses (ROB) was one of the Dutch instruments to realize the goals on climate change. ROB aimed at emission reduction of methane (CH_4) and nitrous oxide (N_2O) following a sector oriented approach. In 2012 ROB will be transformed into a number of specific non-CO_2 greenhouse gas reduction projects. Agriculture is one of the projects.

In 2010 agriculture contributed about 7.9% to the total emission of greenhouse gas in the Netherlands. The emission from manure management (animal houses and manure storage) was 3.9 Mton CO_2-eq., of which 26% was N_2O and 74% was CH_4 (Coenen *et al*., 2012). Anaerobic digestion and treatment of animal manure are denominated as options to reduce emissions of nitrous oxide and methane. Anaerobic (co-)digestion of manure in the Netherlands has increased in the last decade. In 2010 approx. 113 anaerobic digestion plants, fed with animal manure, were in operation (Peene *et al*., 2011). The amount of digested manure in 2010 is estimated at 1.2 Mton which is 1.7% of the total manure production in the Netherlands (CBS, 2011). A further increase of anaerobic co-digestion and manure treatment can be expected as a result of the announced new manure policy, which will force livestock farms to process their manure surplus.Today manure treatment in the Netherlands and other European countries mainly refers to digestion, separation, filtration, drying and composting.

In the in-country review 2011 of UNFCCC it was strongly recommended to include in the National Inventary Report (NIR) the effects of manure treatment on the emissions of greenhouse gasses. However, at this moment not all necessary data are available to record manure treatment in NIR. Wageningen UR Livestock Research (WLR) was asked to carry out a desk study to evaluate the available data and propose a plan how to make missing data available.

The desk study was phased as follows:
(1) Evaluation of available information, which is relevant for the monitoring.
(2) Identification of emission sources, suitable measuring techniques and measuring strategies.
(3) Recommendations.

2 Required information for NIR

The National Inventary Report (NIR) documents the annual greenhouse gas emission inventory in accordance with the Guidelines provided by the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the European Union's Greenhouse Gas Monitoring Mechanism. Emission data in the NIR are calculated according to the protocols of the National System and documented in Common Reporting Format (CRF) spreadsheet files, which can be found on www.greenhousegases.nl. Monitoring protocols, describing methodologies and working processes for estimating greenhouse gas emissions including the activity data and emission factors to be used for the report, are also available at this website. The protocols are yearly updated (if needed). About 40 monitoring protocols are valid at present in the Netherlands. In connection with this study protocols for CH_4 and N_2O from Manure management and N_2O from Agricultural soils are relevant.

2.1 CH4 from manure management

Methane emissions from animal manure are caused by fermentation processes that occur in anaerobic conditions. These conditions generally occur when storing liquid manure in manure cellars under the animal houses and in manure storage facilities outside the animal houses. Methane formation depends on storage conditions, such as storage period and temperature. There is a constant input of manure in the manure cellar and the volume of manure in the cellar increases up to the point where it is emptied, and the manure is distributed over the land, or up to the point where the manure is transferred to the manure storage facility outside the animal house. The methane emissions increase as the amount of manure that is (still) in the storage facility (= inocculation) increases, as the manure temperature rises and the manure is stored for longer periods (Zeeman, 1994). The methane emissions from manure also depend on the chemical composition of the manure, primarily the amount of organic matter.

Calculation method

Methane emissions from manure are basicly calculated from the number of animals and country-specific emission factors. First the amount of manure is calculated annually for each animal category and each manure management system, from the number of animals per category and the amount of manure per animal. Then the country-specific emission factor per kg manure is calculated for each animal category and manure management system. Multiplying the emission factor and annual manure production results in the annual methane emissions from manure storage. The total CH_4 emissions from manure management are calculated by adding the CH_4 emissions per animal category and manure management system.

Emission factors

The formula for calculating the emission factor is:

$$EF_{ij} = VS_{ij} * B_{oij} * MCF_j * \text{methane density } (0.67\ kg/m^3)$$

EF_{ij} : emission factor (kg CH_4/kg manure) per animal category (i) and manure management system (j)
VS_{ij} : fraction of volatile solids (kg VS/kg manure) produced by animal category (i) and manure management system (j)
B_{0ij} : maximum methane production potential (m^3 CH_4/kg VS) for the manure produced by animal category (i) and manure management system (j)
MCF_j : methane conversion factor for a manure management system j (% of B_0)

The amount of solid, liquid and meadow manure per animal (of a specific sub-category) per year is determined by the WUM (working group for uniform calculation of manure and mineral figures). The manure production factors are updated every year if necessary. They are publiced on www.cbs.nl.

The fraction of volatile solids in the manure (VS) varies per animal category depending on feed composition. Dutch values are documented in Van der Hoek & Van Schijndel (2006). The maximum methane formation (B_0) depends on degradability of organic components in the manure. B_0 values per animal category are fixed and taken from Zeeman (1994) and Zeeman & Gerbens (2002).

The methane conversion factor (MCF) indicates the extent to which the degradable substances will actually be converted into methane. The IPCC provides a default value of MCF = 0 for liquid manure stored less than one month, and MCF = 0.39 for liquid manure stored longer than one month. The Netherlands uses a country specific MCF documented in the NIR (Van der Maas *et al.*, 2009)

Activity data

Animal population
Animal numbers per category are monitored in the annual Agricultural Census. They are publiced on www.cbs.nl.

Amounts of manure per management system
The method of calculating amounts of manure differentiates between liquid manure produced in the stable period, solid manure produced in the stable period and manure produced in the meadow. Data on the amounts of manure per management system are determined by the WUM. They are publiced on www.cbs.nl.

2.2 N_2O from manure management

The protocol refers to N_2O emissions from manure produced in animal houses, and then stored and/or processed before being transported elsewhere.

N_2O emissions from animal manure management depend on the nitrogen and carbon content of the manure, the amount of time the manure is stored and the treatment method used. During storage the manure usualy becomes low-oxygen, which slows the nitrification and denitrification process. Nitrification is the process whereby, under high-oxygen circumstances, ammonia (NH_4^+) is converted into nitrate (NO_3^-). N_2O can be formed as a by-product, particularly if the oxygen concentration is low. Nitrification does not require any organic substances (volatile solids) to be present. Denitrification is the process whereby, under low-oxygen circumstances, bacteria can convert nitrate into the gaseous nitrogen compound N_2, with N_2O as a by-product. N_2O emissions from solid manure are higher than from liquid manure, because there is very little nitrification in the latter due to the lack of oxygen.

Calculation method

N_2O emissions from animal manure are calculated as follows:

$$\begin{aligned} N_2O\ emissions = \sum_{ij} [\ EF_{ij}\ ] * 44/28 \\ * [\ amount\ of\ N\ in\ manure\ per\ animal\ in\ animal\ category\ (i) \\ and\ manure\ management\ system\ (j)\ ] \\ * [\ number\ of\ animals\ per\ animal\ category\ (i)\ and\ manure \\ management\ system(j)\ ] \end{aligned}$$

N_2O emissions : N_2O emissions from manure management, in kg
EF_{ij} : emission factor for the defined animal category and manure management system (i) in kg N_2O-N/kg N excreted manure
44/28 : conversion factor from kg N_2O-N to kg N_2O

Two manure management systems are distinguished: system for liquid manure and system for solid manure.

The Tier 2 method is used to determine the animal numbers per category. Default (Tier 1) values are used for the emission factors. The calculations are made within the National Ammonia Emission Model (NEMA), based on the best available data on division over liquid and solid manure.

Emission factors

NEMA uses the default IPCC 1996 emission factors for liquid and solid manure, for poultry extended with the classification and factors from the Good Practice Guidance 2001.

Activity data

Animal population
Animal numbers per category are monitored in the annual Agricultural Census. They are publiced on www.cbs.nl.

Nitrogen excretion per animal and manure management system
The N-excretion and manure production per animal are determined by the WUM (Working group for Uniform calculations of Manure and mineral figures). A more detailed sub-division in solid and liquid manure is made in the working group NEMA. The nitrogen excretion factors are updated every year. An overview of the nitrogen excretion factors used is published on www.cbs.nl.

2.3 N_2O from agricultural soils: direct emissions

The protocol refers to direct emissions of N_2O from the soil as a result of agricultural activities. N_2O is formed in the soil during the microbiological processes of nitrification and denitrification. Nitrification is the conversion process of ammonia (NH_4^+) into nitrate (NO_3^-) by bacteria. N_2O is formed as a byproduct, particularly in low-oxygen circumstances. Denitrification is the microbial process whereby NO_3^- is converted into N_2, with N_2O as a by-product. Organic soils have higher N_2O emissions than mineral soils.

Calculation method

Direct N_2O emissions from agricultural soils are calculated by multiplying the amount of nitrogen per supply source and soil type by the country-specific emission factor, using the following formula:

$$N_2O\ emission\ (in\ kg\ N_2O) = \sum E_i * EF_i * 44/28$$

E_i : amount of N for the defined supply source (i) (kg N)
EF_{ij} : emission factor for the defined supply source (i) in kg N_2O-N/kg N in supply source.
44/28 : conversion factor from N_2O-N to N_2O

The formula differentiates between the following N supply sources:

1. Gross application of N from fertiliser, i.e. not reduced by the NH_3 and NO emission when applying fertiliser.
2. Gross application of N from animal manure, i.e. not reduced by the NH_3 and NO emission when applying animal manure, but minus emissions from stable and storage together with net export (export-import).
3. Gross N in the soil through grazing domestic agricultural animals, i.e. not reduced by the NH_3 and NO emission when grazing.
4. Biological nitrogen fixation by crops.

5. Remaining crop residues.
6. Agricultural use of histosols.
7. Sewage sludge.

The NEMA model is used to determine soil load (in millions of kg N) caused by the application of fertiliser, manure and grazing (Velthof *et al.*, 2012; Van Bruggen, 2011).

Emission factors

The total direct emissions of N_2O from agricultural soils are calculated by multiplying the amount of nitrogen per supply source by a fixed country-specific emission factor, and then to aggregate this over all supply sources (Van der Hoek *et al.*, 2007; Van Schijndel en Van der Sluis, 2011).

Activity data

The required information to carry out the calculation concern the amount of nitrogen in the supply sources and the emission factors as discussed.

2.4 N_2O from agricultural soils: indirect emissions

The protocol refers to indirect emissions of N_2O from the soil as a result of agricultural activities. Direct emissions occur primarily as a result of the application of synthetic fertilisers and animal manure. Indirect emissions concern the formation of N_2O in soils and aquatic systems as a result of nitrogen losses from the soil to air and water. The IPCC differentiates between two sources of indirect N_2O emissions:

- Atmospheric depositions of ammonia and nitrogen oxides released during manure production and storage, and after application of artificial fertiliser and animal manure to agricultural soils.
- Leaching and runoff of nitrogen from agricultural soils. Nitrate undergoes denitrification in groundwater or surface water, which creates laughing gas.

Calculation method

Indirect N_2O emissions from agricultural soils are calculated by multiplying the amount of nitrogen per supply source by the emission factor, using the following formula:

$$N_2O \text{ emission (in kg } N_2O) = \sum E_i * EF_i * 44/28$$

E_i : amount of N for the defined supply source (i) (kg N)
EF_{ij} : emission factor for the defined supply source (i) in kg N_2O-N/kg N in supply source.
44/28 : conversion factor from N_2O-N to N_2O

Two supply sources are distinguished: (1) Atmospheric depositions and (2) Leaching and runoff.

The extent of each supply source is determined by using country specific data at Tier 2 level. The N_2O emissions are determined by Tier 1 analysis.

Emission factors

Default IPCC emission factors are used for calculating N_2O emissions from atmospheric depositions of ammonia and NO_x on the soil.

The IPCC default emission factor is used for calculating N_2O emissions from leaching and runoff of the nitrogen added to the soil. The emission factor concerns that part of the nitrogen that is leaching and running off, the so-called $FRAC_{leach}$. A country-specific value is applied because of the relatively high groundwater tables in the Netherlands (Velthof and Mosquera, 2011).

Activity data

Depositions of ammonia (NH_3) and nitric oxide (NO) on the soil
NH_3 emissions from synthetic fertilizer and animal manure (stables, manure storage, manure application and grazing) are quantified in the National Ammonia Emission Model (NEMA). This model uses country specific emission factors. NO emissions from application of synthetic fertilizer and animal manure and from grazing is included in the annual calculation within the framework of the Emission Registration. EMEP default emission factors are used for these calculations.

Leaching and runoff of nitrogen added to the soil
This supply source refers to nitrogen in synthetic fertilizer and animal manure, without deducting NH_3 and NO evaporation from stables, manure storage, grazing and application of manure. The annual figures showing the amount of nitrogen produced in animal manure are yearly calculated by the Working group for Uniform calculations of Manure and mineral figures (WUM) and published on www.cbs.nl.

2.5 Data related to manure treatment

Manure treatment affects the storage time of fresh manure. If manure is anaerobically treated for biogas production the storage time of the raw manure will be as short as possible to maximally utilize the biogas production potential. Treatment in a (central) treatment facility will decrease the storage time of the manure at the supplying farms. Manure treatment also affects the amount of raw manure that is used directly on agricultural land. On the other hand end products are produced that are stored and applied to soil as a fertilizer. The associated impact on emissions should be considered. Emission factors for digested manure and end products from manure processing, that are used as a fertilizer on agricultural land, should be determined. For the time being a Tier 1 approach could be used. When manure digestion will become more significant upscaling can be considered.

To quantify the impact of manure treatment on CH_4 and N_2O emissions the following activity data is required:

1. Amount of manure treated (co-digestion and other treatments)
2. Amount of end products after treatment
3. Composition (N, NH_4^+ and VS content) of end products
4. Management of end products (storage, application)

3 Evaluation of activity data

In this chapter the availability, accuracy, traceability and frequency of actualization of the required activity data will be discussed.

3.1 Amount of manure treated

Recent data on the amount of manure treated in the Netherlands are available from several sources.

1) Monitor Renewable Energy (CBS, 2011).

Quantitative data on the production of renewable energy is reported on an annual basis. Data are available on www.cbs.nl. Energy sources and calculation methodologies are described in the Protocol Monitoring Renewable Energy (AgentschapNL, 2010). Key sources of renewable energy are: wind energy, solar energy and energy from biomass. Within the source biomass co-digestion is distinguished. Co-digestion refers to production of biogas from digestion of manure together with other organic substrates. The monitor indicates that in 2009 1.5 Mton of wet biomass was digested, ample 50% (0.8 Mton) of which was manure. This was 1-2% of the manure production in the Netherlands. Data on the amount of digested manure and other organic substrates originates from an inquiry among farms in 2009 by CBS, with a 50% respons (van Bruggen, 2011b). This inquiry was carried out in favour of the monitoring of the manure market in the Netherlands in 2010 (Luesink *et al*., 2011). Lacking data were estimated from the real electricity production data from the administration of CertiQ, that provides Source Guarantee certificates for green electricity (www.certiq.nl). These certificates are required for getting a subsidy, which is essential for profitable expoitation of the production facility. Therefore, the administration of CertiQ is a reliable and complete source of information concerning the amount of electricity produced from co-digestion. Quantitative data on the amounts of manure and other substrates that are used is less accurate because they are partly based on an inquiry with 50% respons and partly calculated from electricity production data using assumptions for energy conversion efficiencies and caloric values of the substrates.

2) Evaluation of digesters in the Netherlands (Peene *et al.*, 2011)

This evaluation was based on an inquiry in 2010 among co-digestion plants which received a grant from NL Agency. Agricultural operations without input of manure were included. The respons to the inquiry was 74% (84 from 113 plants responded). The respons was qualified as representative for the complete co-digestion sector in the Netherlands, based on the 70% share of the 84 plants to the granted electricity production. The evaluation provides detailed information on the input of the co-digesters studied. The substrates were differentiated into categories of manure and organic materials. Table 1 gives an overview of the types and amounts of manure processed in the participating co-digesters. The table represents the manure input of 68 manure processing operations.

Table 1 Amounts and types of manure processed in the co-digesters of the study (Peene *et al*., 2011).

Type of manure	*Amount (ton/year)*	*Share (%)*
Pig manure	429,160	51
Cattle manure	328,168	39
Chicken manure	30,250	4
Solid fraction after separation	14,106	2
Other	40,340	5
Total	842,024	100

The amount of 842 kton is approx. 70% of the total amount of manure digested, which means that in 2010 approx. 1.2 Mton of manure was digested in the Netherlands. Manure accounted for 52% to the total digester input of 2.3 Mton, which results in an output of 2.1 Mton.

This one time evaluation provides reliable (based on 74% respons of inquiry) quantitative information on the amounts of livestock manure co-digested in the Netherlands in 2010.

3) Practical initiatives of manure treatment (Timmerman & De Buisonjé, 2010).

This inventory provides an overview of manure treatment operations in the Netherlands in 2009. Co-digestion was excluded from the inventory; operations that used digestate as raw material were included. The reported information was mainly based on an inquiry among the manure treatment operations that are recognized by the Netherlands Food and Consumer Product Safety Authority (NVMA). The treatment technology, capacity, input material, end products and destination of the end products were registered. This information could not be collected from all operations, so only minimal figures could be reported. Table 2 shows the main treatment technics, related to greenhouse gas emission, and the minimal amounts of manure treated.

Table 2 Main manure treatment technologies (co-digestion excluded) and the minimal amounts of manure treated in the Netherlands in 2009 (Timmerman & De Buisonjé, 2010).

Treatment	*Minimal amount of manure treated (ton)*	*Main type of manure*
Nitrification/denitrification	795,000	Veal calf manure
Incineration	353,000	Poultry manure
Composting/drying/pelleting	302,000	Poultry and horse manure and solid fraction
Production of mineral concentrates	253,000	Pig slurry
Solid/liquid separation	152,000	Digestate from cow manure co-digestion

Table 2 gives a valuable overview of the key manure treatment techniques used in the Netherlands in 2009 and their respective relevance. The information concerning amounts of manure treated, amounts of the end products and their destination is qualified as moderate reliable because the information is incomplete. None of the listed treatments are taken into account in determining national emissions of methane and nitrous oxide in the Netherlands today.

4) Monitor manure market 2010 (Luesink *et al.*, 2011)

This monitor pictures the manure market in the Netherlands on an annual basis. The work is carried out according a monitoring protocol which was developed in 2009 (van den Born *et al.*, 2009). The monitor provides broad information on the amount of manure that is treated and the end products from manure treatment as well as the destination of the end products. This information is based on manure transport data as registered by Dienst Regelingen (DR) and on results of additional questioning in the Landbouwtelling by CBS. The reliability of this data source is questionable (see also source 5).

5) Manure transport data from Dienst Regelingen (DR)

DR is the government department for registration of manure transport data within the framework of the Dutch manure regulations. The protocols for the registration of the amount and the N- and P-content of manure transported from one party (provider) to another party (intermediate, user) are described in the Uitvoeringsregeling meststoffenwet (Staatscourant 21 november 2005). Data of an individual transport is registered in a manure transport document (VDM) which is transferred to DR. Within this registration system the transported manure is classified by manure code. Each animal species has its manure code. The system takes account of manure management and distinguishes between solid and liquid fractions of cow and pig manure after separation. There is a manure code for compost, champost and sludge from nitrification/denitrification plants. There is no manure code for digestate; this product is registered under a ‘remark’ code. DR has a built-in check system: if a VDM is not filled in correctly (e.g. missing data) then it is sent back to the provider to be completed. ‘Remark’ codes are not checked. Each truck load of manure is weighed, sampled and analized for N and P.

Amounts and N and P content of organic material supplied from outside the farm that are used for co-digestion are registered in favour of the manure book keeping, as legally obliged. Amounts are weighed, N and P content are default values.

The database of DR holds data from individual farms which are not public. The data are aggregated into manure production statistics as published by Netherlands Statistics (CBS) on an annual basis. Aggregated data can be used for manure transport.

Data of the amount of manure transported is reliable. Data of the amount of manure separated at the farm is not directly available. If all the solid and liquid fraction is discharged from the farm then the original amount can be calculated from the amounts of solid and liquid fraction. If one of the fractions and if both fractions are partly disposed of, then this calculation can not be made. Specific information on co-substrates and end products from manure treatment can be collected by means of the Landbouwtelling by CBS.

3.2 Amount of end products

The two key sources of recent information on the amount of end products of manure treatment are the inventories discussed in section 5.1.

1) Evaluation of digesters in the Netherlands (Peene *et al.*, 2011)

This evaluation provides information on the use of the output from co-digestion (digestate). The digestate was applied as a fertilizer (55%) or was post-treated (45%). The major post-treatments were separation (by press or centrifuge) and drying. Of all end products from co-digestion 85% was applied as a fertilizer in the Netherlands and 15% was exported, mainly Germany and France. Table 3 gives the shares and the destinations of the end products from the participating co-digesters.

Table 3 Shares and distribution over destinations of the end products from the manure processing co-digesters in the study, in % (Peene *et al.*, 2011).

End product	Share of total	Distribution per end product	
		Netherlands	Export
Digestate	55	76	24
Liquid fraction	14	93	7
Solid fraction	12	92	8
Dried cake	1	100	0
Water	16	100	0
Other	2	100	0

This one time evaluation provides reliable (based on 74% respons of inquiry) data of the amounts of the end products of livestock manure co-digested in the Netherlands in 2010 and their destinations.

2) Manure transport data from Dienst Regelingen (DR)

Data on the amounts of solid and liquid fractions from manure separation transported between individual providers and the users are registered by DR. Also amounts of compost, champost and sewage sludge are registered. In section 5.1 the limitations of the information was discussed. The manure codes used in the registration system do not cover all end products from manure treatment, e.g. co-digested manure, solid fraction from separation of veal calf manure, concentrates from ultra filtration and reverse osmosis.

3.3 Composition of end products

Detailed information on the composition of end products from manure treatment is available from several sources:

1) Monitoring pilots mineral concentrates (Hoeksma *et al*., 2011)

Results of a two-year monitoring of all end products from 7 pilot plants for the production of mineral concentrates from raw pig manure and from co-digested cow and pig manure. Provides reliable data of the composition of digestate, solid fraction, liquid fraction, concentrates from ultra filtration and reverse osmosis. Table 4 shows the composition of raw digestate/slurries, solid fractions and mineral concentrates from the 7 pilot plants.

Table 4 Composition (g/kg) of input, solid fraction and mineral concentrates from 7 manure processing plants (Hoeksma *et al*., 2011).

		TS	VS	N-total	N-NH$_4$	P	K
Raw material	Digest./pig	81.8	56.9	6.92	4.32	1.66	4.48
	Pig slurry	71.5	51.3	6.23	4.18	1.59	4.16
	Sow slurry	44.8	27.9	4.00	2.69	1.09	3.40
	Digest./cow	92.1	65.8	6.78	3.83	1.33	5.34
Solid fraction	Digest./pig	290	220	11.2	5.95	7.54	4.24
	Pig slurry	296	229	13.0	5.57	7.06	3.78
	Sow slurry	214	151	9.88	3.88	6.05	3.07
	Digest./cow	260	193	10.4	3.68	4.70	4.51
Mineral conc.	Digest./pig	29.1	10.5	6.41	5.92	0.20	7.08
	Pig slurry	37.8	17.1	8.07	7.25	0.20	7.76
	Sow slurry	22.6	7.07	4.71	4.14	0.10	6.17
	Digest./cow	113	70.7	11.0	10.5	0.27	15.7

2) Mestsamenstelling in Adviesbasis Bemesting Grasland en Voedergewassen (Den Boer *et al*., 2012)

Results of analysis of manure samples collected by a certified lab in the period 2008-2011. The composition of raw manure, solid fraction and liquid fraction of all main animal species, compost and champost is provided as well as information on the composition of digested cow and pig manure and the solid and liquid fractions from these manures. Part of the information is from Schröder *et al*. (2009). Data is reliable and is annually updated.

3) Ammonia emissions from application of treated manure (Huijsmans & Mosquera, 2007)

This desk study provides an overview of the differences in composition of the end products of manure treatments as compared with the raw manure, based on literature review (Table 5).

Table 5 Composition of end products from manure treatments as compared to the raw manure (Huijsmans & Mosquera, 2007).

Treatment	End products	N-total	NH_4^+-N	DM	VS	pH
(Co-)digestion	Digestate	Variable	Higher	Lower	Lower	Higher
Nitrification/denitrification	Effluent	Lower	Lower	Lower	Lower	
	Sludge	Higher		Higher	Higher	
Incineration/gasification	Ash	Lower	Lower	Higher	Lower	
Separation	Liquid fraction	Lower	Equal/Lower	Lower	Lower	Variable
	Solid fraction	Higher	Equal/Higher	Higher	Higher	Variable
Production mineral concentrates	Solid fraction	Higher	Equal/Higher	Higher	Higher	Variable
	Min. concentrate	Higher	Higher	Lower	Lower	Variable
	Permeate	Lower	Lower	Lower	Lower	Higher
Composting	Compost	Variable	Lower	Equal/Higher	Equal/Higher	Variable
Drying and pelleting	Pellets	Higher		Higher		

3.4 Management of end products

Storage

Solid end products, e.g. solid fraction after separation, compost, are usually stored in open or semi-open storage facilities. The storage time varies from days to months, depending on the destination and season. If the product is used as a substrate for further treatment (anaerobic digestion, drying, incineration) then the storage time will be not more than a few days. If the product is applied to land as a fertilizer or soil improver then the storage time may increase to some months.

Liquid end products are obligatory stored in closed storage facilities, as they are considered as animal manure.

Application

Solid and liquid end products are obligatory applied to land in an emission poor manner. Solid products applied to arable land have to be incorporated into the soil directly after spreading. Liquid products are applied with spreading equipment that ensures minimal ammonia emission, for example injection (Groenestein *et al.*, 2011).

4 Emissions from manure treatment chain

In this chapter the main treatment processes are briefly described and the available emission data concerning the treatment processes themselves and from the entire treatment chain (i.e. including emissions from storage and application of manure products) are discussed. Emission sources related to manure treatment systems and measurement methods are elaborated in Appendix 1.

4.1 Manure treatment in the Netherlands

Manure treatment in the Netherlands and other European countries (Belgium, Denmark, Germany) mainly refers to anaerobic (co)-digestion, nitrification/denitrification, incineration, solid/liquid separation, production of mineral concentrates and pelletizing/composting/drying (see section 3.1).

4.1.1 (Co-)digestion

The main objective of (co-)digestion is to transform the easily degradable organic matter in manure and other organic substrates into biogas (mainly CO_2 and CH_4). The produced CO_2 is part of the natural short carbon cycle and is therefor not relevant for the monitoring. The digestion process is performed by specific micro-organisms under anaerobic conditions, in closed reactors. Anaerobic digestion also results in the transformation of organic nitrogen into mineral nitrogen (NH_4^+) and the degradation of volatile organic compounds (including a number of odour compounds). Generally co-substrates are added into the digestion reactor in order to increase the efficiency of the process (co-digestion). Anaerobic (co-)digestion is applied for both pig and cattle manure and results in the production of biogas and digested manure. Digested manure is stored in a closed storage facility and can be directly applied to the field or further treated, for example through separation.

4.1.2 Nitrification/denitrification

Biological treatment using the processes of nitrification and denitrification is a means to remove nitrogen from livestock manure. In the Netherlands it is applied mainly in systems for treating veal calf manure. Nitrification is the biological conversion of ammonia (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-) by autotrofic nitrifying bacteria. Denitrification is the anoxic reduction of nitrate into nitrite and nitrogen gas (N_2) by heterotrofic bacteria. Nitrite is an intermediate in both processes. Willers *et al.* (1996) measured 99% removal of total nitrogen from veal calf slurry in a continuously operated full scale treatment plant.

A new development in the removal of nitrogen is the anammox-process in which ammonia and nitrite are converted into nitrogen gas by anaerobic ammonium-oxidizing bacteria. The anammox-process has the advantage of lower oxygen requirement but higher nitrous oxide emission may be involved compared to the nitrate route.

The end products from biological treatment of veal calf manure, after settlement of treated slurry, are an effluent which is directly discharged to the sewer system, and a sludge (approx. 15% of original volume) which is land spread.

4.1.3 Incineration

Incineration of solid manure is a way to withdraw minerals from the manure market and thus creates space for the use of minerals from liquid manures. In the Netherlands today a large amount of solid poultry manure is incinerated in one plant. The exhaust air from the power plant is cleaned from volatile (nitrogen) compounds, the ash is being exported.

4.1.4 Solid/liquid separation

Manure separation is a process where soluble and not soluble particles are separated using a mechanical separation process, such as filtration or centrifugation. The purpose of the separation process is to obtain a solid and a liquid fraction which (after storage) may be further processed (for example composting of the solid fraction, production of mineral concentrates from liquid fraction) or directly applied into the field. Manure separation is applied for both pig and cattle manure. Manure separation at pig farms is usually the first step of a continuously performed treatment process. This means that the storage time of the raw pig manure is much shorter at farms with manure treatment (several days) than at farms without treatment (several months). Cattle manure is usually separated at the end of the storage period when the liquid fraction can be applied on the field, which means that manure separation at dairy farms has only little effect on the storage time of the raw manure.

4.1.5 Production of mineral concentrates

Mineral concentrates are produced in order to reuse nitrogen from animal manure as much as possible within the boundaries of the manure legislation. Nitrogen is extracted from livestock slurry in a multi-step treatment process including mechanical separation of the raw slurry into a solid and a liquid fraction, polishing of the liquid fraction by removing the remaining suspended solids using coagulation/flocculation and finally concentration of the dissolved minerals by reverse osmosis (RO) to produce a mineral concentrate and a permeate, the latter being relatively clean water.

4.1.6 Composting/drying/pelleting

Composting is a process where microorganisms transform degradable organic matter into CO_2 and water under (normally) aerobic conditions. This process results in an increase of the temperature of the stored manure to values of 50-70 $^{\circ}$C, leading to the evaporation of the produced water and the elimination of existing pathogens in the manure. The manure is usually stored in an open building, meaning that the manure will be protected against the direct influence of rain and sun, and still being in contact with outside air. Manure can either being left during the whole composting process untreated (passive composting), mechanically turned for a number of times (extensive composting), or actively aerated (intensive composting), the latter normally occurring in a closed building. Poultry (solid) manure can be directly used for composting. Liquid manure from pigs, cattle or poultry cannot be directly used for composting. By separating manure in a liquid and solid fraction, the solid fraction (dry matter of 20-35%) may be further being treated and used for composting.

4.2 Emissions

4.2.1 Co-digestion

<u>Treatment</u>

Emissions from an anaerobic digester may occur from storage of substrates, the production reactor, the biogas engine (heat and power unit) and storage of digestate. Koop *et al*. (2011) conclude from a literature review, that the methane slip during conversion in a biogas engine is the main source of methane emissions from anaerobic digestion. The overall emission of methane is estimated at 3% of the total methane production. Recent measurements on methane emissions from a small biogas engine (360 kW) in the Netherlands show a methane slip of 0.5% (van Dijk, 2012). Anaerobic digesters process animal waste under anaerobic conditions (anoxic) to produce methane gas (biogas), which can then be used to generate heat and electricity as an alternative energy source.

At the same time, the remaining manure can be used as a fertilizer. Biogas production is a very efficient way to reduce **GHG emissions**, both via production of renewable energy and through avoidance of emissions from manure management. A long digestion time should be taken into account in order to avoid emissions at storage and from soil applications afterwards (Clemens *et al.*, 2006).

Storage

Anaerobic digestion leads to the production of biogas and digested manure. Due to the digestion process, the composition of the digested manure differs from the composition of untreated manure:

- Digested manure has generally a higher mineral nitrogen content and a lower organic nitrogen content compared to untreated manure (Birkmose, 2000; Bosker & Kool, 2004; Clemens & Huschka, 2001; Clemens *et al.*, 2006; Hansen *et al.*, 2006; Kirchmann & Lundvall, 1998; Kool, 2006; Mosquera & Hol, 2007; Sommer & Husted, 1995; Sommer *et al.*, 2004b, 2006; Timmerman *et al.*, 2005b; Wulf *et al.*, 2002a,b). However, De Boer (2004) found no differences in NH_4^+-N between digested and untreated manure, and Velthof *et al.* (2002) found both an increase and a decrease in the mineral nitrogen content of co-digested manure compared to untreated manure, depending on the co-substrates used in the process.
- Results about total nitrogen content are not consistent. In some cases, no differences are observed (Birkmose, 2000; Clemens *et al.*, 2006), sometimes a higher total nitrogen content has been observed in digested manure compared to untreated manure (Hansen *et al.*, 2006; Sommer *et al.*, 2004b, 2006; Timmerman *et al.*, 2005b; Velthof *et al.*, 2002), but also lower contents have been observed (De Boer, 2004; Kool, 2006; Velthof *et al.*, 2002; Wulf *et al.*, 2002a,b) after digestion.
- The pH of manure increases after digestion (Birkmose, 2000; Clemens & Huschka, 2001; Clemens *et al.*, 2006; De Boer, 2004; Hansen *et al.*, 2006; Mosquera & Hol, 2007; Pain *et al.*, 1990a; Rubaek *et al.*, 1996; Sommer & Husted, 1995; Sommer *et al.*, 2004b, 2006; Timmerman *et al.*, 2005b; Velthof *et al.*, 2002, Wulf *et al.*, 2002a,b).
- The dry matter content of digested manure is normally lower than of untreated manure (Birkmose, 2000; Clemens *et al.*, 2006; De Boer, 2004; Hansen *et al.*, 2006; Kool, 2006; Mosquera & Hol, 2007; Pain *et al.*, 1990a; Sommer & Olesen, 1991; Sommer *et al.*, 2004b, 2006; Timmerman *et al.*, 2005b; Velthof *et al.*, 2002; Wulf *et al.*, 2002a,b). However, Sommer *et al.* (2004b) found no differences in dry matter content between digested and untreated manure, and Clemens & Hutschka (2001) reported even higher dry matter contents after digestion.

Amon *et al.* (2006) found lower CH_4 emissions from digested manure (67% reduction) but 41% higher N_2O emissions compared to untreated cattle slurry during storage. Total greenhouse gas emissions from storage of digested slurry were reduced by 59% compared to untreated manure. Clemens *et al.* (2006) reported 32-68% lower CH_4 and lower (9%) or higher (49%) N_2O emissions from digested cattle manure compared to untreated manure. Total greenhouse gas emissions were reduced by 14-48%. Sommer *et al.* (2000) also reported higher N_2O emissions (by 26%) from digested cattle slurry than from untreated cattle slurry.

		N_2O	CH_4	GHG
Clemens *et al.* (2006)	**Crust_winter**	↓ **9%**	↓ **32%**	↓ **14%**
	Crust_summer	↑ **49%**	↓ **68%**	↓ **48%**
Amon *et al.* (2006)	**Wooden lid**	↑ **41%**	↓ **67%**	↓ **59%**

Application

The results found in the literature about the effect of anaerobic digestion on the emission of NH_3 after manure application are not consistent. Due to the higher pH and NH_4^+-N in digested manure compared to untreated manure, higher NH_3 emissions are expected after manure spreading. However, the lower dry matter content (better infiltration into the soil) of digested manure would suggest just the contrary, lower NH_3 emissions from digested manure after spreading. Mosquera & Hol (2007) found in two of three field experiments higher NH_3 emissions after (narrow band) application of digested manure (compared to untreated manure) to grassland. The other experiment resulted in lower NH_3 emissions. Sommer *et al.* (2006) reported significant higher NH_3 emissions after (broadcast) application of co-digested manure compared to untreated manure. This was explained by the higher pH of digested manure. Amon *et al.* (2006) also found significant higher NH_3 emissions after the application of digested cattle manure compared to untreated cattle manure. Wulf *et al*. (2002a) also came to similar results by (narrow band) application of digested and untreated cattle manure on both grassland and arable land. The emissions were not significantly different. Rubaek *et al.* (1996) found no significant differences in NH_3 emission between co-digested manure (20% rest products with pig and cattle manure) compared to untreated manure by manure injection. (Narrow band) application of digested manure resulted in similar to lower NH_3 emissions compared to untreated manure. Clemens *et al.* (2006) found higher NH_3 emissions after (narrow band) application of digested cattle manure on grassland compared to untreated manure, although the differences were not significant. Pain *et al.* (1990a) found higher NH_3 emissions after (broadcast) application of digested pig manure on grassland compared to untreated manure. The differences were in this study also not significant.

Anaerobic digestion removes organic matter and affects infiltration of manure slurry and the content of volatile solids in the soil-slurry mixture. Reducing VS in the soil-slurry mixture reduces risk of N_2O emissions, as the lower VS content decreases microbial demand for O_2 and consequently denitrification. Some researchers have reported lower N_2O emissions from soils amended with digested slurries than from untreated slurries (Petersen, 1999; Bhandral *et al.*, 2009), but this response has not been consistent (Amon *et al.*, 2006; Clemens *et al.*, 2006; Thomsen *et al.*, 2010), suggesting that application conditions and soil properties may influence effects of digested slurries on N_2O emissions.

Clemens & Huschka (2001) and Amon *et al.* (2006) found lower N_2O emissions after the application of digested cattle manure compared to untreated manure. Wulf *et al.* (2002b) found higher N_2O emissions after the application of digested manure on grassland compared to untreated manure, although the differences were not significant. On arable land, no significant differences between digested and untreated manure were found. Clemens *et al.* (2006) found also no significant differences in N_2O emission between digested and untreated manure after (narrow band) application on grassland.

Wulf *et al.* (2002b) found, both on grassland an on arable land, lower CH_4 emissions after (narrow band) application of digested cattle manure compared to untreated manure. Amon *et al.* (2006) reported higher CH_4 emissions after application of digested cattle manure on grassland compared to untreated manure. Clemens *et al.* (2006) found no significant differences in CH_4 emission after (narrow band) application of digested cattle manure on grassland compared to untreated manure.

Pain *et al.* (1990a) measured a reduction of 70-80% in odour emissions during the first 6 hours after application of digested pig manure compared to untreated manure. Hansen *et al.* (2006) found lower concentrations from the emitting surface (17% reduction) after application of digested pig manure compared to untreated manure. Harreveld (1981) also reported lower odour concentrations for digested manure. The explanation for this reduction in odour concentration and emission is that easy degradable organic matter in digested manure is lower than in untreated manure. Besides, manure can easily infiltrate into the soil (lower dry matter content).

In Denmark's National Inventory Report (Nielsen *et al*., 2011) lower emissions of methane and nitrous oxide are used for anaerobically treated manure (slurry) compared to untreated manure. For calculating the emissions from treated slurry an emission reduction factor E_{lower} is introduced in the calculation formula:

$$CH_{4,\, treated\ slurry} = VS*B_o*MCF*0.67*E_{lower}$$

VS : amount of volatile solids as a percentage of the amount of dry matter
B_0 : maximum methane forming capacity
MCF : methane conversion factor
0.67 : conversion from m^3 to kg
E_{lower} : emission reduction factor for treated slurry compared to untreated slurry

The E_{lower} for anaerobically treated pig slurry is assumed to be 0.60 compared to untreated slurry and for cattle slurry 0.77, as reported by Sommer *et al*. (2001, in Danish). These values are based on Danish normative data for dry matter content and the share of volatile solids in the dry matter. The dry matter content and the share of volatile solids of Dutch pig and cattle slurry is different from the Danish slurries.

Denmark also uses a lower N_2O emission from anaerobically treated pig and cattle slurry compared to untreated slurry. "The lower emission is a result of an increase of the fraction of non-degradable volatile solids in the slurry after anaerobic treatment, which promotes the oxygen content in the soil. These conditions will reduce the potential risk of N_2O emission".
Denmark uses the lower N_2O emission in the calculation of the emission from manure management and not from manure application.
The reduced N_2O emission is calculated as:

$$N_2O\text{-}N_{treated\ slurry} = N_{treated\ slurry}*E_{lower}*EF_{N20}$$

$N_{treated\ slurry}$: amount of N in slurry
E_{lower} : emission reduction factor for treated slurry compared to untreated slurry
EF_{N2O} : N_2O emission factor based on IPCC default (1.25 percent)

It is assumed that the emission of N_2O from treated cattle slurry is 64% of the emission from untreated slurry and 60% for pig slurry.

4.2.2 Nitrification/denitrification

Treatment
By complete nitrification/denitrification, mineral nitrogen is transformed into N_2, resulting in low NH_3 and N_2O emissions. Willers *et al*. (1996) measured losses of 0.1-0.2% as ammonia and 9% as nitrous oxide of the nitrogen load, from a continuous operated veal calf slurry treatment plant with a processing capacity of 180,000 tons per year. By incomplete nitrification and/or denitrification higher NH_3 and N_2O emissions may be expected. The anammox process is not practiced in veal calf slurry treatment at the moment.

Storage/application
There is no information available on the emission of greenhouse gases during storage and after application of the sludge.

4.2.3 Incineration

Incineration of manure leads to the transformation of nitrogen components into N_2 and NO_x. However, by incomplete incineration N_2O and NH_3 may be produced instead. In the plant of BMC in Moerdijk, where in 2010 365,000 tons of solid poultry manure was incinerated, the process is operated in a closed building. The exhaust gasses and ventilation air is scrubbed. No measurement data are available to quantify remaining emissions. Permit documents of the plant indicate that 140 ton NO_x and 10 ton NH_3 are expected. Composting/drying/pelleting

Composting

Treatment and storage

Composting changes the composition of the stored manure:

- In general, dry matter content increases during composting (Fukumoto *et al.*, 2003; Rudrum, 2005; Szanto *et al.*, 2007). However, Rao *et al.* (2007) found no significant differences in dry matter content between untreated and composted manure, and Thorman *et al.* (2007) found even lower dry matter content in composted manure compared to the original raw manure.
- Mineral nitrogen content decreases during composting (Eghball & Power, 1999; Fukumoto *et al.*, 2003; Larney *et al.*, 2006; Rudrum, 2005; Szanto *et al.*, 2007, Thorman *et al.*, 2007; Van Dooren *et al.*, 2005).
- For total nitrogen content, results are not consistent. Eghball & Power (1999), Larney *et al.* (2006), Rao *et al.* (2007), Szanto *et al.* (2007) and Thorman *et al.* (2007) found lower total nitrogen content after composting. Fukumoto *et al.* (2003), Rudrum (2005) and Van Dooren *et al.* (2005) found higher total nitrogen contents after composting.
- For pH, results are also not consistent. Rudrum (2005) and Thorman *et al.* (2007) found higher pH values after composting, Szanto *et al.* (2007) found no significant differences in pH between composted and raw manure, and Fukumoto *et al.* (2003) and Thorman *et al.* (2007) reported higher pH values after composting.

In the initial thermophilic phase of composting deep litter, production of N_2O is low (Czepiel *et al,* 1996; Pedersen *et al*, 1998; Sommer, 2001) because N_2O producing nitrifying and denitrifying microorganisms are generally not thermophilic (Hellmann *et al*, 1997). After the thermophilic phase, N_2O production increases with N_2O production rates being substantial during the following low temperature period.

N_2O emissions range between 0.1 and 7% of the initial N in the manure (Czepiel *et al*., 1996; Fukumoto *et al*., 2003; Hao *et al*., 2001; Kuroda *et al*., 1996; Veeken *et al*., 2002). Increasing the aeration rate will reduce N_2O emissions, but may result in even higher NH_3 emissions. Turning up the manure will result not only in higher NH_3 emissions, but also higher N_2O emissions (nitrate in the surface of the manure heap transported to more anaerobic places inside the manure heap). Bigger compost heaps result in higher N_2O emissions, due to the presence of more anaerobic sites inside the heap where denitrification may occur.

N_2O emissions from solid livestock manure heaps conventionally stored (passive composting) range between 0.0-4.8% (average: 3.0%) of the initial N in the manure for pig manure (Dinuccio *et al.*, 2008; Hansen *et al.*, 2006; Thorman *et al.*, 2007), between 0.0-4.3% (average: 1.0%) of the initial N in the manure for cattle manure (Amon *et al.*, 2001; Chadwick, 2005; Dinuccio *et al.*, 2008; Fangueiro *et al.*, 2008; Hao *et al.*, 2001; Thorman *et al.*, 2007; Yamulki, 2006), and between 0.2-0.8% (average: 0.5%) of the initial N in the manure for poultry manure (Thorman *et al.*, 2006).

CH_4 emissions from solid livestock manure heaps conventionally stored (passive composting) range between 0.6-1.3% (average: 0.9%) of the initial C in the manure for pig manure (Dinuccio *et al.,* 2008; Hansen *et al.,* 2006), and between 0.0-9.7% (average: 1.6%) of the initial C in the manure for cattle manure (Amon *et al.*, 2001; Chadwick, 2005; Dinuccio *et al.*, 2008; Fangueiro *et al.*, 2008; Yamulki, 2006).

Aerating manure allows microorganisms to break down organic material through the addition of oxygen. Aerobic decomposition of manure lowers or eliminates methane emissions, but may increase nitrous oxide emissions. Amon *et al.* (2001) reported a reduction of 7-78% in greenhouse gas emissions after forced aeration and turning of cattle farm yard manure being composted, compared to passive composting. Pattey *et al.* (2005) reported higher N_2O emissions (by 44%), lower CH_4 emissions (by 81%), and a reduction in total greenhouse gas emissions (by 34%) by aerating storage containers compared to stockpile (conventional) stores. Hao *et al.* (2001) reported a reduction in CH_4 emissions (by 29%) after active composting (farm yard manure) relative to passive composting. Lopez-Real and Baptista (1996) also found that forced aeration and turned windrows were effective composting procedures and substantially reduced CH_4 emissions compared with static stockpiles.

		N_2O	**CH_4**	**GHG**
Amon *et al.* (2001)	**Summer**	↓ **35%**	↓ **90%**	↓ **78%**
	Winter	↓ **41%**	↑ **32%**	↓ **7%**
Hao *et al.* (2001)		↑ **73%**	↑ **29%**	↑ **36%**
Lopez-Real and Baptista (1996)			↓	

Drying and pelleting

During the drying process it is expected that NH_3 and N_2O may be formed, due to the aerobic conditions associated to this process. The produced (granulated) manure after pelleting has a high dry matter content (>90%) and is generally used outside agriculture, or exported (after hygienization). There is no information available to quantify the emissions after drying and pelleting.

4.2.4 Production of mineral concentrates

Treatment

In the production of mineral concentrates three main treatment technologies are involved: solid/liquid separation, flotation/microfiltration and reverse osmosis. Emissions during the solid/liquid separation process will be discussed in section 4.2.6, as well as emissions during storage and application of the solid fraction. Emissions from air flotation are not available. Emissions from microfiltration and reverse osmosis are zero, since the processes are performed in closed units. Emissions from the permeate of reverse osmosis is negligible since it is directly discharged into the sewer system or discharged at the surface water.

Storage

No reliable data are available on the emission of methane and nitrous oxide from the storage of mineral concentrate. Mosquera *et al*. (2010) could not present quantitative data from exploratory measurements at two treatment plants. From these measurements De Vries *et al.* (2012) derived for storage of mineral concentrate an emission factor for nitrous oxide of 0.014% of the total N. Greenhouse gas emissions related to the production of mineral concentrates are to be expected mainly from storage of raw material and solid end products.

Application

Data on greenhouse gas emissions after application of mineral concentrates are limited to results from laboratory experiments. In a laboratory experiment Velthof & Hummelink (2011) applied mineral concentrate to grass and arable crop. From their measurements the following emission factors for nitrous oxide were derived: 0.6% for grassland and 1.95% for arable land.

4.2.5 Solid/liquid separation

Treatment

Manure separation takes place in a closed unit, therefore emissions during the separation process are considered to be negligible compared to storage of untreated manure. Emissions related to solid/liquid separation are from (open) storage of the solid fraction. Melse & Verdoes (2005) measured emissions of methane and nitrous oxide from pig slurry treatment systems which included solid/liquid separation. Emissions from slurry separation sec were not measured.

Storage

Manure separation results in a solid and liquid fraction which are stored before being further treated or applied into the field. The separation process results in a change in manure composition for both fractions compared to the raw manure, this means that emissions from the storage of both fractions should be included in the measurement protocol:

- In general, the solid fraction has a higher dry matter, organic matter and phosphate content than the raw manure (Buiter, 2004; Derikx, 1995; Kool *et al.*, 2006; Mattila & Joki-Tokola, 2003; Pain *et al.*, 1990b; Schepers, 1995; Schröder *et al.*, 2007; Have & Schellekens, 1994; Timmerman *et al.*, 2005a; Verlinden, 2005).
- The liquid (solid) fraction has a lower (higher) total nitrogen content compared to the raw manure (Buiter, 2004; Derikx, 1995; Mattila & Joki-Tokola, 2003; Pain *et al.*, 1990b; Timmerman *et al.*, 2005a; Verlinden, 2005; Versluis *et al.*, 2005).
- The mineral nitrogen content in the liquid (solid) fraction is similar or lower (higher) than the mineral nitrogen content in the raw manure (Buiter, 2004; Derikx, 1995; Kool *et al.*, 2006; Mattila & Joki-Tokola, 2003; Pain *et al.*, 1990b; Schepers, 1995; Schröder *et al.*, 2007; Have & Schellekens, 1994; Timmerman *et al.*, 2005a; Verlinden, 2005; Versluis *et al.*, 2005).
- Differences in pH between the raw manure and the solid and liquid fractions are not consistent: sometimes the pH is higher, but in other cases lower after manure separation.

Storage of the liquid fraction can lead to even lower N_2O emission relative to untreated slurry, but overall, slurry separation results in a marked increase in N_2O emissions during storage of the different fractions, because of the large emissions from the stored solid fraction. Fangueiro *et al.* (2008) showed that, compared to whole slurry, separation of cattle slurry into liquid and solid fractions reduced CH_4 emissions by 35%, but increased N_2O emissions by a factor 12. Total greenhouse gas emissions were reduced by 23%. Amon *et al.* (2006) found that separate storage of the liquid fraction and composting of the solid fraction resulted in a reduction in CH_4 emissions by 42%, and an increase in N_2O emissions by 10%. Total greenhouse gas emissions were decreased by 39%. Martinez *et al.* (2003) reported 18-40% lower CH_4 emissions from separated pig slurry. However, Dinuccio *et al*. (2008) reported either a small 3-4% increase or a small 8-9% decrease in CH_4 emissions during storage of separated slurry depending on temperature and slurry type (pig or cattle). Mosquera *et al.* (2010) reported 29% lower greenhouse gas emissions from separated pig slurry, but 25% higher greenhouse gas emissions from separated cattle slurry.

		N_2O	CH_4	GHG
Dinuccio *et al.* (2008)	**Pig slurry (5 ºC)**	**---**	↓	↓ **8%**
	Pig slurry (25 ºC)	↑	↑	↑ **41%**
	Cattle slurry (5 ºC)	**---**	↑	↑ **4%**
	Cattle slurry (25 ºC)	**---**	↓	↓ **9%**
Fangueiro *et al.* (2008)	**Cattle slurry**	↑	↓	↓ **23%**
Amon *et al.* (2006)	**Cattle slurry + wooden lid**	↑	↓	↓ **39%**
Mosquera *et al.* (2011)	**Pig slurry**	↑	↓	↓ **29%**
	Cattle slurry	↑	↓	↑ **25%**
Martinez *et al.* (2003)	**Pig slurry**		↓	↓ **18%**
	Cattle slurry		↓	↓ **40%**

Application

Due to the low total nitrogen content and similar or lower mineral nitrogen content in the liquid fraction compared to the raw manure, it is likely that less nitrogen is available to be emitted. Besides, the lower dry matter content of the liquid fraction makes it easier for the liquid fraction to infiltrate into the soil. All this will lead to lower NH_3 emissions after manure application into the field. Amon *et al.* (2006) found (significant) lower NH_3 emissions after the application of the liquid fraction of dairy cattle compared to untreated manure. Sommer *et al.* (2006) also reported significant lower NH_3 emissions after the application (broadcasting) of the liquid fraction of co-digested pig manure compared to untreated (no separation, no digestion) manure. This was explained by the higher infiltration (lower dry matter content) of the liquid fraction. However, the NH_3 emissions reported in Mattila & Joki-Tokola (2003) after the application (broadcasting) of the liquid fraction of dairy cattle manure were comparable to those from untreated manure. Pain *et al.* (1990b) found higher NH_3 emissions after the application of the liquid fraction of pig manure compared to untreated manure, although the differences were not significant. If the solid fraction of manure is not incorporated into the soil after being applied, all the available mineral nitrogen will be emitted. When both the liquid and solid fractions are applied using low ammonia emission application techniques, no difference in total emission between the application of the raw manure or the application of the fractions is expected.

Amon *et al.* (2006) found higher CH_4 en N_2O emissions after the application of the liquid fraction of dairy cattle manure compared to the raw (untreated) manure.

Hansen *et al.* (2006) found a reduction of 50% in odour concentration (above the emitting surface) measured after the application of the liquid fraction of digested pig manure compared to untreated pig manure. Pain *et al.* (1990b) found a reduction of 26% in odour emission after the application on grassland of the liquid fraction of pig manure compared to untreated manure.

4.3 Quality of activity data and emission factors for manure treatment chain

4.3.1 Activity data

Table 6 gives an overview of the main treatment technologies in the Netherlands with the actual amounts of manure involved and the expected amounts in 2015. The table also gives the relevant greenhouse gasses during the treatment process.

Table 6 Main manure treatment technologies, actual and expected amounts of manure treated in 2015 and relevant greenhouse gasses during treatment only.

Treatment	*Main type of manure*	*Actual amount of manure treated (ton)*	*Expected amount of manure treated in 2015 (ton)**	*Relevant GHG during treatment*	
				CH_4	*N_2O*
Anaerobic digestion	Pig and cattle manure	1 200 000	3 000 000	v	
Nitrification/denitrification	Veal calf manure	795 000	795 000		v
Incineration	Poultry manure	353 000	400 000		v
Composting/drying/pelleting	Poultry and horse manure and solid fraction	302 000	405 000	v	v
Production of mineral concentrates					
Flotation	Pig manure	200 000	850 000		
Ultra filtration	Pig manure	50 000	95 000		
Solid/liquid separation	Digestate from anaerobic digestion	152 000	2 700 000		
	Cattle manure	n.a.	500 000		

* Assumptions:

- 30% of manure surplus is treated in 2015, forced by law
- All treated manure is (co)digested
- All digestate is mechanically solid/liquid separated
- Dairy farms solve their manure problem (P surplus) by solid/liquid separation
- All solid fraction is dried and pelletized
- All liquid fraction is treated to produce mineral concentrates, which are used as substitutes for chemical fertilizer
- Amount of manure that is biologically treated (nitrification/denitrification) does not change
- Amount of manure that is incinerated increases up to available capacity

Table 7 shows the availability and reliability of activity data for the *whole manure chain* which comprises manure treatment as one of the links.

Tabel 7 Availability and reliability of activity data for the whole manure chain comprising selected manure treatment technologies.

Treatment, as part of manure chain	*Activity data*			
	Amount		*Composition*	
	Availability	*Reliability*	*Availability*	*Reliability*
Anaerobic digestion	-	-	-	-
Nitrification/denitrification	+	+	+	+
Incineration	+	+	+	+
Composting/drying/pelleting	-	-	-	-
Production of mineral concentrates				
Flotation	+	-	+	-
Ultra filtration	+	-	+	-
Solid/liquid separation	-	-	-	-

4.3.2 Emission factors

Measurements

One way to establish emission factors is to directly use emission values that were measured. The results of these measurements were described in section 4.2 for the succeeding steps of the manure treatment chain, including storage, treatment and application of manure products. The emissions that were measured in past research, however, show a large variation.

Modelling

Another approach to estimate emissions from the entire manure chain is to model the total emission by using average emission factors for each link of the chain. This approach was chosen in a study by Croezen *et al.* (2003) that was commissioned by Novem. In this study the whole manure chain was described as a number of sequential unit operations, each unit operation having its own conversion or production factor for CO_2, CH_4 and N_2O. Based on the amount of manure and its composition in this way the total greenhouse gas emission can be calculated for the whole chain. Croezen *et al.* (2003) not only described this model but also published a spreadsheet (Visual Basic model embedded in MS Excel) to do the model calculations. The emission factors used in the model were based on literature (as far as available) and expert judgement; in some cases the emission factors were derived by analogy with known emissions and biological processes in other fields of study or known emissions from treatment of other organic materials. A validation or sensivity analysis of the model has not been carried out yet.

5 Discussion and conclusions

For taking up the effects of manure treatment on greenhouse gas emissions in the National Inventory Report reliable values of the amount treated manure, values of the amounts and composition of the end products and values of the emission factors for the treatment process, storage of the end products and application of the end products have to be available. From this study it becomes clear that the required information is only partly available today.

It is expected that manure treatment in the Netherlands will take place at local, regional and central scale. Regional and central treatment means that manure from a number of farms is treated in one processing plant. Different end products are produced. When looking at the expected main treatments of the main categories of manure the picture is as follows:

Manure category	Treatment	Scale	End products
Pig	Production of mineral concentrates	Regional	Dry organic fertilizer Mineral fertilizer
Cattle	Solid/liquid separation	Farm	Dry organic fertilizer Liquid fraction
Poultry	Composting Incineration	Regional Central	Dry organic fertilizer Ash

Data on the amounts of treated manure is not complete. Several sources provide more or less reliable information. The Administration of CertiQ provides reliable data of the amount of manure and co-products that are used in co-digestion. The registrations of Dienst Regelingen provide reliable data of the amount of manure that is delivered to regional and central treatment plants. Lacking data can be generated by means of specific questioning by CBS in Landbouwtelling (all data from the Landbouwtelling are registered by DR).

In the future, when manure treatment is forced by legislation, it would be sensible to introduce an accreditation system for treatment plants, with requirements on the quantity and quality of the input and output of the plants.

A structural data source would be the registration system within the context of the Manure legislation, as used by Dienst Regelingen. All manure transactions are recorded, providing data on amount and N and P content of individual truck loads of manure. The type of manure is identified by manure code. Today over 50 manure codes are used. Codes for end products of manure treatment can be introduced.

Information on the composition of end products from manure treatment is considered to be accurate enough to make the calculations of emissions in accordance with the Guidelines of UNFCCC.

Emission factors for the manure treatment chain are not sufficiently available. As can be seen in chapter 4, the emissions that were measured in past research show a large variation. Apparently process conditions and manure composition differ to such an extent that it is very difficult, if not impossible, to define general emission factors. The wide variation in process conditions and manure composition would require a detailed description of each possible manure treatment chain, with each chain having its own emission factor. The question is whether such a framework is desired or practical. Furthermore, such an approach would require a extensive measurement program as emission factors have to be established for each specific chain approach and process and manure conditions (manure type, temperature, pH etc.).

Besides determining emission factors for manure treatment by new measurements, it might be a more suitable approach to estimate emissions from the entire manure chain by using a model. As described in section 4.3.2, in 2003 a tool was developed to estimate greenhouse gas emissions from the manure treament chain (Croezen *et al*., 2003). This tool might be used to establish an emission factors for manure treatment within the NIR framework, as the model is able to calculate the increase or decrease of greenhouse gas emissions for each manure treatment technology, as compared with a manure chain without treatment step. As mentioned before, the emission factors used in the model were based on literature (as far as available), onexpert judgement, and on knowledge about biological processes or known emissions from treatment of other organic materials. The model was not validated and no sensivity analysis was carried out, however. If the use of this model is being considered as a suitable approach for establishing emission factors for the NIR framwork, the conversion and emission factors used in the model should be validated.

In orde to validate the model the first task would be to define different cases, based on the activity data (manure composition, amount and treatment technique) as they are foreseen for 2015. Next, these cases could be used as input for the model and generate calculated emission factors for each manure treatment chain and each link of the chain. Then a sensivity analysis of the model could be carried out for each modelled case. This would provide insight in the sensivity of the emission and conversion factors that are used in the model for each case. Based on these results, a number of emission and conversion factors can be distinguished having the largest impact on the total emission of the whole chain. Finally a measurement program could be defined in order to increase the quality of these factors. Such a program might include the measurement of emissions from agricultural soils after use of end products from manure treatment (digestate, solid fraction, liquid fraction, mineral concentrate, compost) and measurements of the emissions from specific manure treatment steps.

Without going through the sensivity analysis of the model first, currently it is not possible to define such a measurement program in more detail or to estimate the costs of such a program.

If the emissions from treated manure are lower than from untreated manure, as is expected for methane and nitrous oxide emissions from anaerobically treated manure, then the lower emissions should be subtracted from the emissions. The IPPC Guidelines however, do not provide a description how to include anaerobically treated manure in the NIR. Denmark uses a calculation model for emissions from digested slurry using lower emission factors for methane and nitrous oxide for anaerobically treated cattle and pig slurry compared to untreated slurry (Nielsen *et al*., 2011). The Danish model could (temporarily) be adopted by the Netherlands, on the condition that values for the DM and VS content of the raw slurry and treated slurry and the methane conversion factor (MCF) correspond with the Dutch situation.

In Denmark normative values for DM and VS in anaerobically treated cattle and pig slurry are used. In the Netherlands such values are not available. The Danish calculation is based on a VS share of 80% of the DM for both treated cattle and pig slurry. In Dutch untreated cattle and pig slurry the share of VS is 75% for cattle slurry and 65% for pig slurry. In anaerobically treated slurry the share of VS is even lower. Denmark uses a MCF of 10%, whereas the Netherlands uses a MCF <10%.

The next table shows Danish and Dutch normative and estimated values for DM, VS, total-N and NH_4-N in anaerobically treated and untreated cattle and pig slurry.

	Denmark						Netherlands					
	Untreated			Treated			Untreated			Treated*		
	DM g/kg	VS %	MCF %	DM g/kg	VS %	MCF %	DM g/kg	VS %	MCF %	DM g/kg	VS %	MCF %
Cattle	na	80	10	103	80	10	86	75	<10	64	66	<10
Pig	na	80	10	61	80	10	90	65	<10	69	57	<10

∗ Estimated

Gemany, the European country with the largest number of co-digesters, does not take the effect of anaerobic treatment into account in the National Inventory Report. It is not clear why.

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Appendix 1

Emission sources and measurement methods for greenhouse gasses from manure treatment processes

1 Emission sources

The selection of an adequate measurement method for the measurement of the emissions of greenhouse gases from a manure treatment installation depends on a number of parameters, including:

- the way manure is being stored before being treated;
- whether the manure treatment process occurs in the open air or in a building;
- the way the products of the manure treatment process are being stored/treated.

Because each emission source has unique characteristics, the selection of the measurement equipment and the representativeness of the measurements will also differ for different sources. Five different situations can be considered when looking at the way manure (raw manure, final products after manure treatment, eventually co-products used during the manure treatment process) is being stored:

1. Manure treatment occurs in a completely closed system.
2. Manure storage/treatment occurs in a mechanically ventilated building.
3. Manure storage/treatment occurs in a naturally ventilated building, where inlets and outlets are easily identified.
4. Manure storage/treatment occurs in a naturally ventilated building with no clear in- and outlets.
5. Manure storage/treatment occurs in the open air.

1.1 Closed system

The main characteristics of a closed system is that the main products of the manure treatment process are being transported through controlled and closed pipes, and therefore has (in principle) no emission sources.

In some situations, for example in a fermentation reactor used for anaerobic digestion of manure, emissions of methane may occur due to for example leakages, or through the installed safety overpressure valves. Leakages should be identified and prevented in order to increase the efficiency of the biogas production process, and should therefore not be a source of emissions. Methane emissions from digester reactors through leakage is less than 1 promille of the mehane production (Koop *et al*., 2011). Overpressure valves are necessary, and therefore a source of incidental uncontrolled emissions. Since these valves are usually placed in ventilation ducts, emissions could be easily determined by 1) installing a measuring fan to measure the ventilation rate during these uncontrolled emissions, and 2) by measuring/estimating the concentrations of the gas escaping the treatment unit.

1.2 Mechanically ventilated building

In mechanically ventilated buildings it is assumed that the air in the building is mixed good and leaves the building via the installed ventilation fans. The emission of greenhouse gases (CH_4, N_2O) can therefore be determined by measuring the ventilation rate and the concentrations outside (background) and inside the building (at the ventilation shafts).

1.3 Naturally ventilated building with clearly defined in- and outlets

In naturally ventilated buildings with small and clearly defined inlet openings it is also assumed that the air in the animal house is mixed good. Emissions of greenhouse gases (CH_4, N_2O) can be determined by calculating the ventilation rate and measuring the greenhouse gas concentrations outside (background) and inside the building (in the outgoing air).

1.4 Naturally ventilated building with undefined in- and outlets

In naturally ventilated buildings with large and not clearly defined in- and outlet openings it is not possible to assume that the air in the building is mixed good. This makes it difficult to take representative air samples in the building, and measurements should therefore be performed outside the building. Besides, emissions are not directly measured, but determined by using calculation methods (see section calculation methods).

1.5 Open air

Different methods have been applied both in the Netherlands and elsewhere to determine greenhouse gas emissions from outside manure storage facilities. These include enclosure techniques, micrometeorological techniques, tracer gas ratio methods and dispersion modeling (see section calculation methods).

2 Emission measurements

2.1 Measurement strategy

The measurement strategy applied in the Netherlands to measure emissions from animal houses takes into account the existing variation within and between farm locations with the same housing system, and variations in the measurement method used to perform the measurements. For animal houses the following measuring strategy is being adopted: six measurements spread over a year, on four different farm locations, with a minimum duration of 24 hours per measurement for NH_3, CH_4, N_2O and fine dust and of 2 hours (between 10:00 and 12:00) for odour. Since little information is available for emissions from manure treatment installations, it is advised to start using a similar measurement protocol as for animal houses. Emissions from manure treatment installations with the same manure treatment system may differ due to differences in amount and composition of the manure (and eventually co-products) being treated. The emission of an individual installation may also vary in time, especially under the influence of the weather conditions. And the variation in measurement method due to inaccuracies of the measuring equipment will also play a role as for animal houses. This strategy may be adjusted if available measurement data show that the variation is larger/smaller than the one found in animal houses. Is the variation smaller, then a less extensive measurement strategy might be enough to provide an accurate emission factor for a particular manure treatment system.

The stability of the treatment process may also affect the emissions from processes such as for example anaerobic digestion, manure drying or forced aeration. It is therefore included in the measurement strategy as prerequisite that the processing unit should be proven stable, i.e. with constant process parameters, over a period of at least 14 days prior to the measurements.

2.2 Measurement methods

An extended review of the different existing methods for measuring concentrations, ventilation rate (in animal houses) and emissions can be found in literature (Arogo *et al*., 2001; Hofschreuder *et al*., 2003; McGinn, 2006; Mosquera *et al*., 2002; Mosquera *et al*., 2005a; Neftel *et al*., 2006; Ni and Heber, 2001, Phillips *et al*., 2000; Van 't Klooster *et al.*, 1994).

Concentration measurements

Methane (CH_4) and nitrous oxide (N_2O) concentrations are measured by using gas chromatography. For CH_4 a Flame Ionization Detector (FID) is commonly used, and for N_2O the Electron Capture Detector (ECD). Gas chromatography has been used to measure CH_4 and N_2O concentrations in animal houses (Groenestein and Huis in 't Veld, 1994; Groenestein and Reitsma, 1993; Groenestein and Van Faassen, 1996; Guiziou and Béline, 2005; Huis in 't Veld and Monteny, 2003; Kaharabata *et al.*, 2000; Marik and Levin, 1996; Monteny *et al*., 2005; (Mosquera *et al.*, 2005a; Osada *et al*., 1998; Stout and Richard, 2003) and outside (manure storages, manure application into the field, grazing; Amon *et al.*, 2006; Chadwick, 2005; Clemens *et al.*, 2006; Hargreaves *et al*., 1996; Skiba *et al*., 2006; Sneath *et al.*, 1997; Thorman *et al*., 2006; Yamulki, 2006).

Besides gas chromatography, spectroscopic methods (Laser spectroscopy, Fourier Transform InfraRed (FTIR), Photoacoustic Spectroscopy, Differential Optical Absorption Spectroscopy (DOAS)) are also applied to measure greenhouse gas concentrations in animal houses (Amon *et al.*, 2001; Guiziou and Béline, 2005; Haeussermann *et al.,* 2006; Jungbluth *et al*., 2001; Kinsman *et al.*, 1995; Nicks *et al.*, 2003; Osada *et al*., 1998; Snell *et al*., 2003; Zhang *et al*., 2005) and outside (manure storages, manure application into the field, grazing; Amon *et al*., 2006; Brown *et al*., 2002; Clemens *et al*., 2006; Coates *et al.*, 2004; Ellis *et al*., 2001; Hargreaves *et al*., 1996; Harper *et al.*, 1999; Hellebrand and Kalk, 2001; Hensen *et al*., 2006; Monteny *et al*., 2005; Skiba *et al*., 2006; Thorman *et al*., 2006).

Ventilation rate measurements

Ventilation rate measurements are only applied in mechanically ventilated buildings or in naturally ventilated buildings with small and clearly defined inlet openings. Three methods are commonly used:

- Fan-wheel anemometers, placed under the ventilator and covering the whole ventilation shaft area. These anemometers are calibrated in a wind tunnel, resulting in a regression curve relating the frequency of the fan (pulses per minute) and the ventilation rate. This method is usually applied in mechanically ventilated animal houses (Amon *et al*., 2001; Blanes and Pedersen, 2005; Groenestein and Huis in 't Veld, 1994; Groenestein and Reitsma, 1993; Groenestein and Van Faassen, 1996; Haeussermann *et al*., 2006; Kinsman *et al*., 1995; Li *et al*., 2004; Nicks *et al*., 2003; Osada *et al.*, 1998; Xin *et al*., 2006).
- Internal tracer gas ratio method. In this method, a tracer gas is introduced in the animal house at a constant rate. The second step is to measure the greenhouse gas concentrations and the concentration of the tracer gas at a place inside the animal house where a representative sample can be obtained. The most commonly used tracer gas is sulphur hexafluoride (SF_6), although other tracers are known (Greatorex, 2000). This method has been applied in naturally ventilated animal houses with small inlet openings (Huis in 't Veld and Monteny, 2003; Monteny *et al*., 2005; Mosquera *et al*., 2005a; Snell *et al*., 2003; Stout and Richard, 2003; Zhang *et al.*, 2005), but also in mechanically ventilated animal houses (Kaharabata *et al*., 2000; Marik and Levin, 1996).
- CO_2 mass balance method. The CO_2 mass balance method is also an internal tracer gas ratio method. However, in this method a naturally produce tracer (CO_2) is used in combination with determined calculation methods (CIGR, 2002; Pedersen *et al.*, 2008). This method has been applied in naturally ventilated animal houses with small inlet openings (Van 't Klooster en Heitlager , 1994; Zhang *et al*., 2005), but also in mechanically ventilated animal houses (Blanes and Pedersen, 2005; Li *et al.*, 2004; Pedersen *et al.*, 1998; Xin *et al*., 2006).

Calculation methods

In mechanically ventilated buildings and naturally ventilated buildings with small inlet openings, greenhouse gas emissions are determined by multiplying the ventilation rate and the difference in concentration between the air leaving the building and the background concentration (Amon *et al*., 2001; Groenestein and Huis in 't Veld, 1994; Groenestein and Reitsma, 1993; Groenestein and Van Faassen, 1996; Guiziou and Béline, 2005; Haeussermann *et al.*, 2006; Huis in 't Veld and Monteny, 2003; Jungbluth *et al*., 2001; Kinsman *et al.*, 1995; Marik and Levin, 1996; Monteny *et al*., 2005; Mosquera *et al.*, 2005a; Nicks *et al*., 2003; Osada *et al.*, 1998; Snell *et al*., 2003; Zhang *et al*., 2005).

In naturally ventilated buildings with large inlet openings it is not possible to determine directly the ventilation rate, and calculation methods have to be applied. These include:

- External tracer gas ratio method (Dore *et al.*, 2004; Kaharabata *et al.*, 2000; Mosquera *et al.*, 2002; Mosquera *et al.*, 2005a; Scholtens *et al.*, 2004; Singh *et al.*, 2003; Skiba *et al.*, 2006; Sneath *et al.*, 1997; Sonneveld *et al.*, 2008; Stout and Richard, 2003). In this method, a tracer gas is introduced in the animal house at a constant rate, and the greenhouse gas concentrations and the concentration of the tracer gas are measured outside the animal house. The emission is then calculated by using the ratio between the measured concentrations (greenhouse gases vs. tracer gas) and the injection rate of the tracer gas. Tracer gas methods have also been used for direct measurement of CH_4 from ruminant livestock and manure storages (Soussana *et al.*, 2007).
- Integrated horizontal flux method (Brown *et al.*, 2002; Harper *et al.*, 1999; Laubach and Kelliher, 2005, 2004; Mosquera *et al.*, 2002; Mosquera *et al.*, 2005a; Sommer *et al.*, 2004a). This method uses the principle of measuring all input and output gas emissions within a “control volume” defined around a source. Greenhouse gas emissions are calculated as the difference between the horizontal fluxes through the vertical planes upwind and downwind the animal house.
- Dispersion modelling, including Gauss plume models (Czepiel *et al.*, 1996; Erbrink, 1995; Fritz *et al.*, 2005; Hensen *et al.*, 2006; Hensen and Scharff, 2001; Jaarsveld, 1995; Scharff and Hensen, 1999; Skiba *et al.*, 2006) and the backwards Lagrangian Stochastic (bLS) model (Flesch, 1995; Flesch *et al.*, 2004; Flesch *et al.*, 1995; Laubach and Kelliher, 2005, 2004; Sommer *et al.*, 2004a).

Greenhouse gas emissions from manure storage, after the application of manure or in grazed fields, can be measured by using enclosure techniques (flux chambers) and micrometeorological techniques. There are various designs of chambers: static and dynamic (open or closed) chambers and tunnels. There is little uniformity in design of the chambers. In the simplest configuration, static chambers are open-bottom cylinders or boxes placed on the soil in fields for a period of time, during which gases emitted from the soil accumulate within the enclosed headspace. Static chambers can be operated manually or automatically with on- or off-line measurements (Neftel *et al.*, 2006). In dynamic chamber measurements, the chamber is flushed with ambient air and the gas flux is calculated from the concentration difference between incoming and outgoing air. Chambers covers only a small field area. Chamber methods have been applied to measure greenhouse gas emission from manure storages (Amon *et al.*, 2006; Chadwick, 2005; Clemens *et al.*, 2006; Fukumoto *et al.*, 2003; Hellebrand and Kalk, 2001; Hensen *et al.*, 2006; Park *et al.*, 2010; Thorman *et al.*, 2006; Yamulki, 2006), after the application of manure into land (Amon *et al.*, 2006; Clemens *et al.*, 2006; Flechard *et al.*, 2007; Glatzel and Stahr, 2001; Hansen *et al.*, 1993; Mosier *et al.*, 1991; Mosier *et al.*, 1997; Mosquera *et al.*, 2005b, c; Mosquera *et al.*, 2007; Skiba *et al.*, 2006; Soussana *et al.*, 2007; Thorman *et al.*, 2006; Van den Pol-van Dasselaar, 1998; Velthof *et al.*, 2010), or from outdoor yards/grazing (Ellis *et al.*, 2001; Misselbrook *et al.*, 2001; Webb *et al.*, 2001).

Micrometeorological techniques measure the turbulent transfer of gases from the ground surface to the lower atmosphere. Sensors mounted on towers detect the movement and gas content of air. These techniques are used to determining field-scale fluxes, and include mass balance (Integrated Horizontal Flux, as described above), vertical flux (flux-gradient technique (FG), eddy covariance (EC), and modelling (Gauss plume model, backwards Lagrangian Stochastic (bLS) model, as described above). Vertical flux techniques measure the vertical flux of gas above the ground. Fluxes are typically measured for field areas as large as 1-10 km^2. Among the micrometeorological approaches, the eddy covariance or eddy correlation technique is the most direct one for flux-measurement (Neftel *et al.*, 2006). Some examples of the use of micrometeorological techniques are: at herd of dairy cows freely grazing within a fenced paddock (Laubach and Kelliher, 2005, 2004), stored liquid dairy manure (Van der Zaag *et al.*, 2011), and stored swine liquid manure (Park *et al.*, 2010).

Available measurement and monitoring protocols

Greenhouse gas emissions from animal houses with the objective of determining emission factors should be measured by using standard measurement protocols as described in Groenestein and Mosquera (2011) for CH_4, and in Mosquera and Groenestein (2011) for N_2O.

Model calculations are also used in NIR monitoring protocols to determine the emission of greenhouse gases from agricultural activities. These monitoring protocols are based on the IPCC Guidelines and are adapted to specific country situations. The monitoring protocols relevant for this study are discussed in Chapter 2.

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