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Abstract

Livestock farming is blamed to bear the bulk of certain gaseous emissions from agriculture such as ammonia (NH_3) and methane (CH_4). Emission measurement in naturally ventilated buildings in general, but the determination of the air exchange rate in particular, is very complex. Consequently, there is a lack of knowledge regarding gaseous emissions from modern, naturally ventilated dairy cattle buildings. The objectives of the thesis comprise the development and the utilization of measuring and modeling methods in order to determine NH_3 and CH_4 emissions from dairy barns.

The first study focused on the development of a robust method for the long-term measurement of CH_4 and NH_3 emissions from a naturally ventilated dairy barn. A rough but solid model for the calculation of the ventilation rate by means of wind parameters was developed. At zero wind speed, the ventilation level in the building was over 870 m^3 h^{-1} LU^{-1} and each m s^{-1} increase in wind speed increased the ventilation rate by 1,500 m^3 h^{-1} LU^{-1}.

The second study presents results of a one-year measurement campaign in a tripartite, naturally cross ventilated dairy barn allowing for an accurate comparison of the two housing systems slatted floor and solid floor including emissions from barn and storage. Emissions from slatted floor including storage with low intensity of slurry homogenization led to lowest NH_3 and CH_4 emissions (324.9 ± 123.6 g CH_4 LU^{-1} and 29.8 ± 13.1 g NH_3 LU^{-1} d^{-1} as annual average, respectively). The effect of slurry homogenization beneath the slatted floor was affecting the level of both CH_4 and NH_3 emissions in a similar way (+17 and +29% higher emissions due to higher intensity of manure homogenization).

Furthermore, in the third chapter emission modeling and measuring science was brought together and discussed in an interdisciplinary study. Therefore, the greenhouse gas calculation module of the dairy farm-level model DAIRYDYN was validated by long-term measurement data. The comparison of indicator-modeled CH_4 emissions with online measurements offered relatively moderate deviations in case of very detailed indicator schemes (between -6.4 and 10.5%) compared with findings from literature.

As a whole, the thesis contributes to the development and improvement of measuring methods for gaseous emissions from naturally ventilated dairy barns offering links for further research activities in this field. The thesis provides emission factors for different housing systems and manure management practices for dairy cows.

Kurzfassung

Die landwirtschaftliche Nutztierhaltung ist für einen Großteil der gasförmigen Emissionen des Agrarsektors, wie Methan (CH_4) und Ammoniak (NH_3), verantwortlich. Die Messung dieser umwelt- oder klimaschädlichen Gase und insbesondere die Bestimmung des Luftwechsels von frei belüfteten, modernen Tierställen ist jedoch sehr komplex und die Datengrundlage daher gering. Ziel dieser Arbeit war die Entwicklung und Anwendung von Messmethoden und Modellen zur Bestimmung von gasförmigen Emissionen aus Milchviehställen.

Die erste Studie beschreibt die Entwicklung einer robusten Messmethodik für die Bestimmung der CH_4 und NH_3 Emissionen aus einem frei belüfteten Milchviehstall. Dazu wurde anhand von Windparametern ein Luftwechselmodell für das Stallgebäude entwickelt. Bei Windstille wurde ein Luftvolumenstrom von mehr als 870 $m^3\ h^{-1}\ LU^{-1}$ ermittelt, wobei ein Anstieg der Windgeschwindigkeit um 1 $m\ s^{-1}$ eine Erhöhung des Luftvolumenstroms von etwa 1.500 $m^3\ h^{-1}\ LU^{-1}$ zur Folge hatte.

Die zweite Studie umfasst Ergebnisse einer einjährigen Messreihe in einem frei belüfteten, dreigeteilten Milchviehstall und ermöglichte einen Vergleich der zwei Haltungsvarianten „Spaltenboden“ und „planbefestigte Laufflächen“ unter Einbeziehung der Emissionen aus dem Flüssigmistlager. Das Stallabteil mit Spaltenboden wies bei geringer Intensität des Flüssigmist-Homogenisierens im Jahresmittel die geringsten NH_3 und CH_4 Emissionen auf (324,9 ± 123,6 g CH_4 $GV^{-1}\ d^{-1}$ und 29,8 ± 13,1 g NH_3 $GV^{-1}\ d^{-1}$). Das intensive Homogenisieren des Flüssigmistes unter dem Spaltenboden führte im Jahresmittel sowohl bei CH_4 als auch bei NH_3 zu signifikant höheren Emissionsraten im Vergleich zum weniger intensiven Homogenisieren (+17% bei CH_4 und +29% bei NH_3).

Darüber hinaus wurden in der dritten Studie Erkenntnisse aus Emissionsmessung und -modellierung in einer interdisziplinären Arbeit zusammengeführt. Das Klimagas-Berechnungsmodul des einzelbetrieblichen Simulationsmodells DAIRYDYN wurde anhand von Ergebnissen aus Langzeit Messungen validiert. Bei Einbeziehung sehr detaillierter Produktionsparameter in das Modell wurden im Vergleich zur Literatur relativ geringe Abweichungen (-6,4 bis 10,5%) zu den Messergebnissen festgestellt.

Die vorliegende Arbeit leistet somit einen Beitrag zur Entwicklung und Verbesserung der Messmethoden für gasförmige Emissionen aus frei belüfteten Milchviehställen und zeigt weiteren Forschungsbedarf in diesem Themengebiet auf. Darüber hinaus liefert die Arbeit Emissionsfaktoren für verschiedene Haltungsverfahren bzw. Entmistungsvarianten für Milchkühe bei unterschiedlichem Flüssigmistmanagement.

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General Introduction

Livestock farming and environment

The interaction of agriculture and environment, namely climate and ecosystems, has become an important issue in politics, science and consequently in the media worldwide. Especially livestock farming is blamed to bear the bulk of certain gaseous emissions from agriculture with impact on the environment, such as ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O). Livestock's contribution to global anthropogenic greenhouse gas emissions is estimated at 18% in an FAO study (FAO, 2006). Within the European Union (EU) the share of livestock in total anthropogenic greenhouse gas emissions is given with 9.1% (excl. land use and land use change, LEIP et al. 2010). About 30% of the livestock sector greenhouse gas emissions originate from dairy farming and another 30% is stemming from beef cattle[1] (LEIP et al., 2010). The relevant greenhouse gases from agriculture are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Furthermore, ammonia (NH_3) emissions from agriculture have a significant impact on the environment.

Methane (CH_4)

It is estimated that in Germany 54% of methane (CH_4) emissions originate from agriculture - more than 97% of which are from livestock production (UBA, 2013). With regard to dairy cattle, about 75-92% of CH_4 emissions are coming from enteric fermentation, the rest is stemming from manure (MONTENY et al., 2001; KÜLLING et al., 2002).

Methane is an odorless and colorless gas with a global warming potential of 21 CO_2-equivalents (on basis of a 100 year global warming potential (UBA, 2012 according to IPCC, 2006)). In general, CH_4 represents a more or less unavoidable by-product of the microbial anaerobic digestion of organic matter. Regarding enteric fermentation, the bulk of CH_4 emissions is generated in the rumen (87%) and – to a smaller extent – also in the large intestine (MURRAY et al., 1976). However, even if this own study is considering CH_4 because of its role as a greenhouse gas/pollutant, much effort has been made in the past to reduce enteric CH_4 emissions with regard to the corresponding energy loss. It is estimated that the energy loss by CH_4 generation is about 6-7% of gross energy intake (YAN et al.,

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[1] based on a cradle to gate life cycle assessment

2000; NISHIDA, et al., 2007). Specific microbes are responsible for the formation of CH_4: *Methanogenic Archaea*. One of the main tasks of the *Methanogenic Archaea* is to utilize the surplus hydrogen which is deriving from fiber digestion. There are several biochemical processes of CH_4 synthesis in the rumen, while the direct synthesis by means of CO_2 is the most important one (ROUVIERE & WOLFE, 1988; FLACHOWSKY & BRADE, 2007; KREUZER, 2011):

$$(1) \qquad 4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O\,.$$

One further important biochemical process of CH_4 synthesis in the rumen is the usage of formic acid as an H_2-acceptor:

$$(2) \qquad 4\,HCOOH \rightarrow CH_4 + 2\,H_2O + 3CO_2\,.$$

In addition there are several other carbon sources used for methanogenesis (FLACHOWSKY & BRADE, 2007).

There is a broad variation (>100%) of CH_4 emissions between individual animals (FLACHOWSKY & BRADE, 2007). Within one species, this may to a certain extent be explained in production type, live weight, performance and feeding (feed ration, feed intake, feed conversion ratio). But even in a more or less homogenous dairy cattle herd, GARNSWORTHY et al. (2012) recently reported broad differences in daily CH_4 emissions between individual cows.

Apart from rumen digestion, liquid manure storage is an important source of CH_4 emissions contributing about 20% to total CH_4 emissions from cattle as already indicated above. The biochemical processes of the methanogenesis in liquid manure are similar to the processes in the rumen: anaerobic digestion of organic compounds performed by the same microbes. However, differences do occur in temperature, mixing status of the substrate and the status of carbohydrates, being already digested in the slurry (MONTENY et al., 2001). Containing a large amount of organic compounds and a high content of anaerobic microbes, liquid manure offers a high CH_4 production potential; thus the level of CH_4 production is mainly determined by temperature and storage time (MONTENY et al., 2001). Since straw based production systems are usually more aerate, CH_4 emissions from solid manure are expected to be lower than from liquid manure (AMON, 1998). Discussing CH_4 as a pollutant and as a threat for the environment, one should keep in mind that a high

CH_4 yield from slurry storages is a benefit for biogas production (CUELLAR & WEBBER, 2008).

A description of CH_4 emission levels, measurement and modeling techniques, as well as results from experiments in practical dairy farms is given and discussed in chapters 1-3.

Nitrous Oxide (N_2O)

The share of agriculture in the German nitrous oxide (N_2O) emissions is 76 %, with fertilization of soils (mineral and manure) playing an important role (UBA, 2013). Nitrous oxide is a colorless gas with a slightly sweet odor and with a very high global warming potential of 310 CO_2-equivalents (on basis of a 100 year global warming potential (IPCC, 2006; UBA, 2012)). In contrast to CH_4, N_2O production results from combined aerobic and anaerobic processes: aerobic nitrification of ammonium (NH_4) and anaerobic de-nitrification of nitrate (NO_3). Under optimal conditions, N_2O is not an intermediate product of nitrification but may be produced when oxygen availability is too low. In denitrification, N_2O is an intermediate product (‘hole in the pipe’ model by FIRESTONE & DAVIDSON, 1989; MONTENY et al., 2001; MONTENY et al., 2006). Nitrous oxide emissions are of relevance in aerated slurry systems or in housing systems with straw, where a passive aeration is given and an uncontrolled nitrification and denitrification occurs (GROENESTEIN & VANFAASSEN, 1996). Further, ammonia (NH_3) may serve as a precursor for N_2O production (PETERSEN & SOMMER, 2011).

Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) sources within dairy barns are: respiration of animals and emissions from feed, manure and in negligible proportion emissions from process energy (fuels, electricity, e.g. feed mixer). Nevertheless, CO_2 from livestock is not considered as net source of CO_2, because it has been ’imported’ into the system by feed stuffs which were created by photosynthesis (IPCC 2006; HERRERO et al. 2011).

Ammonia (NH_3)

Beside greenhouse gases, ammonia (NH_3) emissions play an important role in airborne pollutants from agriculture. Ammonia is a caustic, colorless gas with pungent odor. It is involved in environmental degradation and acidification and may cause harmful effects in humans and animals. But not only the direct effects of NH_3, also the role as a precursor for the highly climate relevant gas N_2O is of particular importance. In Germany >90% of NH_3

emissions originate in agriculture, in particular in livestock farming. Regarding NH_3 emissions from dairy cattle 63% are stemming from field application of manure, 29% from housing and 8% from manure storage (RÖSEMANN et al., 2011). Ammonia is produced on emitting surfaces within the barn rather than by the animals themselves. It is known that a high urea excretion is strongly affecting the NH_3 emissions from manure and that feeding does impact the urea concentration of urine, feces and milk from dairy cows significantly (DE BOER et al., 2002; MONTENY et al., 2002). About 80% of the N-intake by dairy cows is excreted by urine and feces, the rest is excreted by milk and a small proportion is metabolized (TAMMINGA, 1992). As indicated above, manure NH_3 is formed primarily from the hydrolysis of urea from cattle urine (MOBLEY & HAUSINGER, 1989). The enzyme responsible for the hydrolysis of urea to ammonia (NH_3) and carbon dioxide (CO_2) is *urease*. The following equation shows the process of urea hydrolysis in a liquid environment (e.g. slurry):

$$(3) \qquad H_2N-CO-NH_2+H_2O \rightarrow 2NH_3 \ +CO_2 \ .$$

The rate of urea hydrolysis depends on the urea concentration and the ‘urease activity’ which is temperature related and requires a pH between 7 and 9. Ammonia hydrolysis is mostly completed after a few hours, whereas further volatilization may last for months when manure is stored (MONTENY & ERISMAN, 1998).

In manure (= in the liquid), NH_3 exists primarily as two types in a pH- and temperature dependent equilibrium: ammonia (NH_3) and ammonium (NH_4^+):

$$(4) \qquad \mathrm{NH_3+H_2O} \ \leftrightarrow \ \mathrm{NH_4^+ + OH^-} \ .$$

At pH below 6-7 most *Total Ammoniacal Nitrogen* (TAN= $NH_3 + NH_4^+$) is present in ionized form (NH_4^+). Above pH 11, NH_3 is predominant. Ammonia is water-soluble and exists in equilibrium between liquid and gaseous NH_3. The amount of gaseous NH_3 depends - inter alia - on temperature and air velocity above the surface - high temperatures and high air velocities result in a higher share of gaseous NH_3 (SVENSSON & FERM, 1993; ERISMAN & MONTENY, 1998).

Emission levels from different housing and manure management systems for dairy cows as well as measurement techniques and results are presented and discussed in chapters 1 and 2 of this thesis.

Emission measurements in livestock farming

Much research has been conducted to measure enteric CH_4 emissions (in vivo, in vitro, modeling). For example, very detailed information has been obtained by using respiration chambers for single animals or by means of tracer gas techniques (e.g. DERNO et al., 2009; GARNSWORTHY et al., 2012). STORM et al. (2012) present an overview of common measurement and modeling techniques to quantify enteric CH_4 emissions from cattle. Furthermore, there are several approaches of CH_4 emission calculation based on enteric fermentation (e.g. ELLIS et al., 2007) or on farm level (see chapter 3). Emission measurement at barn level includes emissions from enteric fermentation (mainly CH_4) **and** other emission sources within the barn, e.g. from walking areas, slurry pits and feed stuffs (NH_3, CH_4 and N_2O).

Due to the negative impact on the environment, NH_3 emissions from livestock have been an issue for many years in many Western European countries. Consequently, the knowledge about NH_3 emissions from dairy barns and manure storage is more comprehensive than about other gases, like CH_4 and N_2O. However, livestock farming in Western Europe has been moving towards better animal welfare in recent years, and as a consequence housing systems for cattle and in particular for dairy cows have changed. Turned away from tie-stalls, modern dairy barns are designed as free stalls, offering cubicles and exercise areas. With regard to air quality and heat dispersion, modern barns are mostly built with large open surfaces and natural ventilation. That implies that existing emission factors at barn level have to be verified and amended under these modern conditions. To sum up, there is uncertainty about emission rates from naturally ventilated dairy cattle buildings.

Emission measurement in naturally ventilated buildings in general, but determination of the ventilation rate in particular, is complex. There are several methods discussed in the literature: Tracer gas methods are supposed to deliver the most precise results for naturally ventilated buildings, but they risk errors from the prerequisite of exact positioning of dosing and sampling points and the proper mixing of the tracer within the building (e.g. SAMER et al., 2011b; SCHRADE et al., 2011). Anyway, the preparation of those measurements is time-consuming and expensive. Balancing methods based on carbon dioxide (CO_2), moisture or heat ratios are simpler, but bear the risk of inaccuracy and biases due to external sources of the considered unit, and gradients within the building (PEDERSEN et al., 1998; CIGR, 2002; SAMER et al., 2011a; SAMER et al., 2012). Another possibility is computer fluid dynamics modeling, which may be a good option in future, when the accuracy of the technique has been further improved (Wu et al., 2012).

An overview of emission measurements in naturally ventilated dairy barns and an explanation of usual calculation methods for gaseous emissions is given in chapter 1. Chapter 1 further presents an approach for the determination of the ventilation rate based on tracer gas measurements.

Variables affecting the level of emissions

Of course, there are numerous variables influencing the level of gaseous emissions from dairy farms. The following table presents exemplary variables affecting CH_4 and/or NH_3 emissions from dairy barns (Tab I). Regarding the variability of farm and animal characteristics, it is difficult to quantify the effect of single measures on the emission level. Especially for CH_4, where the proportion of barn/manure borne emissions is relatively low and the variation between individual animals may be quite high, the influence of housing system or manure management is difficult to determine exactly. Therefore, the own investigations were set up as simultaneous long term experiments within one building, always including high numbers of animals per group (see chapters 1-3).

Table I Variables affecting the level of gaseous emissions from dairy barns (own illustration)

Animal	Feeding	Exposition of the barn	Barn construction	Manure removal system	Manure storage and management
Live weight Milk yield Lactation day Individual feed conversion ratio (↔ genetics) Breed Activity (NH_3)	Feed ration Feed intake Additives Feeding management, e.g. grazing	Climate Min. / max. temperatures Wind direction and wind speed Humidity	Ventilation system Internal wind speed (NH_3) Emitting area per cow (NH_3)	Floor design Cleaning frequency Cleaning intensity (e.g. water cleaning, drain) Additives	Within the barn or external Covered or open storage Surface area Crusting Additives Slurry management (e.g. homogenization)

Objectives

The overall objectives of the presented studies were:

1) Further development of methods for the measurement of gaseous emissions from naturally cross ventilated dairy barns

a) Development of a building-specific air exchange model for the calculation of the air exchange rate

b) Development of a robust measurement system for the long-term-measurement of CH_4, NH_3, *and* CO_2 *outdoor and indoor concentrations*

2) Long-term measurement of CH_4 and NH_3 emissions from differently managed naturally ventilated dairy barns

a) Comparison of the dairy cow housing systems: slatted floor with subfloor storage and solid floor with external storage

b) Effect of manure management on CH_4 *and* NH_3 *emissions*

3) Validation of the dairy farm-level model DAIRYDYN with long-term measurement results.

Scope of the thesis

The following chapters present results of the development and utilization of measuring and modeling methods in order to determine gaseous emissions from dairy farming. The presented results may serve as a basis for future investigations regarding emission reducing strategies.

Chapter 1 - Development of a building-specific air ventilation model for estimations of methane and ammonia emissions from a naturally ventilated dairy barn in spring

The first chapter is focused on the development of a robust method for the long-term measurement of CH_4 and NH_3 emissions from a naturally cross ventilated dairy barn. The study comprises the development of a model for the calculation of the air exchange rate by using data on wind direction and wind speed, and the high resolution measurement of gas concentrations in the dairy barn. First results of the measurement series in spring 2011 are presented within this study. This chapter refers to objectives 1a and 1b and forms the basis for the following investigations described in chapters 2 and 3.

Chapter 2 - Effect of manure removal and storage management on methane and ammonia emissions from a naturally ventilated dairy barn

This section presents results of a one-year measurement campaign in a naturally ventilated dairy barn. The investigation was focused on the simultaneous comparison of CH_4 and NH_3 emissions from different manure removal systems for dairy cattle within one building. In addition to the measured barn level emissions the emissions from external liquid manure storage were calculated in three common practice scenarios. Hence, an accurate comparison of two housing systems (emissions from barn **and** storage) could be carried out (objectives 2a and 2b).

Chapter 3 - A comparison of emission calculations using different modeled indicators with 1-year online-measurements

This interdisciplinary study aimed at validating the greenhouse gas calculation module of the dairy farm-level optimization model DAIRYDYN including CH_4 from enteric fermentation and managed manure. It is discussed whether the modeled CH_4 emission level on a specific dairy farm matches the results of real long-term measurements (objective 3).

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Chapter 1 - Development of a building-specific air ventilation model for estimations of methane and ammonia emissions from a naturally ventilated dairy barn in spring[2]

Abstract

Dairy cow barns are an important source of methane and other environment relevant gases. Most dairy cow barns are naturally ventilated, making it complex to precisely determine gaseous emissions at barn level. Furthermore, broad variations in practice resulting from differences in animal productivity, diet, management and ventilation make it difficult to determine the influence of housing system and floor type on the emissions. In this investigation CH_4 and NH_3 emission rates from a naturally cross ventilated dairy barn were calculated. Therefore the ventilation rate was determined using a building-specific air exchange model. This model was designed after performing several tracer gas experiments within the building and considering various weather conditions. The measured ventilation rate of the building was significantly correlated with the actual wind conditions outside the barn, leading to a linear model which allowed prediction of the ventilation rate on an hourly basis with a regression of 0.92. Methane emissions were 331 ± 143 and 261 ± 108 g LU^{-1} d^{-1} for the slatted floor sections, and 387 ± 147 g LU^{-1} d^{-1} for the solid floor section. Ammonia emissions were 37.3 ± 18.5 and 24.2 ± 12.4 g LU^{-1} d^{-1} for the slatted floor sections, and 35.9 ± 15.2 g LU^{-1} d^{-1} for the solid floor section.

Keywords: *ventilation rate; emissions; air exchange rate; tracer gas; manure management*

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[2] This chapter is based on a revised manuscript submitted to the Journal 'Biosystems Engineering' as SCHIEFLER, I. and W. BÜSCHER: Development of a building-specific air ventilation model for estimations of methane and ammonia emissions from a naturally ventilated dairy barn in spring.

Nomenclature

A = impulses at t = 0

AER = Air exchange rate [h^{-1}]

b = air exchange rate per second [s^{-1}]

C_{inside} = concentration of outgoing air [$mg\ m^{-3}$]

$C_{outside}$ = background concentration [$mg\ m^{-3}$]

d = day

E = emission rate [$mg\ h^{-1}\ LU^{-1}$]

LU = livestock unit (500 kg of live weight; 1 cow is 1.4 LU)

n = number of livestock units in the barn

VR = ventilation rate [$m^{-3}\ h^{-1}\ LU^{-1}$]

VR_{mod} = ventilation rate by tracer gas model [$m^{-3}\ h^{-1}\ LU^{-1}$]

VR_{bal} = ventilation rate by CO_2 mass balance [$m^{-3}\ h^{-1}\ LU^{-1}$]

t = time [s]

v = wind speed [$m\ s^{-1}$]

V = air volume of the barn [m^3]

Y = impulses recorded by the SF_6 detector

1.1 Introduction

Livestock farming contributes 9.1% of the total greenhouse gas (GHG) emissions in the European Union with animal barns being of major importance (LEIP et al., 2010). In addition, barns in general and dairy cow barns in particular are also an important source of other environment polluting gases like ammonia (NH_3; UMWELTBUNDESAMT, 2011). In general, gaseous emissions from dairy cow barns originate from the animals, and the manure or slurry present on the floors of walking alleys and in manure channels and pits inside the building. Most research on GHG emissions from livestock has been conducted at the individual cow level focussing on enteric methane (CH_4) emissions and using either respiration chambers or the SF_6 tracer technique (BELYEA, MARIN, & SEDGWICK, 1985; BOADI, WITTENBERG, & MCCAUGHEY, 2002; KINSMAN, SAUER, JACKSON, & WOLYNETZ, 1995). In contrast to this emission rates at the barn level (sum of animal and manure/slurry) have been studied less thoroughly (NGWABIE et al., 2009; SAMER et al., 2011; SCHRADE et al., 2012).

Reducing environmental pollution from dairy cow husbandry is an important policy to meet sustainability criteria in the near future. Most dairy cow barns are naturally ventilated with cross-ventilation occurring regularly due to broad open walls, hence making difficult the precise determination of gaseous emissions. This may be the most important reason why there is a lack of data on the influence of the housing system (e.g. type of floor, slurry storage and management) on gaseous emission levels, as well as on options for reducing emissions. Substantive data on emission levels related to different housing systems are necessary to develop recommendations for barn construction and equipment as well as for management strategies to lower emission rates. However, the outcome of these investigations would be biased by the broad variations at barn level caused by differences in building design, animal productivity (age and lactation stage), diet and management.

Several studies have shown that floor design has a strong influence on NH_3 emission levels from dairy cow barns (BRAAM, SMITS, GUNNINK, & SWIERSTRA, 1997; MORSING, STROM, ZHANG, & KAI, 2008; PEREIRA et al., 2011), whereas their influence on CH_4 emission has been poorly studied. ZHANG et al. (2005) have investigated gaseous emissions from different housing systems for dairy cows in nine buildings and reported a strong positive influence of temperature on NH_3 emissions. Several other authors reported a similar relationship for CH_4 emissions from liquid manure (MASSE, MASSE, CLAVEAU, BENCHAAR, & THOMAS, 2008; MONTENY, BANNINK, & CHADWICK, 2006; SOMMER et al., 2007). In addition, MASSE et al. (2008) also reported that frequent removal of manure in summer reduces CH_4 emissions. Recent investigations of SCHRADE et al. (2012) have shown that, besides outside temperature, wind speed and urea content of the tank milk were significant variables in determining NH_3 emission levels from commercial dairy cow barns.

The numerous sources of variation at barn level imply that emission measurements in commercial dairy cow barns to assess the potential of emission reducing options may not be accurate. Therefore, simultaneous case/control (case: emission reduction system; control: traditional system) investigations on the same site would be advantageous since sources of variation would apply to both systems. A major problem for accurate estimations of emissions from naturally ventilated barns is the difficulty to measure the building ventilation rate. The tracer technique and the CO_2 mass balance are the methods most used to estimate the ventilation rate. Recent investigations have shown the specific requirements of the respective investigated building and the need to assess the best experimental set up for each site (SAMER et al., 2011; SCHRADE et al., 2012; NANNEN, SCHNEIDER, & BÜSCHER, 2006). DEMMERS et al. (2001) stated that the constant tracer release method gives the most reliable results and SCHRADE et al. (2012) confirmed this. SNELL, SEIPELT, & VAN DEN WEGHE (2003) have reported that the tracer decay method was an appropriate technique within naturally ventilated dairy houses. SAMER et al. (2011) have further developed this method for cross-ventilated buildings, and came to the conclusion that linear dosing showed the best results. However, independent of the type of tracer gas and the dosing and sampling system, one of the main issues is the prerequisite of total mixing of the tracer gas within the building. A second common approach to estimate the ventilation rate is calculation by the CO_2-balance method (CIGR, 2002; PEDERSEN et al., 1998). SAMER et al. (2011) recently compared the CO_2-balance method with the tracer gas decay method through summer seasons, and stated that tracer gas techniques showed more reliable results. There is a great need for improving methods in the determination of VR of naturally ventilated buildings. Since SF_6 has a high global warming potential, one can expect that its use may be prohibited in several countries in the near future. Building specific models may help to reduce the required amount of tracer gases.

The objective of this study was to develop a building specific wind-related air exchange model based on tracer gas experiments in order to calculate the ventilation rate (VR) by using data on wind speed and wind direction. By this, CH_4 and NH_3 emissions were determined for three differently managed barn sections.

1.2 Material and Methods

1.2.1 Site description and production

Measurements were carried out in a newly built dairy barn of the Chamber of Agriculture North-Rhine Westphalia at the Centre of Agriculture Haus Riswick in Northwest Germany. The free stall dairy barn for 144 dairy cows was divided by foil partitions into three equal sections (Fig 1.1), each with a volume of 4,500 m^3 and a capacity for 48 dairy cows. The total floor available per cow was 10 m^2, of which 7 m^2 per cow was used as a walking area, with the remaining area used for lying and feeding. The building was 68 m long and 34 m wide. Measured from floor level, the eave height was 5.15 m and that of the ridge was 13 m. The barn was cross-ventilated. There were no outside walls along the long sides of the building; however, there was a facility to close the western eave side of the building with curtains. During the measurement period in spring 2011, the curtains were completely open.

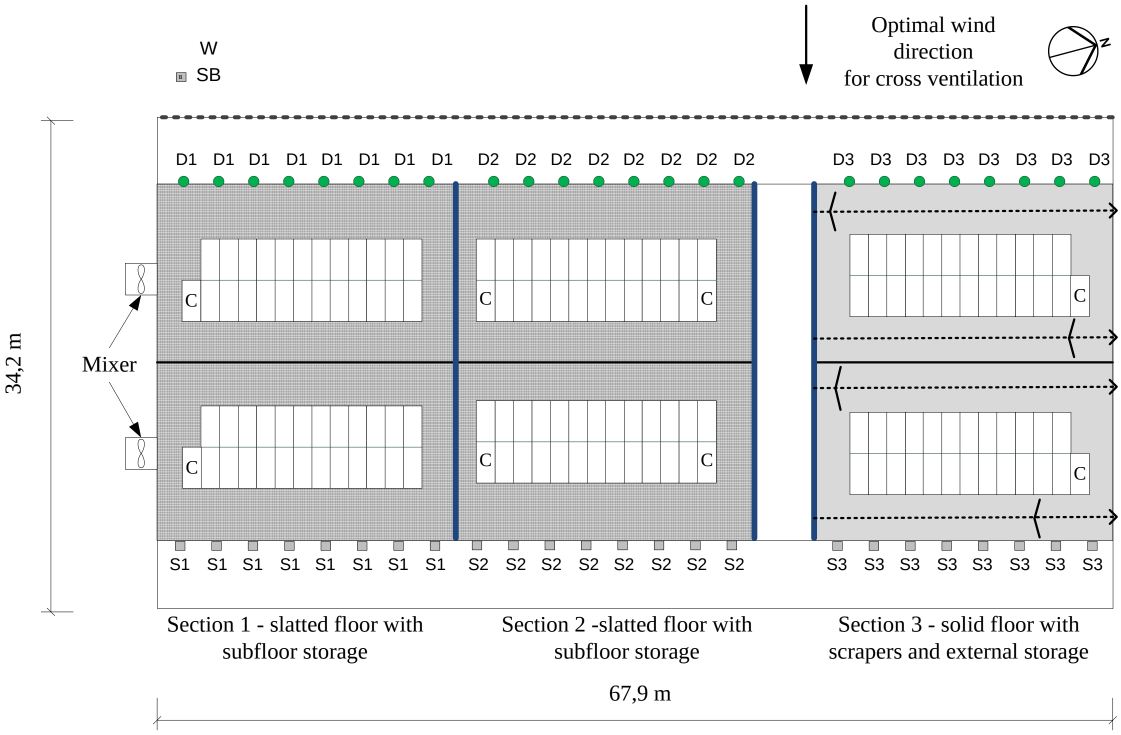

Figure 1.1 Layout of the dairy cattle building, where C represents concentrate feeder, M external manure shaft, S1–3 sampling points for exhaust air, SB sampling background, W location of weather station, D1–3 tracer gas dosing points

Barn sections 1 and 2 had a slatted floor with shared subfloor storage of liquid manure (‘slurry pit’), and a robot system for fully automated water cleaning of the slatted floor. The cleaning robot on the slatted floor was running continuously, and performed water-cleaning of each square meter at least 4 times a day (Joz Tech JT100, Joz B.V., Netherlands). The slurry stored in the pit was homogenized twice a day for a duration of 30 minutes. The mixer for homogenisation of the liquid manure beneath the slatted floor sections was located at the gable wall next to section 1 of the barn (Fig. 1.1). This resulted in a high intensity of homogenization of liquid manure in section 1, and a lower intensity of homogenization of liquid manure in section 2. By this it was possible to compare two differently managed slatted floor variations with a solid floor (section 3). Section 3 had a solid floor with a scraper and an external discharge with a preliminary tank and an external storage tank. The solid floor was cleaned 20 times a day (hourly, except 4 times distributed over the day) using four cable pulled scrapers.

The milking parlour was located in a separate building with a cow waiting area (Fig 1.2).

Figure 1.2 Farmstead layout where 1 is free stalls, 2 is the milking house (Haus Riswick)

Milking was performed in the early morning at 5:30 am and in the afternoon at 3:30 pm. With the start of milking all cows were driven into the waiting area within the external milking house for a short period of time. After milking in the rotary parlour each single cow was directed into its respective compartment in the building by selection gates directly after the milking procedure. Hence, the herd was not completely inside the barn for two hours in the morning and again in the afternoon. These time periods have not been considered in the calculations of emission rates.

During the study, the dairy cows were in early or mid lactation, with an average daily milk yield of 34 kg and an average live weight of 700 kg (≙1.4 LU). The cows were fed once a day with a grass and a maize silage-based mixed ration, and were able to obtain additional concentrates related to their production in separate feeding stations (2.5 kg concentrate feed on average). The total average dry matter feed intake per cow was 19 kg d^{-1}. The mean crude protein of the mixed ration was 16.7% (dry matter) and crude fiber was 17.4% (dry matter).

1.2.2 General procedures

Measurements were conducted from 27 April to 06 June 2011 for 40 days covering the late spring conditions with an average temperature of 17°C and an average wind speed of 1.5 m s^{-1}. The main wind directions were south and west. With completely open walls at the eave sides of the building one eave side could either be exhaust or incoming air (Fig 1.1). Considering that the main wind direction was westerly, the exhaust location for measurement of gas concentrations was chosen at the eastern eave side of the building while the background sample was taken at the western side of the building. Nevertheless, only those time periods when the wind direction was between 230° and 330° (delivering a certain west-to-east cross-ventilation; more than 50% of the measurement period) were considered for this study, the rest was discarded. This was necessary, because the cross ventilation was required to determine incoming and exhaust air positions exactly.

1.2.3 Measurement of ventilation rates

The ventilation rates of the barn sections were estimated on basis of the air exchange rate of the building and the building volume. The air exchange rate was determined for one section of the building by means of the tracer decay method (see also NIEBAUM, 2001; SCHNEIDER, 2006; SEIPELT, 1999). It was assumed, that the VRs of the sections were the same. Cows were inside the building during measurements.

The tracer decay method was performed for twelve 24h periods covering various weather conditions.

The duration of each single tracer gas measurement was about 10–15 minutes, including dosing, decay and damping times. A mixture of sulphurhexafluroide (SF_6) and nitrogen (N_2) in equal parts was released for 90 seconds in one section of the building. The tracer gas was released as a line source at the windward side of the barn at 4 m height from the floor, which allowed proper mixing of the tracer within the compartment. The sampling system used for the tracer gas measurement was the same as used for the gas concentration measurement (explained in 1.2.4). The SF_6-Electron Capture Detector (ECD; Leakmeter 200, Meltron Qualitek Messtechnik GmbH), allowed for a high frequency of impulses and delivered one value every second.

Regarding one tracer gas experiment, the decay of the exhaust SF_6 concentration can be mathematically described as an exponential function, where Y is impulses recorded by the SF_6 detector, A is the impulses at t = 0, t is the time and b is the air exchange rate of the building per second.

(1) $Y= A \exp(-bt)$

The term b [s^{-1}] (AER of the building per second) was converted to AER per hour (*3600), multiplied with the volume of the building (V in m^3) and divided by the number of LUs in the barn (n) in order to receive the ventilation rate in $m^3\ h^{-1}\ LU^{-1}$ (VR).

(2) $VR = b*3600 * V * n^{-1}$

Additionally, the CO_2 mass balance method (CIGR 2002) was applied in order to compare results to the tracer gas modeling method.

1.2.4 Measurement of gas concentrations

Each section of the building was equipped with eight sampling points in a row above the feed alley (exhaust air side of the barn) which were combined to produce a single aggregate sample for each section. Sampling tubes were located at a 4 m height above floor level in order to represent the main exhaust air flow below the eaves. The exhaust air was sampled separately from each barn section and the background by a separate vacuum pump and tube system into the respective sample bottle. The four sample bottles, four vacuum pumps, the multiplexer and the gas analyzer were placed in the adjacent building in order to offer constant conditions. The sample bottles were flushed by overpressure and constantly provided actual exhaust air samples from the respective barn section or background. By this, tube distances between sample bottles, multiplexer (used for switching between samples), and gas analyser could be minimised in order to reduce flushing times (Gas Analyzer 1412 and Multiplexer 1303, Lumasense Technologies SA, Ballerup, Denmark). The sample interval was chosen 300 s for each sampling point. This was verified by preliminary tests in which tracer gas was injected in the barn. All materials used for sampling were polytetrafluoroethylene (PTFE) in order to prevent NH_3 accumulation in the tubing system. By heating the final 15 m of the tubes between the barn and the adjacent building (laid underground) the influence of temperature and condensation was minimised (BREHME, 2003).

The accuracy of the gas analyzer was checked in the beginning and again after 4 weeks of measurements by using calibration gases with known concentrations for each gas as well as pure nitrogen for zero level. The calibration of the gas analyzer was done by the manufacturer prior to the measurements.

1.2.5 Calculation of emissions

The hourly emission rates of CH_4 and NH_3 were calculated by using the hourly means of the measured concentrations [mg m^{-3}] and the hourly means of the calculated VR [m^{-3} h^{-1} LU^{-1}] according to the following equation:

(3) $E = VR * (C_{inside}-C_{outside})$.

1.2.6 Measurement of weather parameters

A station for weather conditions was positioned at the western side of the barn at a height of 6 m from floor level. Wind direction, wind speed, air temperature and humidity were measured at one minute intervals (anemometer and wind vane “Industry”, Lambrecht GmbH, Germany).

1.3 Results

1.3.1 Model for the calculation of the ventilation rate

The results of the tracer gas experiments over 12 days are shown in Table 1.1. For the model the VR was classified according to eight categories of wind speed. The categories, expected and measured values of wind speed, VR and deviations from the model are shown in Table 1.2.

Table 1.1 Air exchange rates, ventilation rate and average wind speed subject to the tracer gas experiments

Day of tracer gas experiment	Average AER	Average ventilation rate m^3 LU^{-1} h^{-1}	Average wind speed m s^{-1}
1	97.8 ± 45.9	6361.6 ± 3072.3	3.1
2	39.1 ± 18.2	2611.5 ± 1228.3	1.0
3	72.5 ± 37.5	4900.6 ± 2550.1	2.7
4	67.2 ± 35.4	4506.1 ± 2354.8	2.0
5	41.1 ± 18.2	2752.2 ± 1204.9	1.3
6	50.2 ± 18.2	3461.0 ± 1254.1	1.7
7	21.8 ± 3.6	1458.1 ± 231.6	0.4
8	36.9 ± 8.1	2437.3 ± 532.1	1.7
9	66.5 ± 37.1	4579.0 ± 2705.6	3.0
10	69.1 ± 26.1	4566.6 ± 1725.9	3.0
11	41.7 ± 16.9	2755.1 ± 1115.9	1.5
12	39.2 ± 8.4	2614.1 ± 556.6	1.4

Based on the data from all the tracer gas experiments the linear VR model for the whole building with curtains completely open was (see Fig 1.3):

(1) $VR_{mod} = 870 + 1499v$

The deviation between modeled and measured values ranged from -14 to +31%; R^2 was 0.92. This means that the predictability of the model was good for situations where east-west cross-ventilation occurred. At wind speed below 0.2 m s^{-1} (detection limit of wind sensor), the ventilation level in the building was 870 m^3 h^{-1} LU^{-1}.

In the range of 0-5 m s^{-1} each m s^{-1} increase in wind speed increased the ventilation rate by almost 1,500 m^3 h^{-1} LU^{-1}.

Table 1.2 Categories, expected and measured values of wind speed, ventilation rate and deviations from the model

Wind speed m s^{-1}			Ventilation rate m^3 LU^{-1} h^{-1}		
Category	**Expected mean**	**Measurement value**	**Expected VR by model**	**Measurement value**	**Rel. difference**
0.0-0.5	0,25	0.26 ± 0.11	1245	1349.9 ± 155.8	-8%
0.5-1.0	0,75	0.71 ± 0.11	1995	1853.3 ± 540.1	7%
1.0-1.5	1,25	1.27 ± 0.15	2744	3175.5 ± 1333.9	-14%
1.5-2.0	1,75	1.70 ± 0.17	3494	3145.4 ± 1431.9	10%
2.0-2.5	2,25	2.20 ± 0.15	4244	4443.1 ± 2145.7	-6%
2.5-3.0	2,75	2.72 ± 0.14	4993	3764.3 ± 1256.4	31%
3.0-3.5	3,25	3.21 ± 0.16	5743	6199.2 ± 1974.1	-9%
3.5-4.0	3,75	3.84 ± 0.16	6492	6874.5 ± 3533.4	-7%

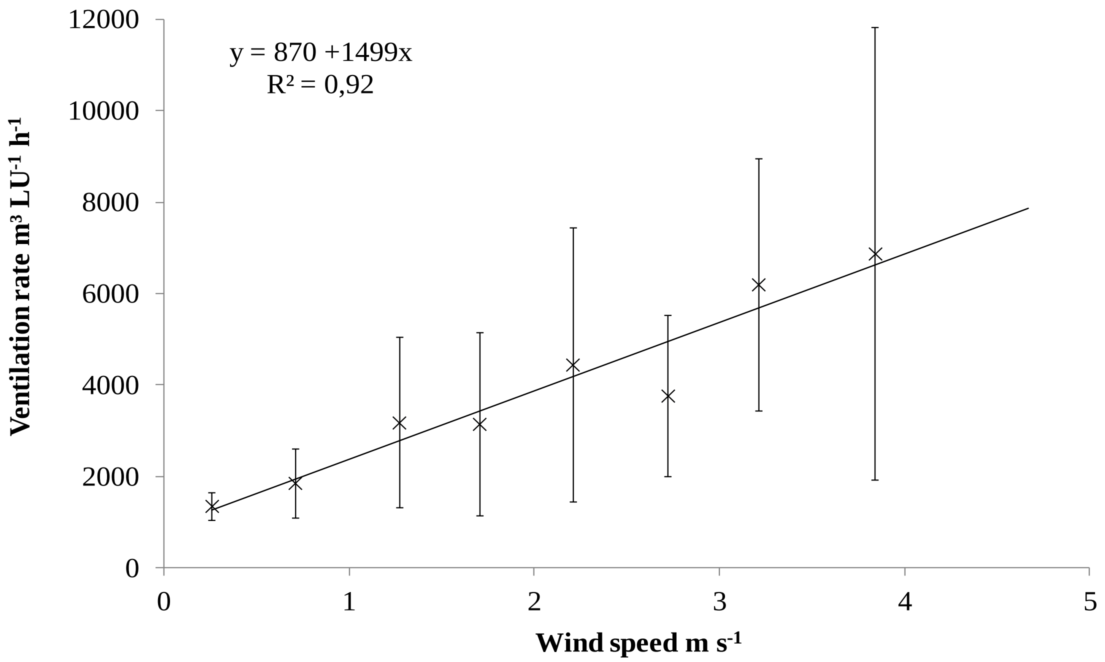

Figure 1.3 Categories of wind speed and measured ventilation rate

1.3.2 Ventilation rate

The average VR by model was 3,339 ± 1,365 m^3 LU^{-1} h^{-1}, and ranged from 870 - 6,888 m^3 LU^{-1} h^{-1}. The average wind speed for the considered wind directions was 1.6 m s^{-1}.

The average VR by CO_2 mass balance was 2,016 ± 765 m^3 LU^{-1} h^{-1} and ranged from 610 - 3,441 m^3 LU^{-1} h^{-1}. The VR by CO_2 mass balance was significantly lower than VR by model but following a similar course (Fig 1.4).

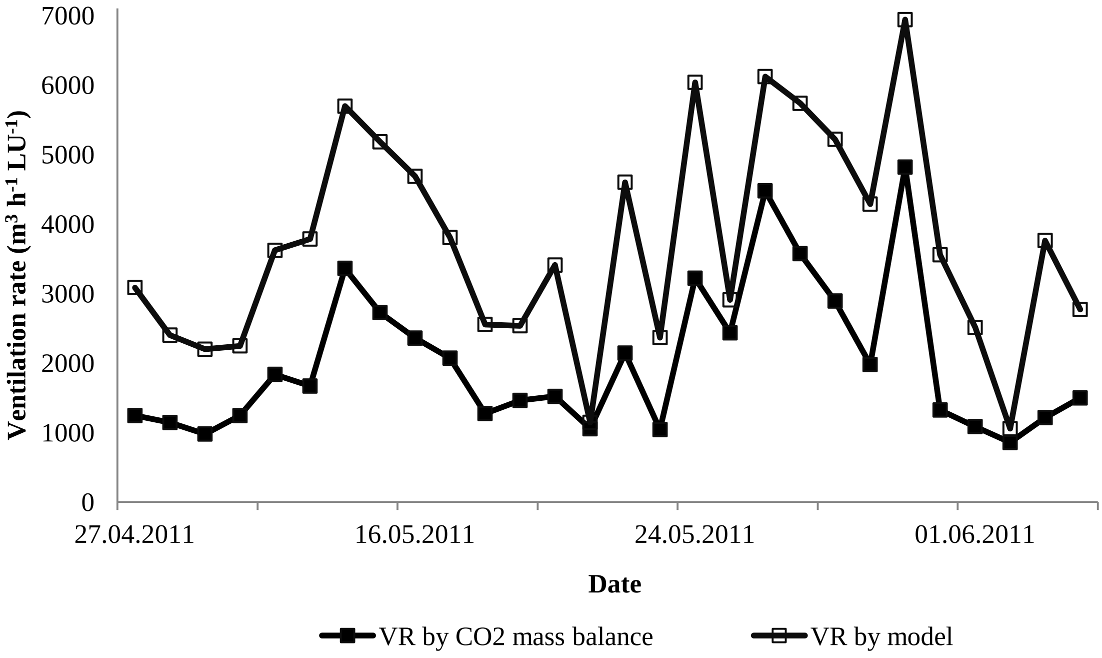

Figure 1.4 Ventilation rate by CO_2 mass balance and by model

1.3.3 Gas concentrations and emissions

Gas concentrations appeared to fluctuate greatly within a single day which corresponded to specific activities in the operating procedure of the farm (milking, homogenisation of liquid manure; Fig 1.5). In particular, CH_4 and CO_2 concentrations which mainly depend on the animals' release decreased immediately when the cows left the barn for milking. Also, the effect of slurry mixing on the gas concentrations was clear. Ammonia emissions increased immediately after milking, when the cows came back into the barn. Especially in the morning, the ammonia emissions increased significantly after feeding (Fig 1.5).

The CH_4 emissions based on VR_{mod} were 331± 143 and 261 ± 108 g LU^{-1} d^{-1} for the slatted floor sections with intensive and not intensive homogenisation, respectively, and 387 ± 147 g LU^{-1} d^{-1} for the solid floor section. The NH_3 emissions based on VR_{mod} were 37.3 ± 18.5 and 24.2 ± 12.4 g LU^{-1} d^{-1} for the slatted floor sections, respectively, and 36 ± 15 g LU^{-1} d^{-1} for the solid floor section. The slatted floor with a low intensity of homogenization of liquid manure led to significantly lower emissions than the slatted floor with intensive homogenization (-21% and -35% CH_4 and NH_3, respectively) and than the solid floor (-33% and -33% CH_4 and NH_3, respectively; Table 1.3). In consequence of the underestimation of the VR by CO_2 mass balance, the emissions using VR_{bal} were significantly lower than by using VR by model (Table 1.3).

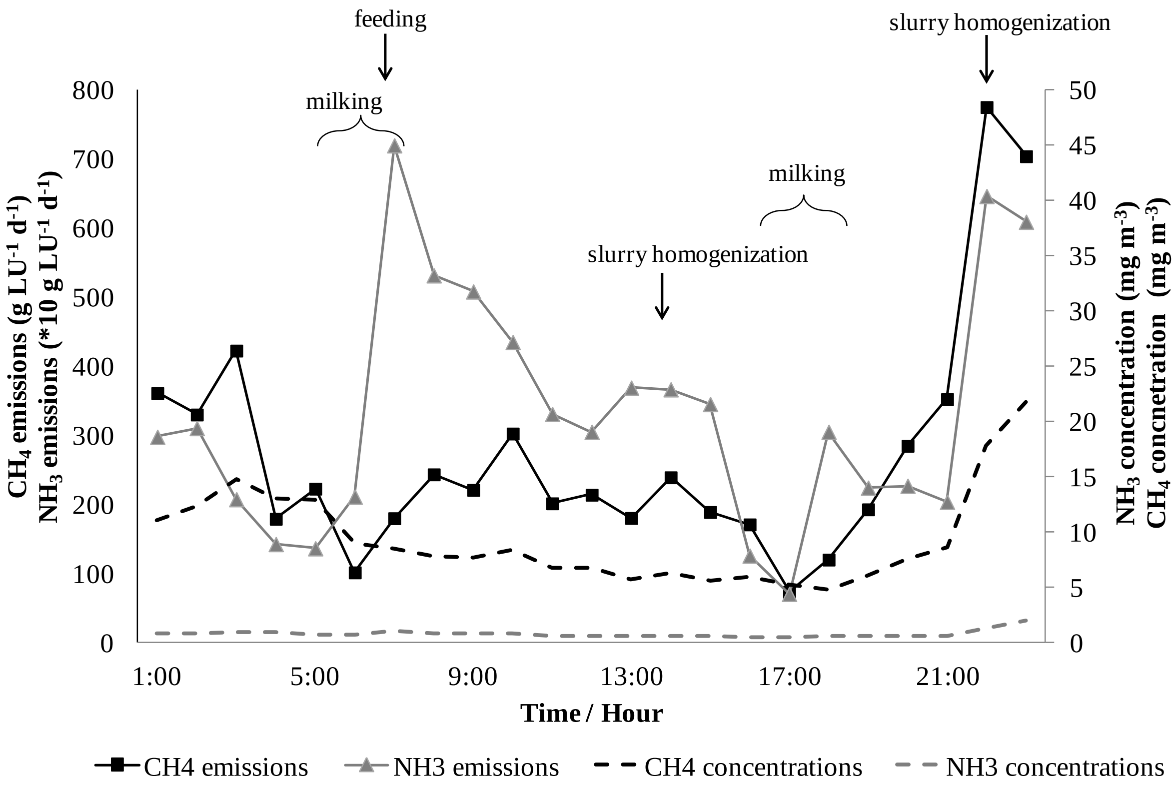

Figure 1.5 Typical concentrations and emissions of CH_4 and NH_3 over the course of a day (24.05.2011); CH_4 and NH_3 emissions based on VR_{mod}

Table 1.3 Emission rates of CH_4 and NH_3 for the three sections; arithmetic means; only the spring season was considered for annual emission rates; statistical analysis using the non-parametric Friedman and Bonferroni post hoc test ($\alpha = 0.05$); VR_{mod} = ventilation rate by tracer gas model; VR_{bal} = ventilation rate by CO_2 mass balance

	Section 1 slatted floor + high intensity of slurry mixing in pit		Section 2 slatted floor + low intensity of slurry mixing in pit		Section 3 solid floor; no pit	
	based on VR_{mod}	based on VR_{bal}	based on VR_{mod}	based on VR_{bal}	based on VR_{mod}	based on VR_{bal}
CH_4						
g LU^{-1} d^{-1}	331^a	191	261^b	167	387^a	184
SD	± 143	± 61	± 108	± 20	± 147	± 22
kg LU^{-1} yr^{-1}	121^a	70	95^b	61	141^a	67
SD	± 52	± 22	± 39	± 7	± 53	± 8
NH_3						
g LU^{-1} d^{-1}	37.3^a	22.2	24.2^b	15.4	35.9^a	17.5
SD	± 18.5	± 6.5	± 12.4	± 3.4	± 15.2	± 5.3
kg LU^{-1} yr^{-1}	13.6^a	8.1	8.8^b	5.6	13.1^a	6.4
SD	± 6.7	± 2.4	± 4.5	± 1.3	± 5.6	± 1.9

1.4 Discussion

This building-specific model to calculate VR_{mod} was delivering rough, but reasonable results with minimal effort, and thus serves as preliminary work for further long-term investigations in this experimental barn. However, the approach has to be further developed and/or supplemented. Especially for time periods when the curtains are closed (e.g. in winter), the tracer gas set up has to be adapted and the model to calculate VR has to be modified. This is of particular importance for the calculation of emission factors, which must consider measurements during all seasons of the year.

In case of open curtains there were decisive constraints on the applied technology by the wind direction. Thus the tracer gas technology utilized and the resulting model were applicable for the determination of VR_{mod} as long as a West-East cross-ventilation was occurring (R= 0.92). The correlation between wind conditions and VR_{mod} in our own investigation was quite close; in that regard, SNELL et al. (2003) reported correlations of 0.59–0.84 in four eave-to-ridge ventilated buildings. However, it can be assumed that the influence of wind speed in a naturally cross-ventilated building is even higher than in eave-to-ridge ventilated buildings with only small air inlet dimensions (SNELL et al., 2003).

The range of VR_{mod} in our own investigations of 870 – 6,888 m^3 LU^{-1} h^{-1} was broad, but similar to the range reported by Samer et al. (2011[3]) of about 900 up to slightly over 9,000 m^3 LU^{-1} h^{-1}. The obtained results in this study meet the recommendation of DLG (2005) for Germany, to achieve a VR greater than 700 m^3 h^{-1} per LU in Summer[4] for high yielding dairy cows. The high variation of VR can be explained by the highly fluctuating wind speed and the close dependency of VR on wind speed.

From a physical point of view, the cross ventilated dairy barn can be seen as an aerodynamic drag. Considering the inlet dimension of 82.8 m^2 per compartment and an incoming wind speed of e.g. 1 m s^{-1}, one would expect a ventilation rate of 4,436 m^3 LU^{-1} h^{-1} per compartment in the case of no air flow resistance. The VR_{mod} at wind speed of 1 m s^{-1} is actually 2,369 m^3 LU^{-1} h^{-1} for one compartment in the own investigation. This shows that the barn and its equipment as well as the animals inside derive a flow resistance of 53%.

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[3] converted from air exchange rate, assuming 1.4 LU per cow

[4] converted from original recommendation of 1,000 m^3 cow^{-1} h^{-1}

The building-specific air exchange model is not transferable from one building to another without transformation, since the exposition, especially the wind flow (e.g. influenced by topography or neighbouring buildings) may affect the sensitivity of VR to the wind speed. However, it might be useful to gather information on the level of flow resistance of several barns and different barn types.

For both CH_4 and NH_3 emissions it was possible to record significant differences between different sections of the building. The lowest emission rates for CH_4 and NH_3 were found for the slatted floor with subfloor storage of liquid manure, with a low intensity of homogenization of the liquid manure. In contrast, ZHANG et al. (2005) found the lowest NH_3 emission rates in a building with solid floors with a smooth surface, scraper and drain. The levels of NH_3 and CH_4 emissions using VR_{mod} (37.3, 24.2 and 35.9 g NH_3 LU^{-1} d^{-1} and 331, 261 and 387 g CH_4 LU^{-1} d^{-1} for sections 1–3, respectively) agree with the results of NGWABIE et al. (2009) of 27 g NH_3 LU^{-1} d^{-1} and 271 g CH_4 LU^{-1} d^{-1} in March with a partially slatted floor. SAMER et al. (2011) reported a higher level of emissions (93.6 g NH_3 LU^{-1} $d^{-1}$and 456 g CH_4 LU^{-1} d^{-1}) whereas these measurements were conducted during summer seasons.

Applying an equation based on the dry matter intake of dairy cows (equation 2d, ELLIS et al. 2007) the enteric CH_4 release by the cows under investigation is 242 g CH_4 d^{-1} LU^{-1}. In relation to the own measurements (VR_{mod}) this would lead to a percentage of CH_4 emissions from the barn/manure of 27% (slatted floor intensive), 7% (slatted floor not intensive), and 37% (solid floor). These findings agree with results from other authors reporting a percentage of emissions from manure of 7-27% (HINDRICHSEN et al., 2006; HINDRICHSEN et al., 2005; KÜLLING et al., 2002). When assessing the level of gaseous emissions the VR_{mod} seems much more realistic than emissions received by VR_{bal}. The CH_4 emissions from barn and storage using VR_{bal} (167-201 g CH_4 d^{-1} LU^{-1}) were even below the level expected from enteric fermentation only (242 g CH_4 d^{-1} LU^{-1}). This leads to the conclusion that the applied CO_2 mass balance is underestimating the VR of the barn. One reason for this may be that the higher the VR of the barn, the lower the difference between indoor and outdoor CO_2 concentration leading to uncertainties in the calculation of the VR. Furthermore, there may be other sources of CO_2 within the barn not being considered by the equation.

The reported emission rates are only representative of the spring season and are not transferable to the whole year, since temperature strongly influences levels of CH_4 and

NH_3 emissions (MASSE et al., 2008; MONTENY et al., 2006; NGWABIE, JEPPSSON, GUSTAFSSON, & NIMMERMARK, 2011; NGWABIE et al., 2009; SOMMER et al., 2007).

1.5 Conclusions

The building-specific model based on data on wind direction and speed is a rough, but solid method for estimating VR whereas the CO_2 mass balance was underestimating VR. It was found that each increase of 1 m s^{-1} increased VR_{mod} by almost 1,500 m^3 h^{-1} LU^{-1}. However, when the curtains are closed and no cross-ventilation is found, other methods to calculate VR have to be developed. This is of particular importance when determining emission factors which must consider seasonal effects. In conclusion the development of a building-specific model for the calculation of VR is complex and time consuming but very efficient and cost effective for long-term measurements at the same site.

Slurry management, in this case the lower intensity of slurry homogenization within the subfloor storage, resulted in a 21% reduction in CH_4 emissions and a 35% reduction of NH_3 emissions. For a final conclusion and for future investigations comparing the influence of floor type on gaseous emissions in dairy farming all seasons of the year should be considered. If emissions from two housing systems are compared, additionally required external slurry storages and their gaseous emissions have to be included into analyses.

1.6 Acknowledgements

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Chapter 2 - **Effect of manure removal and storage management on methane and ammonia emissions from a naturally ventilated dairy barn**[5]

Abstract

Dairy barns represent a significant source of gaseous emissions such as methane (CH_4) and ammonia (NH_3). There is still a lack of knowledge regarding the influence of the floor design and manure management on CH_4 and NH_3 emissions from dairy barns. The objective of this work was a simultaneous comparison of CH_4 and NH_3 emissions from different floor designs and manure-management strategies within the same dairy barn. Therefore long-term emission measurement data for the barn and model-based estimations for the external manure storage (using the process-based farm level model DAIRYDYN) were brought together in order to compare the total emission amounts precisely. The investigated naturally cross-ventilated dairy barn was divided into three equally sized compartments, each of which was designed for 48 lactating Holstein cows. One compartment had a slatted floor with subfloor storage and was run with a high intensity of manure homogenization, one compartment had a slatted floor with subfloor storage and a low intensity of homogenization, and one compartment had a solid floor with scrapers and external manure storage. On annual average the highest CH_4 and NH_3 emissions at barn level were found on the slatted floor with high intensity of homogenization (381.7 ± 149.2 g CH_4 LU^{-1} $d^{-1}$and 38.4 ± 15.1 g NH_3 LU^{-1} d^{-1}). Considering an uncovered external manure storage in the solid floor scenario on annual average the CH_4 emissions from the solid floor including storage exceeded the level of the slatted floor with intensive homogenization on annual average (417.8 g CH_4 LU^{-1} d^{-1}) whereas NH_3 emissions remained at the level of the slatted floor with intensive homogenization (37.9 g NH_3 LU^{-1} d^{-1}). In all cases and seasons the lowest emissions were found on slatted floor with low intensity of homogenization (e.g., 324.9 ± 123.6 g CH_4 LU^{-1} and 29.8 ± 13.1g NH_3 LU^{-1} d^{-1} on annual average). The results show that the influence of manure management, especially homogenization intensity of liquid manure beneath the slatted floor, led to higher differences than the floor design itself. Thus there is no general recommendation for one of the tested floor designs (slatted floor or solid floor) regarding CH_4 and NH_3 emissions.

Keywords: *ammonia, methane, emissions, dairy barn, manure storage, emission modeling*

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[5] This chapter is based on a manuscript submitted to the Journal 'Agriculture, Ecosystems and Environment' as SCHIEFLER I., LENGERS B., SCHMITHAUSEN A. and W. BÜSCHER: Effect of manure removal and storage management on methane and ammonia emissions from a naturally ventilated dairy barn. Inga Schiefler was responsible for the whole manuscript and contributed significantly to all sections except 2.2.3.

Nomenclature

d = day

GHG = greenhouse gases

h = hour

LU = livestock unit (500 kg of live weight; 1 cow is 700kg)

VR = ventilation rate [m^{-3} h^{-1}]

yr = year

2.1 Introduction

Livestock production is a significant source of gaseous emissions, such as methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3). Several studies have been published estimating livestocks' contribution to the anthropogenic greenhouse gas emissions. The indicated percentage of livestock worldwide was stated at 18% in an FAO study (FAO, 2006), within the EU the percentage was estimated at 9.1% by LEIP et al. (2010). However, there is a broad discussion about where to put the system border and 'the importance of getting the numbers right' (HERRERO et al., 2011). Emission factors on barn level are composed of the animals' release and by the emission generation of the manure on floors and channels. There are several studies in the literature focusing on CH_4 emissions from enteric fermentation (AGUERRE et al., 2011; DERNO et al., 2009; Ellis et al., 2007; GARNSWORTHY et al., 2012; PLACE et al., 2011; VAN ZIJDERVELD et al., 2011) whereas emissions at the barn level have been studied less thoroughly (Ngwabie et al., 2009; Samer et al., 2011; Wu et al., 2012). Furthermore, some studies may be limited to model/scale studies (AGUERRE et al., 2007; PEREIRA et al., 2011). The proportion of CH_4 emissions from manure is estimated to be about 20% for dairy cattle worldwide (FAO, 2006). Other authors reported a percentage of CH_4 emissions from manure of 7-27% (HINDRICHSEN et al., 2006; HINDRICHSEN et al., 2005; KÜLLING et al., 2002). The influence of floor design on CH_4 emissions at barn level has been poorly studied. However, PEREIRA, et al. (2011) reported higher emissions from solid floors than from slatted floors at all temperatures, but this investigation was performed as a scale-model study. PEREIRA et al. (2012) reported a positive correlation of CH_4 release and temperature, and illustrated that CH_4 emission from cattle excreta is increased with temperature up to a temperature of 25°C.

In contrast to CH_4 which is mainly directly emitted by the animals, NH_3 emissions mainly originate from feces and urine on floors and channels, and manure storage. Much research has been conducted to measure NH_3 emissions from dairy barns in the past (for instance BRAAM et al., 1997; KROODSMA et al., 1993; SOMMER et al., 2006). Recent studies of SCHRADE et al. (2012) and Wu et al. (2012) have investigated the correlation of weather parameters as well as of production parameters with NH_3 emissions in different housing systems. Since scientists agree on the positive correlation between NH_3 emission and temperature in general, the issue of floor design on NH_3 emissions is still not yet clarified (PEREIRA et al., 2012; PEREIRA, et al., 2011; PEREIRA et al. 2010; SCHRADE, et al., 2012; WU et al., 2012).

Apart from floor design as a matter of construction, the manure management - e.g., slurry treatment and stirring - may play an important role for the emission levels (PETERSEN and SOMMER, 2011; PETERSEN et al., 2005; SOMMER et al. 2007; SOMMER et al., 2000).

There are several approaches of slurry storage in dairy farming. The storage may be entirely or partly within the building (slatted floor with subfloor storage) as a part of the total barn-level emissions. Other systems (e.g., solid floors with scrapers) include an external slurry tank, which may be designed in a more or less emitting manner. The external tank can either be open or covered, e.g., by a gastight foil, solid cover or loose materials like straw. Furthermore, there are certain effects on the emissions by management of the stored slurry, in particular stirring or crusting. For instance, MISSELBROOK et al. (2005) stated that the NH_3 emissions of uncrusted storages were more than twice as high as from crusted storages. Regarding CH_4 emissions, anaerobic covered storages are of major importance in combination with biogas plants (CUELLAR and WEBBER, 2008; MONTENY et al. 2006). In conclusion, an honest comparison of two dairy housing systems regarding the level of gaseous emissions should always include manure storage whether inside or outside the building.

In summary, there is a lack of knowledge regarding the influence of floor design, manure removal and manure homogenization on CH_4 and NH_3 emissions. The investigations reported here were set up in a simultaneous comparison of housing systems within the same building and covering the same basic parameters (e.g., number of animals, breed, lactation day, milk yield, feeding and management as well as barn construction and ventilation).

The objective of this study was to evaluate whether one of the tested manure removal and related indoor/external manure storage strategies leads to significantly lower CH_4 and NH_3 emissions on annual average. Therefore, long-term measurement data for the barn- and model-based estimations for the external storage were brought together in order to compare the total emission amounts precisely.

2.2 Material and Methods

2.2.1 Procedures

Three common-practice scenarios were investigated within this study (Tab 2.1). There were two barn sections with slatted floor and subfloor storage and one section with solid floor and scrapers whereas manure storage in the slatted floor sections was included, for the solid floor section an external storage was considered.

Table 2.1 Description of the tested common practice scenarios

	Slatted floor		**Solid floor**		
Scenario No.	1a	1b	2a	2b	2c
Liquid manure storage	subfloor	subfloor	external	external	external
Intensity of liquid manure homogenization	high	low	-	-	-
Coverage of storage	-	-	airtight cover	straw cover	none

Range of measurement:

The emission measurements were conducted at barn level covering all sources **within** the building which implies emissions released by the animals and the emissions from floors, channels, and subfloor liquid manure storages. In our investigation the measurement covered the emissions from the slatted floor sections including the entire liquid manure storage of these sections (Fig 2.1, Fig 2.2).

Emissions from liquid manure storages from the solid floor section outside the building were not covered by emission measurements (e.g., external manure shafts, pits and storage tank, Fig 2.2).

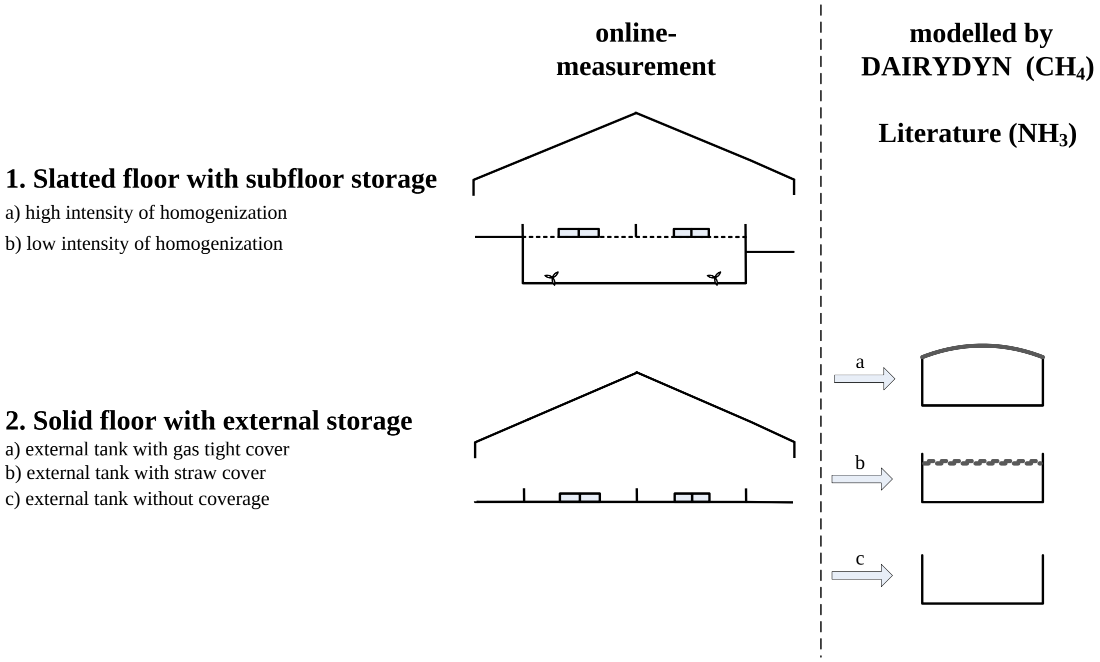


Figure 2.1 Range of measurement and range of model/literature data

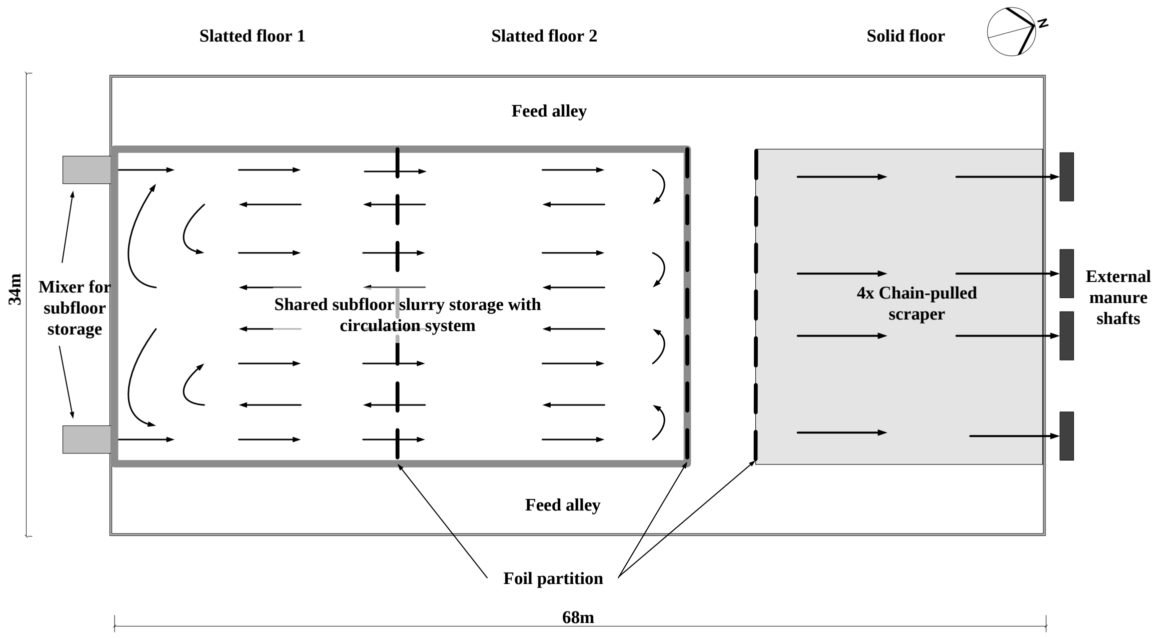


Figure 2.2 Scheme of dairy barn, liquid manure removal and storage

Range of model DAIRYDYN and literature-based data

The model DAIRYDYN was used to calculate the CH_4 emissions from external liquid manure storage of the entire year, based on specific data of the investigated farm (e.g., milk yield, feed composition, body weight). In our investigation the model was applied to calculate CH_4 emissions from storage of manure coming from the solid floor section.

For the estimation of NH_3 emissions from liquid manure storage, the authors calculated the emission factor for the liquid manure storage based on our own measurements of slurry amount and data from the literature with similar conditions (AMON et al., 2006; BALSARI et al., 2007; MISSELBROOK, et al., 2005; MISSELBROOK et al., 2000; SMITH et al., 2007).

2.2.2 Description of measurement procedures

The experimental farm was located in Kleve, Germany. The measurements were conducted from December 2010 to December 2011 covering the entire year (Tab 2.2). Limited by wind direction and other experimental restrictions, 120 days were included in the final analysis. 144 lactating Holstein cows with an average milk yield of 34 kg per day were held in three equally sized sections of a free-stall dairy barn leading to groups of 48 animals in each section. The total average dry matter feed intake per cow was 19 kg d^{-1}, with a mean crude protein of the mixed ration of 16.6% (dry matter) and crude fiber of 17.4% (dry matter).

Figure 2.3 Foil partition of the investigated dairy barn

The air spaces of the sections were separated by foil partition (Fig 2.3). Two sections of the barn were equipped with a slatted floor and a shared subfloor manure storage (slalom system, Fig 2.2). The slurry stored in the pit beneath the slatted floor was stirred twice a day for 30 minutes from December 2010 to September 2011, and from October 2011 to December 2011 only once every 10 days. Due to the position of the mixer at the gable wall of the building it was possible to derive one section with intensively mixed slurry (section 1) and one section with less intensively homogenized and thus less aerated slurry (section 2, Fig 2.2). The slatted floor was water-cleaned by an automated cleaning robot (Joz Tech JT100, Joz B.V., Netherlands) at least four times a day. The third section of the barn had a solid floor with four cable-pulled scrapers with a frequency of 20 times a day. There was an external manure discharge, forwarding the liquid manure to an external slurry pit. The emitting area (walking area) in all sections was 7 m² per cow.

Table 2.2 Description of measurement periods and conditions

Season	Measurement period	Temperature °C $\bar{x}$ ± SD	Wind speed m s^{-1} $\bar{x}$ ± SD	Position of Curtains	VR method	Comments
Winter	20.12.2010 - 26.01.2011	3.6 ± 4.1	2.1 ± 0.9	closed	CO_2 mass balance	
	07.12.2011 - 21.12.2011	5.9 ± 1.5	3.4 ± 1.0	closed	CO_2 mass balance	
Spring	03.03.2011 - 16.03.2011	2.7 ± 4.8	1.9 ± 0.7	partly open	CO_2 mass balance	very cold period from 03.-08.03.2011
	20.04.2011 - 06.06.2011	17.4 ± 3.1	1.5 ± 0.6	open	Model (tracer gas)	
Summer	07.06.2011 - 10.08.2011	18.2 ± 2.7	2.0 ± 0.6	open	Model (tracer gas)	
Autumn	25.11.2011 - 05.12.2011	8.2 ± 1.0	2.9 ± 0.6	partly open	CO_2 mass balance	

The barn was cross-ventilated with an eave height of 5 m and a ridge height of 13 m. The curtains at the west side of the barn were closed during wintertime. Milking was performed twice a day in the adjacent building including the waiting area. Milking time was not included in the emission calculation. The emissions (E) were calculated using the gas concentrations from the exhaust air ($C_{exhaust}$) minus the background concentration ($C_{background}$) of the respective section and the ventilation rate of the barn (VR) using the following equation:

$$E = VR * (C_{exhaust} - C_{background}).$$

The measurements of gas concentrations were performed every 5 minutes at the eastern eave side (exhaust position), as long as west-to-east cross-ventilation occurred (photo-acoustic multi-gas analyzer 1412 and a multiplexer 1303, Lumasense Technologies SA, Ballerup, Denmark). The exhaust air was sampled at eight measurement points at 4 m height in each section by vacuum pumps and forwarded through poly-tetrafluoro-ethylene (PTFE) to the multiplexer and gas monitor in the adjacent building (Fig 2.4).

Figure 2.4 Sampling points at the eastern eave side of the building (foil partition was lowered at measurement start)

In summer, spring and autumn the VR was calculated using a building-specific air exchange model. The model was developed on the basis of a series of several measurements with the tracer-decay method (sulfur hexafluoride, SF_6; NIEBAUM, 2001; SCHNEIDER, 2006; SEIPELT, 1999) and the actual wind conditions. In winter, when the curtains were closed, the VR was estimated by means of the CO_2 mass balance (CIGR, 2002). The calculation of the emissions was performed using hourly means of the gas concentrations and the VR, respectively. The statistical analysis of the results included non-parametric Friedman tests, post hoc Bonferroni tests ($\alpha=0.05$) and Pearson correlation analysis. CH_4 and NH_3 emissions from the barn (measurement data) were calculated on average for each season leading to the annual average in equal parts.

2.2.3 Description of modeling procedure

The model DAIRYDYN is a highly detailed process-based farm level model that was developed to quantify GHG emissions, promising mitigation strategies and adherent abatement costs on specialized dairy farms (LENGERS and BRITZ, 2012). The general model is based on a mixed integer linear programming approach with a profit-maximizing objective function. The model encompasses different modules for animal, milk, feed and cash crop production. Further on, it observes detailed mass flows between the modules to account for, e.g., manure amounts depending on animal number and milk output as well as manure in different storages. For the quantification of emissions stemming from arable production, digestive processes and manure management, the approach implies a GHG accounting module that calculates emissions following IPCC (2006) guidelines. Due to the high disaggregation of the farm-level model and a GHG quantification scheme that delivers also CH_4 amounts from manure storages on monthly resolution for different surface storages with different coverage techniques, the model is capable to estimate CH_4 emissions from external storages. This is necessary to quantify emissions from the solid floored barn complex including measurable in-barn emissions and not measurable emissions of external slurry tanks. The yearly CH_4 amount of the manure in external tanks is calculated concerning the following formula based on equation 10.23 of the IPCC (2006) framework and adherent formulas and tables:

$$\mathrm{CH_4} = \sum_{cows}\sum_{m} VS_{m,s} \times B0 \times 0.67 \times MCF_s$$

$VS_{m,s}$ = volatile solid excretion cow^{-1} month^{-1} on a dry-organic matter basis in storage type s (in m^3 month^{-1}); B0 = maximum methane production capacity for manure (m^3 CH_4 kg^{-1} of VS); 0.67 = conversion factor of m^3 CH_4 to kg CH_4; MCF_s = monthly methane conversion factor for specific surface manure storage with specific coverage.

Hence, production-specific information (cow number, milk output, temperature, etc.) of the barn complex under investigation are implemented into DAIRYDYN to simulate occurring CH_4 outputs from open, straw- or foil-covered external manure tanks depending on the amount of manure stemming from the solid floor section.

2.3 Results

The slatted floor section with intensive mixing (Scenario 1a, 381.7 g CH_4 LU^{-1} d^{-1}) led to the highest CH_4 emissions from the barn on annual average and to significantly higher CH_4 emissions compared to the slatted floor section with lower mixing intensity (Scenario 1b, 324.9 g CH_4 LU^{-1} d^{-1}, Tab. 2.3, significance level α=5%). However, there were no significant differences between the solid floor section (external storage not considered or external storage with gastight cover, Scenario 2a, 352.6 g CH_4 LU^{-1} d^{-1}) and each of the slatted floor sections on annual average (Tab 2.3). Considering CH_4 from external liquid manure storage (solid floor section) the emissions from the solid floor on annual average increased by 37.9 g CH_4 LU^{-1} d^{-1} in the case of straw-covered storage (Scenario 2b) and by 65.2 g CH_4 LU^{-1} d^{-1} in the case of storage without coverage (Scenario 2c, Fig 2.5). Thus, the emissions of barn and storage in total are the highest for the solid floor section (Scenario 2b - straw coverage 390.5 g CH_4 LU^{-1} d^{-1} and Scenario 2c - no coverage 417.8 g CH_4 LU^{-1} d^{-1}) and remain the lowest for the slatted section with less intensive mixing annual average (Scenario 1b, 324.9 g CH_4 LU^{-1} d^{-1}, Fig 2.5). That implies, that the 'worst case' - Scenario 2c, solid floor and storage without coverage - leads to 29% higher CH_4 emissions than the best case - Scenario 1b slatted floor with low mixing intensity - on annual average.

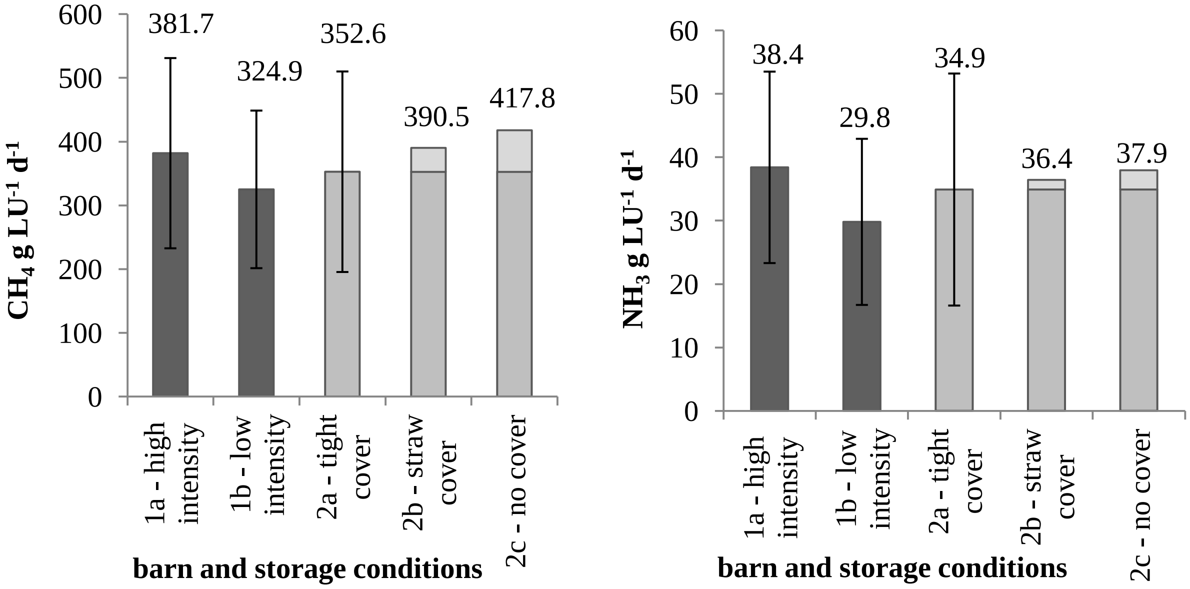


Figure 2.5 Average CH_4 and NH_3 emissions of the barn sections over the four seasons. Standard deviation limited to emissions from the barn. CH_4 emissions from storage derived from model calculation with DAIRYDYN (Scenario 2b and 2c, light grey field). NH_3 emissions from storage are estimated by the authors based on literature findings.

Table 2.3 Barn level CH_4 and NH_3 emissions on average over the four seasons

CH_4	Section 1 Slatted Floor	Section 2 Slatted Floor	Section 3 Solid Floor
g LU^{-1} d^{-1}	381.7 ± 149.2	324.9 ± 123.6	352.6 ± 157.3
kg LU^{-1} yr^{-1}	139.3 ± 54.5	118.6 ± 45.1	128.7 ± 57.4
Sign. α=5%	a	b	ab
NH_3	**Section 1 Slatted Floor**	**Section 2 Slatted Floor**	**Section 3 Solid Floor**
g LU^{-1} d^{-1}	38.4 ± 15.1	29.8 ± 13.1	34.9 ± 18.3
kg LU^{-1} yr^{-1}	14.0 ± 5.5	10.9 ± 4.8	12.7 ± 6.7
Sign. α=5%	a	b	ab

Ammonia emissions from the barn ranged from 29.8 g NH_3 LU^{-1} d^{-1} on annual average from the slatted floor section with low intensity of homogenization (Scenario 1b) to 38.4 g NH_3 LU^{-1} d^{-1} on annual average from the slatted floor section with high intensity of homogenization (Scenario 1a, Tab. 2.3). There was a significant difference in the a/m NH_3 emissions between the two slatted floor sections (significance level α=5%). The solid floor section (Scenario 2a - expecting no additional emissions from storage, 34.9 g NH_3 LU^{-1} d^{-1}) did not significantly differ from both slatted floor sections with high and low intensity of homogenization. Assuming 3.0 g NH_3 LU^{-1} d^{-1} from storage in Scenario 2c, the solid floor with external uncovered storage remains with 37.9 g NH_3 LU^{-1} d^{-1} at the level of the emissions from slatted floor with high intensity of homogenization (38.4 g NH_3 LU^{-1} d^{-1}). In the case of coverage with straw emissions from storage are estimated as 1.5 g NH_3 LU^{-1} d^{-1} and lead to total emissions from barn and storage of 36.4 g NH_3 LU^{-1} d^{-1} (Fig 2.5).

Regarding the influence of season, NH_3 emissions at the barn level ranged from 24.7 ± 5.5, 20.2 ± 9.2 and 18.5 ± 2.2 g NH_3 LU^{-1} d^{-1} in the winter measurement period averaging 4.7°C to 59.4 ± 15.9, 49.2 ± 10.0 and 60.9 ± 13.4 g NH_3 LU^{-1} d^{-1} in the summer measurement period averaging 18.2°C from slatted floor intensive, slatted floor not intensive, and solid floor, respectively. CH_4 emissions at the barn level ranged from 293.8 ± 51.2, 290.9 ± 63.0 and 250.0 ± 19.5 g CH_4 LU^{-1} d^{-1} in the winter measurement period to 604.04 ± 115.7, 507.9 ± 80.0 and 586.0 ± 94.8 g CH_4 LU^{-1} d^{-1} in the summer measurement period from slatted floor intensive, slatted floor not intensive, and solid floor, respectively. During winter season, there was no significant difference between slatted floor intensive and slatted floor not intensive (significance level α=5%), whereas in all other seasons significant differences between the slatted floor sections were found.

There were significant correlations between temperature and CH_4 and NH_3 emissions in each section (Fig 2.6 and 2.7). The correlations were the highest for the solid floor (Pearson correlation coefficient r=0.64, r=0.47, r=0.76, for NH_3 and r=0.55, r=0.38, r=0.71 for CH_4 for slatted floor intensive, slatted floor not intensive, and solid floor, respectively).

VR per cow ranged from 1,384 ± 166 m^{-3} h^{-1} during the winter season with closed curtains to 6,355 ± 956 m^{-3} h^{-1} per cow in the summer season with open curtains.

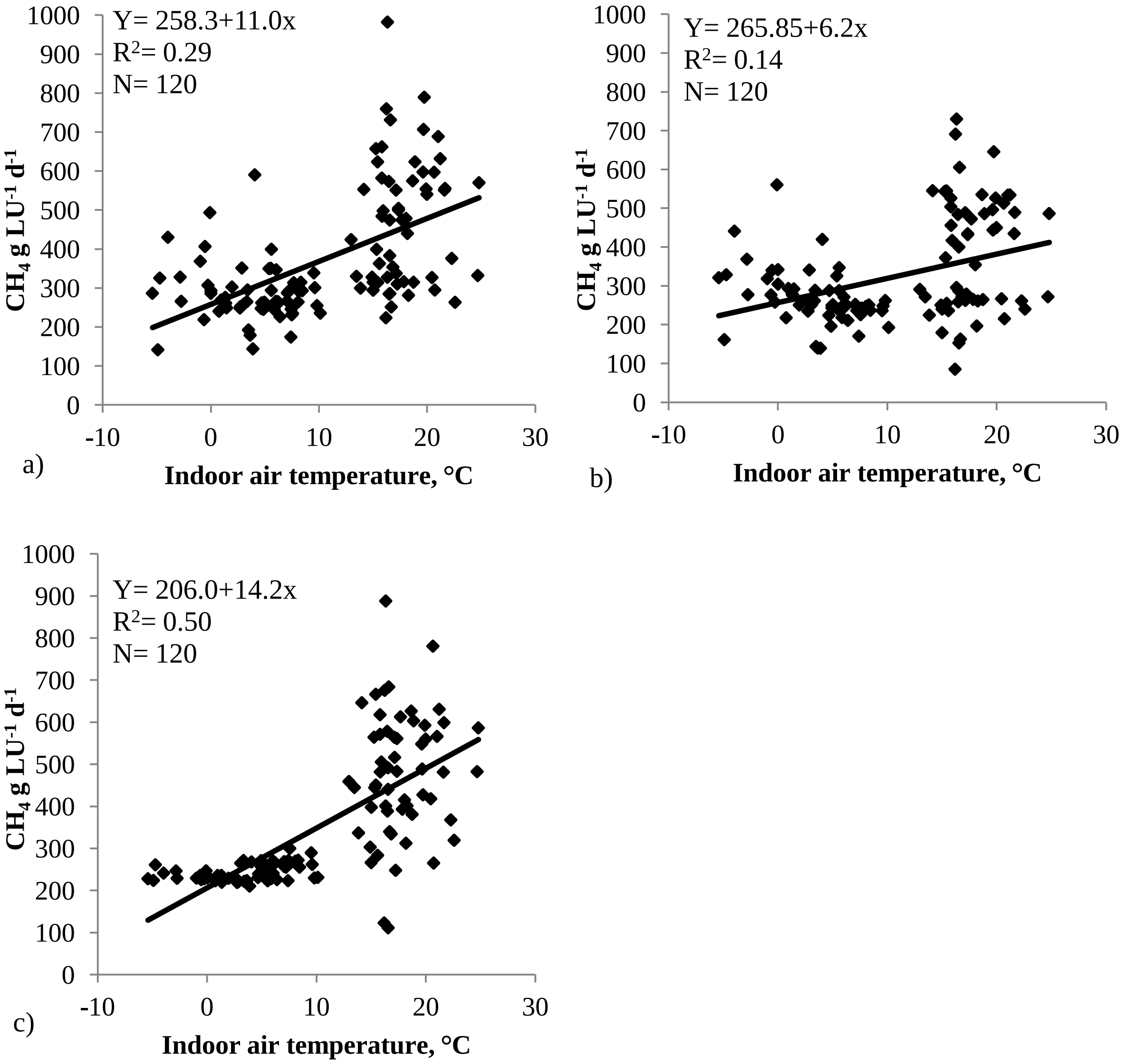
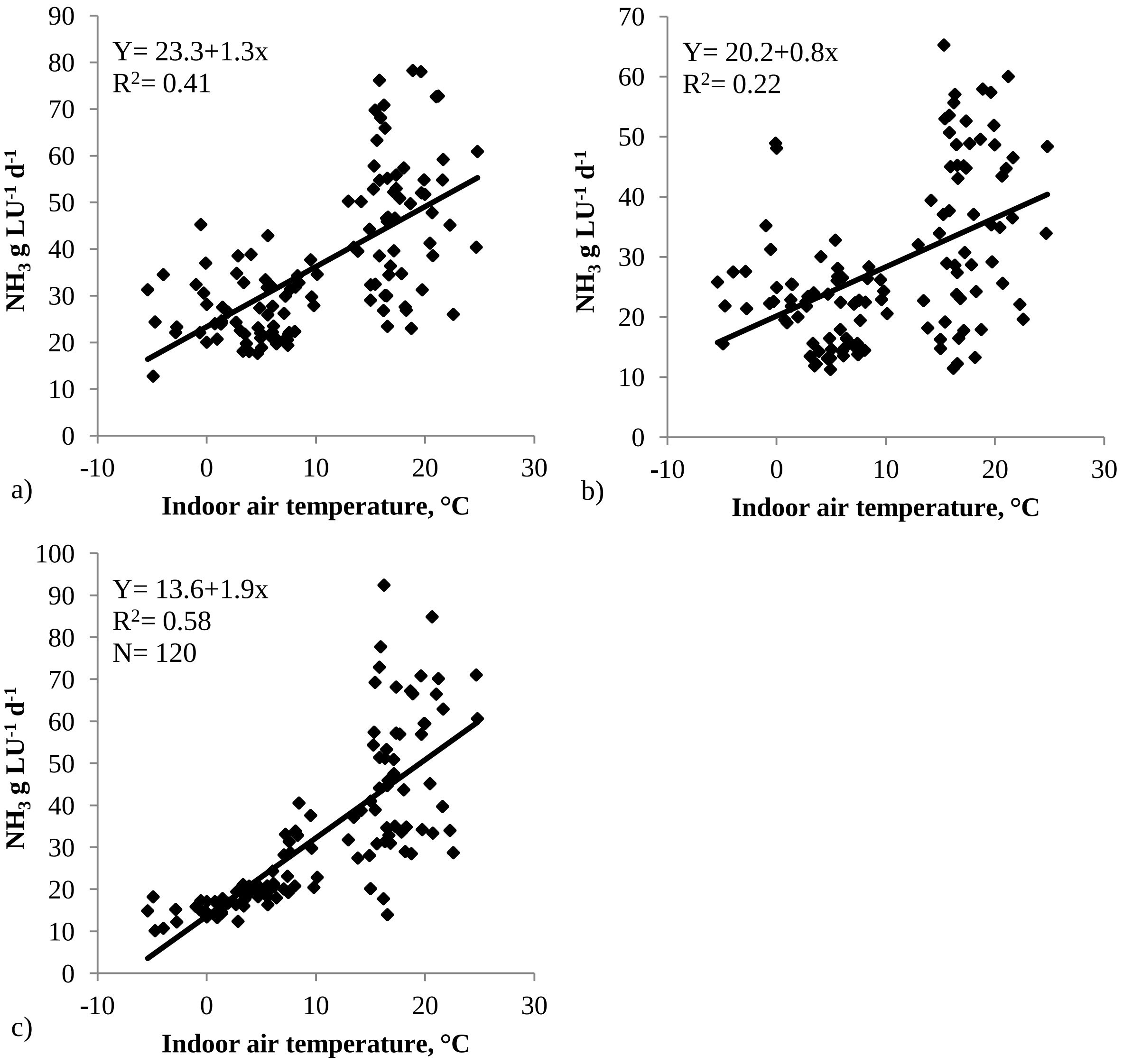


Figure 2.6 CH_4 emission rates on daily average for (a) slatted floor intensive, (b) slatted floor not intensive, and (c) solid floor



a)

b)

c)

Figure 2.7 NH_3 emission rates on daily average for (a) slatted floor intensive, (b) slatted floor not intensive, (c) and solid floor.

2.4 Discussion

The applied methods for measuring the gas emissions were suitable and reliable for long-term-conditions. However, it has to be considered that measurement errors do occur, especially when calculating the VR. The equation for the CO_2 mass balance (CIGR, 2002) does not, for example, include other CO_2 sources in the barn. Further, it has been developed for mechanically ventilated buildings and is not suitable for naturally ventilated buildings with large open surfaces since the accuracy decreases with increasing VR. However, since this method was applied in the situation of closed curtains which leads to a lower VR, this effect did not affect our own measurements strongly. Further, it has to be considered that the tracer gas technique in naturally ventilated buildings may also lead to errors of up to 10% (SCHNEIDER, 2006). For this reason, the applied method is not suitable to determine minor differences (<10%) between two systems.

The highest average VR was found in the summer period at 6,355 ± 956 m^{-3} h^{-1} with open curtains. This seems to be relatively high with regard to the recommendation of the German Agricultural Society (DLG 2005), which states that the ventilation rate should be greater than 1,000 m^3 h^{-1} per cow in summer for high-yielding dairy cows. However, considering the large open walls in the building and the natural cross-ventilation, the level of VR is realistic. For instance, SAMER et al. (2011) found ventilation rates of more than 12,000 m^3 h^{-1} per cow in experiments in a naturally cross-ventilated dairy barn during the summer season.

Our own results for the winter season of 250-294 g CH_4 LU^{-1} d^{-1} and 19-25 g NH_3 LU^{-1} d^{-1} correspond with results of NGWABIE et al. (2009) of 278-315 g CH_4 LU^{-1} d^{-1} and 24-25 g NH_3 LU^{-1} d^{-1} which were also measured during the winter season. For the summer season the measured emission rates of 508-604 g CH_4 LU^{-1} d^{-1} and 49-61 g NH_3 LU^{-1} d^{-1}, respectively, are only slightly varying from the results of SAMER et al. (2011) reported for the summer season (456 g CH_4 LU^{-1} d^{-1} and 93 g NH_3 LU^{-1} d^{-1}). In a recent study, SAMER et al. (2012) reported even higher emission factors from a naturally ventilated building in Germany using a tracergas technique (855 g CH_4 LU^{-1} d^{-1} and 191 g NH_3 LU^{-1} d^{-1}). Further, SAMER, et al. (2012) also found high differences between the summer and winter seasons which corresponds exactly with our findings.

Regarding our investigation the recommendation of one of the applied manure removal systems ‘slatted floor or solid floor’ with respect to the CH_4 and NH_3 emissions is not feasible. Due to different management practices, both ‘best’ and ‘worst’ case for CH_4 and NH_3 were found within the same floor design. The effect of manure management beneath the slatted floor is affecting the level of both CH_4 and NH_3 in a similar way (+17 and +29% due to higher homogenization level). This agrees with the findings of ZHANG et al. (2005) who stated that in buildings with high NH_3 emissions high CH_4 emissions were found at the same time. Assuming that intensive slurry mixing is leading to a higher aeration of the slurry one could have expected that the intensive mixing might reduce CH_4 emissions. However, this expectation could not be confirmed in our investigation.

PEREIRA et al. (2011) reported higher CH_4 and NH_3 emissions from solid floors at all temperatures in comparison to slatted floors. These findings can be confirmed by our results only for the case of a low mixing intensity beneath the slatted floor and a high cleaning intensity. Nevertheless, PEREIRA et al. (2011) performed a scale-model study and did not consider a large slurry storage. In our investigation on annual average the lowest emissions from barn and storage in total, both for CH_4 and NH_3, could be achieved with a slatted floor and a low mixing intensity. ZHANG et al. (2005) found the lowest NH_3 emissions in a barn with a solid floor. The fact that the floor design may not be the main factor affecting the level of NH_3 emissions has also been stated by PEREIRA et al. (2010).

There was a positive effect of temperature on the CH_4 and NH_3 emissions (Fig 2.6 and 2.7). The coefficient of determination was highest for the solid floor, both for CH_4 and NH_3. One reason for the lower number of outliers on the solid floor could be the influence of the slurry storage beneath the slatted floor sections, leading to higher variations.

Apart from floor design and manure removal within the barn, the design of the external slurry tank may affect the level of gaseous emissions significantly. The coverage of the slurry storage with an organic layer such as straw may reduce NH_3 emissions, but it may also enhance the dry matter content of the slurry which may lead to higher NH_3 emissions after field application (AMON et al., 2006). It should be considered that the further treatment and application of the slurry may affect the NH_3 balance dramatically (DINUCCIO et al., 2012). Regarding mitigation options, it always has to be considered whether a reduction of emissions of one certain gas may affect an increase of other gaseous emissions. This effect may occur especially in the case of NH_3 and N_2O (PETERSEN and SOMMER, 2011).

2.5 Conclusions

This investigation was focused on the comparison of CH_4 and NH_3 emissions from different manure removal systems for dairy cattle within one building. The results show that the influence of manure management, especially homogenization of liquid manure beneath the slatted floor, led to higher differences than the floor design itself. The effect of manure management beneath the slatted floor is affecting the level of both CH_4 and NH_3 emissions in a similar way (+17% and +29% higher emissions due to higher intensity of manure homogenization). Hence, on annual average the highest CH_4 and NH_3 emissions at the barn level were found to be from the slatted floor with high intensity of homogenization (381.7 ± 149.2 g CH_4 LU^{-1} $d^{-1}$and 38.4 ± 15.1 g NH_3 LU^{-1} d^{-1}).
Considering emissions from external uncovered slurry storage for the solid floor section CH_4 emissions of the solid floor section exceeded the emission level of the slatted floor with intensive homogenization, whereas NH_3 emissions remained at the level of the slatted floor with intensive homogenization. In all cases and seasons the lowest emissions were found to be from the slatted floor with low intensity of homogenization (e.g. on annual average 324.9 ± 123.6 g CH_4 LU^{-1} and 29.8 ± 13.1g NH_3 LU^{-1} d^{-1}, respectively).

This investigation provides important information regarding the influence of the housing system and manure management on gaseous emissions of dairy housings, covering all seasons and comparing floor systems simultaneously within one building and a high number of animals per group. Unfortunately, the investigation was limited to CH_4 and NH_3 and did not include N_2O which may play an important role regarding the calculation of CO_2-equivalents and the evaluation of mitigation options. Furthermore, the conclusions from this investigation are not transferable to other housings and sites in general because there may be many affecting variables in dairy farming (e.g., the feed ration, manure removal, and cleaning frequency may influence the level of emissions on the different floors with a different intensity). Further studies at the barn level are required to consolidate information of the influence of the housing system and of the manure management under various conditions. Furthermore, the proportion of emissions (CH_4, NH_3 and N_2O) from slurry storage should be included in future research activities.

2.6 Acknowledgements

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Chapter 3 - **A comparison of emission calculations using different modeled indicators with 1-year online measurements**[6]

Abstract

The overall measurement of farm level greenhouse gas (GHG) emissions in dairy production is not feasible, from either an engineering or administrative point of view. Instead, computational model systems are used to generate emission inventories, demanding a validation by measurement data. This paper tests the GHG calculation of the dairy farm-level optimization model DAIRYDYN, including methane (CH_4) from enteric fermentation and managed manure. The model involves four emission calculation procedures (indicators), differing in the aggregation level of relevant input variables. The corresponding emission factors used by the indicators range from default per cow (activity level) emissions up to emission factors based on feed intake, manure amount and milk production intensity. For validation of the CH_4 accounting of the model one-year CH_4 measurements of an experimental free-stall dairy farm in Germany are compared to model simulation results. An advantage of this interdisciplinary study is given by the correspondence of the model parameterization and simulation horizon with the experimental farm´s characteristics and measurement period. The results clarify that modeled emission inventories (2,898, 4,637, 4,247, 3,600 kg CO_2-eq. cow^{-1} year^{-1}) lead to more or less good approximations of online measurements (av. 3,845 kg CO_2-eq. cow^{-1} year^{-1} (±275 owing to manure management)) depending on the indicator utilized. The more farm-specific characteristics are used by the GHG indicator; the lower is the bias of the modeled emissions. Results underline that an accurate emission calculation procedure should capture differences in energy intake, owing to milk production intensity as well as manure storage time. Despite the differences between indicator estimates, the deviation of modeled GHGs using detailed indicators in DAIRYDYN from on-farm measurements is relatively low (between -6.4 and 10.5%), compared with findings from the literature.

Keywords: *agricultural modeling; GHG measurement; validity of modeled GHGs; emission indicators; dairy farm methane emissions*

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[6] This chapter is based on the publication: LENGERS, B.,SCHIEFLER, I. and W. BÜSCHER (2013): A comparison of emission calculations using different modeled indicators with 1-year online measurements. *Journal of Environmental Monitoring and Assessment* (doi:10.1007/s10661-013-3288-y, available under http://link.springer.com/article/10.1007/s10661-013-3288-y). Inga Schiefler contributed to all sections except 3.2.1.

3.1 Introduction

Greenhouse gases from agricultural production systems are discussed broadly in a scientific as well as a public and political context. As mentioned by the Food and Agricultural Organization (FAO), in 2007, dairy production systems in particular, supposedly bore a large part of global agricultural livestock GHG inventories (ca. 16%), and about 2.7% of global total anthropogenic GHGs (FAO 2010; HAGEMANN et al. 2012). However, real measurements of emissions are not realizable for a large number of farms, or even whole regions. Many methods and schemes have been designed to calculate GHG emissions from arable production systems and animal husbandry, while only knowing some farm- or regional-specific data on different aggregation levels. Implemented into specific model approaches - for example, RAINS (ALCAMO et al. 1990); EFEM (KAZENWADEL and DOLUSCHITZ 1998); MDSM (LOVETT et al. 2006); a study by HAGEMANN et al. (2012), based on methane equations from KIRCHGESSNER et al. (1991); or a model approach used by DECARA and JAYET (2000), which calculates GHG inventories from specified regions in the European context - the available information led to modeled GHG estimates. Others also developed single-farm approaches for predefined single-farm types. For instance, SCHILS et al. (2007) used the single farm model DairyWise for their estimations and WEISKE et al. (2006) presented results using a farm GHG model which was originally developed by OLESEN et al. (2004)).

Since the modeled GHG emissions have to be seen as a proxy for the actual GHG emissions of the modeled real-world systems, the question arises if the validity of computational models is given on a sufficiently high level. This topic has already been discussed by BURTON and OBEL (1995), depicting the balance of model realism, and the overall purpose of the modeling approach. The inherent model functions are not able to show real ongoing biochemical or bio-economic processes precisely. For instance, there are assumptions and simplifications, and also not yet full understanding of biochemical processes e.g. in the rumen (STORM et al. 2012). However, the results should, nevertheless, display an adequate proxy for outputs of the real-world system. But as the predictive character of a model can only be ‘[...] as good as the accuracy of the mathematical method or equations [...]’ (ELLIS et al. 2010), it is quite difficult to build up a consistent model approach for GHG release from complex production systems (HERRERO et al. 2011). Hence, depending on the specific definition of emission calculation procedures, different accounting biases concerning the GHG inventories may occur.

Validation of GHG modeling is done mostly by using small-scale and/or short-term measurements (respiration chambers, indirect calorimetry, mass balance, hood calorimetry). ELLIS et al. (2010) for example used such data for the validation of nine different ruminant dairy CH_4 equations and MILLS et al. (2001) applied it for validation of their modeling of methanogenesis in a lactating cow. Only TALLEC and HENSEN (2011), up to now, have compared modeled and measured CH_4 estimates over a longer time period of more than a few days duration (one-month field experiments) from dairy livestock on grassland, by using a simple Gaussian plume model formerly developed by HENSEN and SCHARFF (2001). However, as also criticized by the authors themselves, measurements over one month are not sufficient for accurate validation results. For our purposes, there are few published CH_4 emission factors from modern dairy free-stalls with a slatted floor: e.g. KÜLLING et al. (2002), SCHNEIDER et al. (2006), SNELL et al. (2003) and ZHANG et al. (2005).

However, the published data stem mostly from short-term measurement intervals (from 2-3 days per season (SNELL et al. 2003) to several weeks (SCHNEIDER et al. 2006)). Other data, based on individual animal measurements, are often restricted to a limited number of animals, and/or do not include emissions from managed manure (e.g. respiration chambers (DERNO et al. 2009)). Hence, the estimates may be biased by not being able to cover seasonal and yearly external or internal variability in the production process, when extrapolating the derived per day emission factors to default one-year emission parameters, per animal, or per livestock unit (LU; one LU is equivalent to, for example, a cow with a live weight of 500kg). The comparability of literature estimates is especially hindered with regard to the differing cattle breeds, milk output intensities and present lactation phase of the animal population investigated in the studies. Additionally, the above mentioned studies offer highly varying CH_4 emission factors per LU and year, ranging between 2,221.8 kg CO_2-eq. and 4,063.9 kg CO_2-eq. (ZHANG et al. 2005), and hence would lead to imprecise validation of emission simulations when applying these as reference. Owing to a lack of production-specific information about the experimental units underlying these studies, one is not even able to adjust parameters in a farm-level model approach for equivalent circumstances, which would perhaps increase the usability of the literature findings for validation purposes. Furthermore, small-scale measurement results are regarded as not being appropriate for comparison with long-term calculations for high animal numbers (STORM et al. 2012).

The problem of obtaining reliable data for validation is also of relevance for the simulation of GHG emissions by the bio-economic dairy farm-level model DAIRYDYN (LENGERS and BRITZ 2012), for specialized dairy farms on slatted floors. The model allows for choosing one out of four different emission-calculation schemes (indicators), and accessing more or fewer aggregated system variables of the dairy production process (e.g. default emission factors per activity or precisely connected to feed intake). LENGERS and BRITZ (2012) applied the approach to analyze the effect of GHG accounting on chosen abatement measures and adherent mitigation costs, if farms are restricted by emission ceilings.

The objective of this study is to test the accuracy of CH_4 calculation by different designed GHG calculation schemes for lactating cows and stored manure of the DAIRYDYN model. Therefore, we apply the model approach with adherent GHG calculation procedures on a real existing dairy barn complex. Modeling results are compared with results from experimental measurements in a free-stall dairy barn in Germany (Haus Riswick). The experiments are characterized by long-term measurements over one year, covering seasonal variations, and thus result in more precise values than emission factors based on projections with only a few measurement days (in contrast to ELLIS et al. (2010)). For biological processes, long-term estimation horizons are particularly important. Recent studies have shown that there is a significant variation of individual CH_4 emissions between single cows (278 to 456 g CH_4 day^{-1}; GARNSWORTHY et al. 2012), whereby the number of animals investigated may play an important role in the measurement accuracy.

Furthermore, the own measurements include emissions from animals' release, as well as emissions from liquid manure, hence reflecting all sources of emissions from the dairy barn. Since the quantification of GHG emissions at barn level (sum of animal and manure) is studied less thoroughly, this is a clear advantage over some other studies, which may be limited to the animals' release (e.g. static respiration chambers), and only measure small livestock numbers (JOHNSON et al. 1994; MOE and TYRRELL 2010).

To follow the objective, the computational modeling approach, used by the DAIRYDYN model, will be explained; in particular, concerning the different emission calculation schemes which can be chosen by the user. Afterwards, the experimental set-up of the dairy barn on Haus Riswick will be explained, focusing briefly on the measurement approach. The implementation of specific farm characteristics of the dairy free-stall on Haus Riswick into DAIRYDYN will allow for simulation and comparison of an equivalent model farm and adherent CH_4 release. The modeled and the measured data cover the same time period with a high representative animal number. This will improve the validation of model calculations by more reliable results, because seasonal and farm exogenous aspects are also captured by the measurements.

3.2 Material and methods

3.2.1 Model concept of DAIRYDYN

The DAIRYDYN model is a farm-level model developed by LENGERS and BRITZ (2012), with an objective function of maximizing net present value of future profits, using different natural states. DAIRYDYN was built for the process-based modeling of single dairy farm development, *inter alia* the occurring GHG emissions combined with the production process. Therefore, the model user can choose from four different emission calculation schemes, based on consistency-proven IPCC (Intergovernmental Panel on Climate Change) methodology with several enhancements.

The model uses a fully dynamic mixed integer linear programming approach. It is programmed with the general algebraic modeling system GAMS, using the industrial solver CPLEX (IBM 2011). It enables the user to simulate farm-level development of specialized dairy farms (including calves, heifers and acreage) over various planning horizons. Animals are differentiated concerning milk yield potential, lactation number, as well as lactation phase. Feeding rations can be changed quarterly, whereby self-produced ground-bait can be supplemented by different concentrates. Manure excretion rates and adherent nitrogen amounts are also captured on a monthly basis. Beneath the baseline farm development, management and cost implications through farm-level emission ceilings can be analyzed, deriving GHG-indicator-specific marginal abatement cost for GHG mitigation efforts at the single-farm level. Figure 3.1 shows bio-economic interactions between the modules that are implemented into the used model approach. The inherent emission calculation rules (indicators) quantify production-specific GHG inventories. Emission calculations are related to source (manure management, enteric fermentation, arable production, etc.) and gas type (CH_4, N_2O and CO_2). The measurements on Haus Riswick were limited to the barn including manure storage and did not include emissions from e.g. crop production, fertilizers or machines. Hence, only those modules within the dotted line are of relevance for the following model calculations (Fig 3.1).

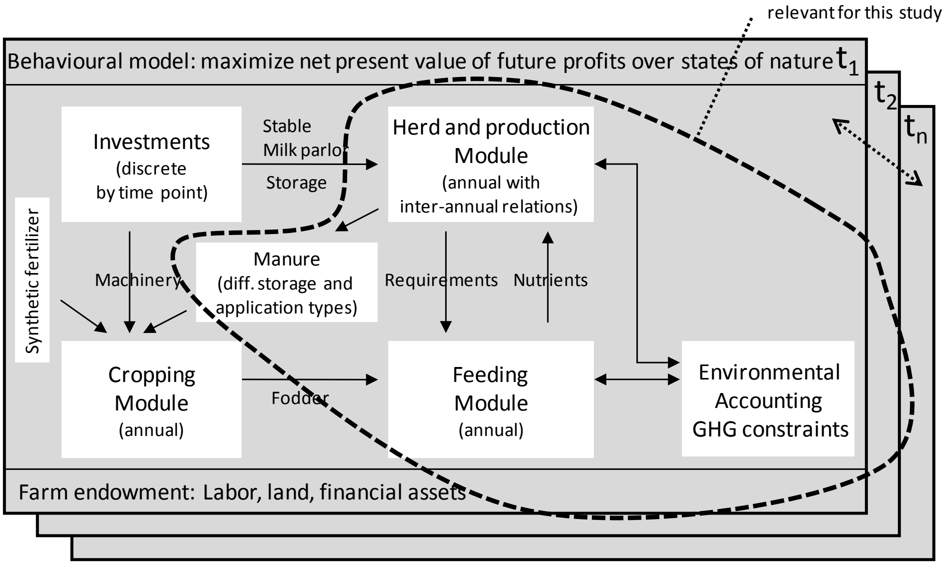

Figure 3.1 Overview of DAIRYDYN model and relevant modules (following LENGERS and BRITZ 2012)

Emission indicators for GHG modeling

As noted above, different emission calculation schemes can be chosen by the model user. The four calculation schemes differ in the detail of farm specific production variables that are relevant for the calculation. For instance, emissions can be calculated in a very simplified way only using parameters of the principle activity (herd size and cropping ha). To go one step further, more detailed parameters, like mass flow and feed composition can be included in the calculation.

A detailed description of the indicator schemes is given by a former study of LENGERS and BRITZ (2012). The simplest indicator is the activity-based one *(actBased).* It multiplies default emission factors per head or per ha (taken from IPCC (2006) Tier 1 level) with activity levels to derive whole-farm emissions. The production-based *(prodBased)* indicator differs in calculation of emissions from cows and crops. Therefore, the prodBased indicator is implementing static emission factors per unit of product (e.g. per kg of milk output). These emission factors are derived from the default Tier 1 values (emission parameter for milk is derived by dividing IPCC Tier 1 default factor by an assumed average milk yield per cow per year of 6,000 kg). However, the default per unit of product emission factors lead to various overall emissions depending on per ha or per barn place output level as it suggests a linear increase in CH_4 release per cow or per ha with increasing output. The *genProdBased* indicator also recognizes the diminishing emissions per kg of milk, when intensity level of cows increases (emissions from gross energy intake for maintenance and activity are allocated to higher milk output), assuming decreasing emissions per kg milk with increasing milk yield per cow and year (derived by Tier 2 approach with standard energy digestibility of 60% (IPCC, 2006)). Manure is assumed to be stored for half a year on average. A more detailed emission calculation is presented by the *NBased* indicator, recognizing single animal gross energy demand for animal emission calculation, depending on the actual lactation phase, and with adjusted average feed digestibility for real circumstances. Furthermore, it uses monthly manure amounts in storage to calculate emissions by different manure management types (subfloor, surface storage, coverage techniques). Emissions stemming from arable production processes are based on N application (synthetic and organic). Emissions from storage and arable N application are implemented on a monthly basis, to capture effects of manure removal and application frequency as well.

Table 3.1 Methane production equations relevant for the investigated farm unit (following IPCC 2006 and LENGERS and BRITZ 2012)

		Equations*			
Indicator	**Unit**	**Enteric fermentation**	**Manure storage**	**Comments**	**Source**
actBased	CH_4 (kg cow^{-1} year^{-1})	*117*	*21*	default values	IPCC (2006) Tier 1
prodBased	CH_4 (kg cow^{-1} year^{-1})	*117/6,000 liter × milk yield (liter cow^{-1})*	*21/6,000 liter × milk yield (liter cow^{-1})*	linear increase per output unit	IPCC (2006) Tier 1
genProdBased	CH_4 (kg cow^{-1} year^{-1})	GE_l (MJ year^{-1}) × $Y_m/100/55.65$	VS (m^3 year^{-1}) × B_0 × 0.67 × $MCF/2$	half year manure storage assumed & default energy digestibility of 60%	IPCC (2006) Tier 2
NBased	CH_4 (kg cow^{-1} year^{-1})	$\sum_p GE_{pl}$(MJ phase^{-1}) × $Y_m/100/55.65$	$\sum_m VS_m$ (m^3 month^{-1}) × B_0 × 0.67 × $MCF/5.66$	monthly storage emissions & experiment adjusted digestibility	IPCC (2006) Tier 2

*selection of equation relevant default parameters in line with IPCC (2006) methodology for Western Europe.

GEl = one year gross energy demand for cow with specific milk yield level *l*; *GEpl* = gross energy demand for specific phase of lactation *p* and milk output potential *l* of each cow; *Ym* = methane conversion factor (6.5% of GE in feed converted to methane); *VS* = volatile solid excretion cow-1 year-1 on a dry-organic matter basis; *B0* = maximum methane production capacity for manure (m3 CH4 kg-1 of VS); *0.67* = conversion factor of m3 CH4 to kg CH4; *MCF* = one year methane conversion factor for sub-floor manure storage; *VSm* = monthly VS in sub-floor pit.

The CH_4 calculation formulas, implemented into the model to derive emissions from lactating cows and sub-floor stored manure, are shown in Table 3.1.

Table 3.1 gives a systematic view of the CH_4 calculation concepts of the four applied indicator schemes, for CH_4 release from enteric fermentation as well as stored manure amounts, presenting a growing level of detail from top to bottom.

3.2.2 Measurement installation on Haus Riswick

Site description

Measurements used for model validation were carried out in a newly built dairy barn of the Chamber of Agriculture North-Rhine Westphalia, at the Centre of Agriculture, Haus Riswick, in North-Western Germany. The annual average temperature of the investigated site was 9.8°C (see Fig. 3.2, measured at feed alley with open curtains). The average outdoor temperature ranged from 4.3°C monthly mean in January 2011 up to 18.6°C monthly mean in August. Mean humidity in 2011 was 79%, mean wind speed was 1.9 m s^{-1} and the main wind directions in 2011 were South-West and West (data from nearest official weather station in Goch). The dairy cows were kept in a free-stall dairy barn with an external milking parlor, during the whole year. Two equal-sized compartments (section 1, section 2) of the barn, with separate air-spaces, were considered for the measurement (Fig. 3.2), and were investigated separately for their CH_4 emissions. Each compartment was designed for 48 dairy cows offering a total area available per cow of 10 m^2. Having no solid eave-side walls, the building is naturally cross-ventilated. However, there was a facility to close the western eave-side of the building with curtains. The curtains were open during the summer, partly open in spring and autumn, and closed during winter. The barn had a slatted floor with subfloor storage of liquid manure, and a robot system for fully automated water cleaning of the slatted floor. The two power take-off mixer with electric motors (7.5 KW) for homogenization of the liquid manure beneath the slatted floor were located at the gable wall, next to section 1 (Fig. 3.2). This resulted in a high intensity of homogenization of liquid manure in section 1 (‘intensive mixing case’), and a low intensity of homogenization of liquid manure in section 2 (‘no intensive mixing case’).

There were 96 lactating Holstein dairy cows in the compartments, with an average milk yield of 34 kg (28-39) per day, and an average live mass of 700 kg (550-870). Cows in the measurement-relevant sections were between the 95th and 190th day of lactation. The cows were fed once a day with a grass and maize silage-based mixed rations, and were able to get concentrate feed at concentrate stations additionally, according to their production (2.5 kg per cow and day on average). The total average dry matter feed intake per cow was 19 kg. The mean crude protein of the mixed ration was 16.6% (dry matter) and crude fiber was 17.4% (dry matter).

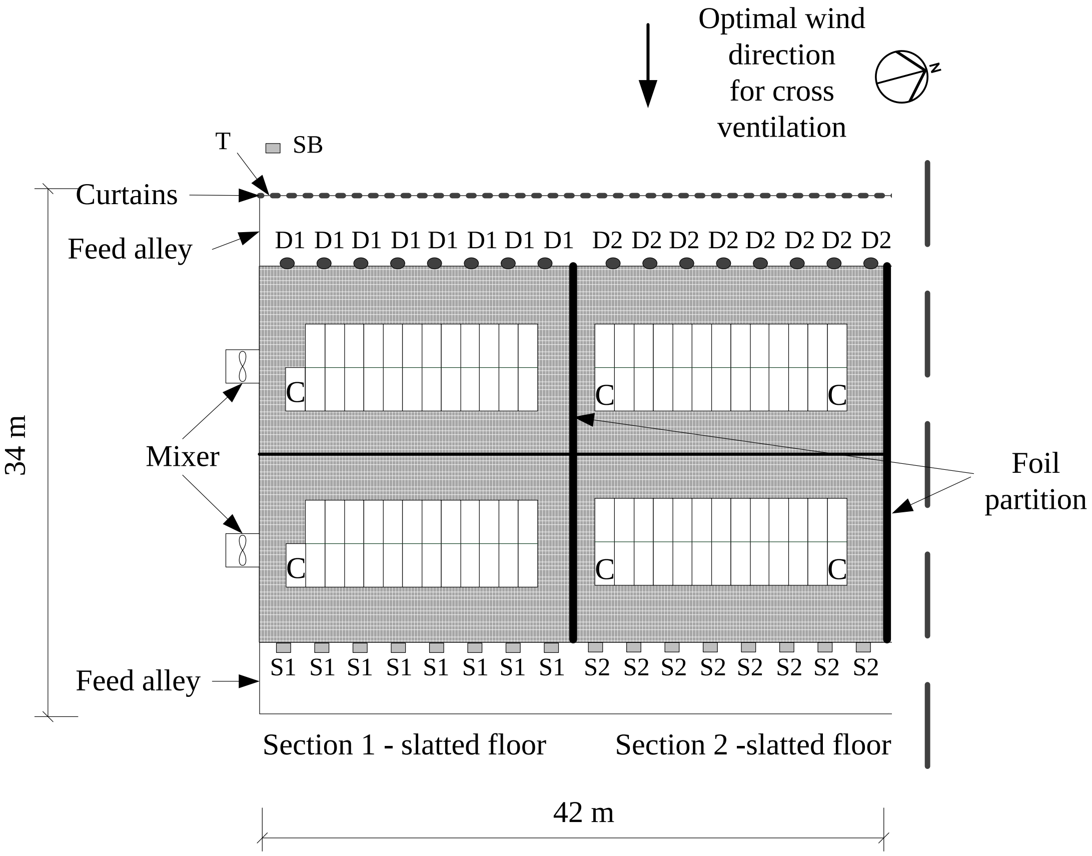

Figure 3.2 **Layout of the dairy barn with measuring units (where D is dosing points for tracer gas injection, S are sampling points, C concentrate feeder, SB is sampling background and T is temperature measurement)**

General procedures

Measurements were conducted from 20 December 2010 to 05 December 2011, covering all seasons of the year and various weather conditions.

Gas concentrations were measured in the exhaust air of the compartments. Owing to the large open walls of the barn, the air-outlet location was highly dependent on wind direction. Considering the regional conditions, it was assumed that the exhaust location for measurement of gas concentrations was at the eastern eave-side of the building. Nevertheless, only those time periods (daily basis) when the wind direction led to a west to east cross-ventilation were taken into account, the rest was discarded. In 2011, about 50% of the time period could be used for the analysis. Methane and ammonia emissions from the barn were calculated on average for each season leading to the annual average in equal parts.

Measurement of gas concentrations

Measurements of gas concentration were carried out for more than 300 days, recording exhaust concentrations of CO_2 and CH_4 for each compartment. Each compartment was equipped with eight sampling points, in line above the feed alley, put together into one aggregate sample for each compartment. The background (incoming) air was sampled at the western side of the building (Fig. 3.2). The exhaust air of the compartments and the background air were sampled by vacuum pumps through separate polytetrafluoroethylene (PTFE) sampling tubes into PTFE sample bottles. The sample bottles, the multiplexer (used for switching between samples) and the gas analyzer were placed in the adjacent building (multi-gas analyzer 1412, and a multiplexer 1303 Lumasense Technologies SA, Ballerup, Denmark). On the distance between the barn and the adjacent building the sampling tubes were laid underground and heated. This procedure was performed in order to offer constant measuring conditions throughout the whole year and further to avoid condensation.

The gas analyzer was sent to the manufacturer for calibration after 4 weeks due to a drift in methane concentrations and afterwards every 6 months. In order to check the accuracy of the measurement system in the meantime, calibration gases with known concentrations were used after 4 weeks.

Measurement of volumetric air flow rate

The air exchange rate was calculated using the tracer decay method (NIEBAUM 2001; SAMER et al. 2011; SCHNEIDER et al. 2006; SEIPELT 1999) with a SF_6 electronic capture detector, and converted subsequently into volumetric air flow, per cow per hour. The tracer gas was released as a line source at the windward side of the barn at a height of 4 m from the floor, which allowed proper mixing of the tracer within the compartment (Fig. 3.2). The sampling system used for the tracer gas measurement was the same as used for the gas concentration measurement. Tracer gas measurements were performed during summer with open curtains when a cross ventilation (west to east) was given. Based on wind direction and wind velocity data, the air exchange rate and the volumetric air flow rate could be estimated for the periods of cross-ventilation. The volumetric air flow rate was determined on an hourly basis considering the average wind velocity per hour.

In the case of closed curtains, the CO_2 mass balance, according to CIGR (2002), was applied to calculate the volumetric air flow.

Calculation of emissions

The emission rates E [mg h^{-1} cow^{-1}] were calculated on an hourly basis, with the measured gas concentrations and the calculated volumetric air flow rate Q_m [m^3 h^{-1} cow^{-1}], using the following equation:

$$E = Q_m * (C_{in} - C_{out}) .$$

Where C_{in} [mg m^{-3}] is the exhaust concentration and C_{out} [mg m^{-3}] is the background concentration of the relevant gas. Multiplying E by the global warming potential of CH_4 (21) leads to emission quantity in CO_2-eq (UBA, 2009).

Procedure of comparison

The specific farm characteristics of Haus Riswick were implemented into the model, in order to simulate the identical farm for comparison of results on CH_4 emissions.

Emission factors taken from IPCC (2006) were also elected, corresponding to the average annual temperature of 9.8°C, and an average live-weight of 700 kg per cow. Limited to the system boundaries of the experimental farm installation, only emissions from lactating cows were comparable. Furthermore, only high phase lactating cows, between the 95th and 190th day of lactation, were held in the investigated sections of the barn. Implementing a phenotypic milk yield potential of 9,600 kg per cow per year, results in a model per day lactation parameter of 0.354% of yearly milk yield (34kg/9,600kg=0.354%) for the high lactation phase, which is necessary for feed requirement functions of the herd. For comparison, the daily output parameter derived from HUTH (1995) for high lactation phase is 0.33% of yearly milk yield. Considering that only highly lactating cows were held in the relevant barn sections, a milk output potential per barn place of 12,410 kg/year (34 kg * 365 days) is assumed. Referring to the barn characteristics on Haus Riswick, the model was adapted to only simulate emission amounts from lactating cows, on slatted floors with a full-year subfloor manure storage capacity. The simulation horizon also corresponds to the measurement interval of one year on Haus Riswick.

Farm simulations were done for a farm implementing the above-stated farm characteristics, and using each of the explained GHG indicators separately. This leads to different emission estimates depending on the calculation rules of the specific indicators.

3.3 Results

The results enabled the evaluation of the CH_4 emission calculation accuracy of the different model-defined GHG indicators. Table 3.2 shows the estimated CH_4 emissions per cow and per kg of milk, respectively. CH_4-measurements of the barn sections, denoted above, with and without intensive mixing of liquid manure, are displayed separately. Furthermore, an average case for manure handling is made by taking the average over both measurement districts.

Table 3.2 Per year CO_2-eq. derived by different indicators and results of real measurement on Haus Riswick.

	model results of different indicators				**real measurement**		
Unit	**actBased**	**prodBased**	**genProdBased**	**Nbased**	**no intensive mixing**	**intensive mixing**	**average**
[kg CO_2-eq./cow]	2,898	4,637	4,247	3,600	3,570	4,120	3,845
[kg CO_2-eq./kg milk]	0.234	0.374	0.342	0.290	0.288	0.332	0.310

As illustrated in Table 3.2, online measurements for CH_4 release lie between 3,570 kg and 4,120 kg CO_2-eq. per cow per year. Obviously, a high mixing intensity of manure leads to overall CH_4 emissions from the barn, 15.4% higher than in the case of low manure homogenization. Dividing the average CH_4 emissions of 3,845 kg CO_2-eq. by the yearly milk yield potential per barn-place of 12,410 kg leads to 0.310 kg CO_2-eq. per kg of milk on average for the experimental installations on Haus Riswick. Accordant calculation results by the model show partial great differences, accounting for 2,898 kg up to 4,637 kg CO_2-eq. per cow for the identical farm. Estimates by the *actBased* indicator lie below the measurement values. The results from Table 3.2 are taken to quantify the absolute and relative deviations of indicator GHGs from the actual measured CH_4 emissions. Measurements from the barn part with and without intensive mixing of manure are taken as a representation of lower and upper boundaries of actually occurring emissions, depending on the intensity of manure homogenization.

The comparison of indicator-derived CH_4 emissions with measurement results is shown in Table 3.3. Compared with ‘no intensive mixing’ measurements, the NBased indicator leads to the most adequate CH_4 estimates, with only a slight overestimation of 0.9%. As the defined upper bound by the ‘intensive mixing’ barn section, with 4,120 kg CO_2-eq. per cow, is 15.4% higher than the lower bound, the overestimation of the indicators prodBased and genProdBased diminishes. The NBased estimation is even 12.6% below the measured upper value. In contrast, the underestimation of the actBased calculation increases to 29.7%, when compared with the measurements from the intensively homogenized barn section.

The estimates from the actBased indicator lead to a clear underestimation of actual emissions per cow, occurring from the barn section with low manure homogenization. The model-calculations by the prodBased and genProdBased indicators even overestimate the upper bound. However, overestimating the online-measurements by only 3.1%, the genProdBased indicator can be identified as a good proxy for dairy cow emissions, with high rates of subfloor manure homogenization for our specific farm.

Table 3.3 Deviations of indicator results from real measurements

		actBased	**prodBased**	**genProdBased**	**Nbased**
no intensive mixing					
absolute deviation per cow	[kg CO_2-eq.]	-672	1067	677	31
absolute deviation per kg of milk	[kg CO_2-eq.]	-0.05	0.09	0.05	0.00
relative deviation	%	-18.8%	29.9%	19.0%	0.9%
intensive mixing					
absolute deviation per cow	[kg CO_2-eq.]	-1,222	517	128	-519
absolute deviation per kg of milk	[kg CO_2-eq.]	-0.10	0.04	0.01	-0.04
relative deviation	%	-29.7%	12.6%	3.1%	-12.6%
average mixing intensity					
absolute deviation per cow	[kg CO_2-eq.]	-947	792	403	-244
absolute deviation per kg of milk	[kg CO_2-eq.]	-0.08	0.06	0.03	-0.02
relative deviation	%	-24.6%	20.6%	10.5%	-6.4%

Comparing the average of the measurements from both barn sections with the model results, the prodBased estimator routinely overestimates the real emissions by large amounts (20.6% on average). The NBased indicator scheme underestimates the average CH_4 values by about 6.4%, whereas the actBased one leads to an aberration of -24.6%. The actBased indicator, routinely, has negative deviations, while the prodBased and genProdBased indicator schemes have positive deviations from actual measurements. Only the calculations of the Nbased indicator lie between the upper- and lower-bound of actual measurements. Considering these results, the genProdBased indicator seems to be an adequate proxy for the upper bound of the measured emissions from the barn, with high homogenization intensity of liquid manure. The NBased indicator shows the highest accuracy in CH_4 calculations for the lower bound, defined by the barn section with low movements of manure, and even emerges as a good proxy for the average emissions per cow measured over both barn sections (average).

As seen in Figure 3.3, indicator estimates of the NBased lie between the minimum and maximum of measurements from Haus Riswick. Furthermore, model estimates can be compared with findings from the literature, bearing in mind the limited usability of literature findings as stated beforehand. Therefore, model estimates, as well as online-measurement results from Haus Riswick, are expressed as emission amounts per LU, comparable with findings reported in the literature. Emission inventories per LU derived from the literature are higher compared to long-term measurements from Haus Riswick. Only the estimates from KÜLLING et al. (2002) are comparable to the measured amounts. This underlines the gain in validation accuracy of the model approach of DAIRYDYN, by using one-year online-measurements instead of literature information, as mentioned in the introduction.

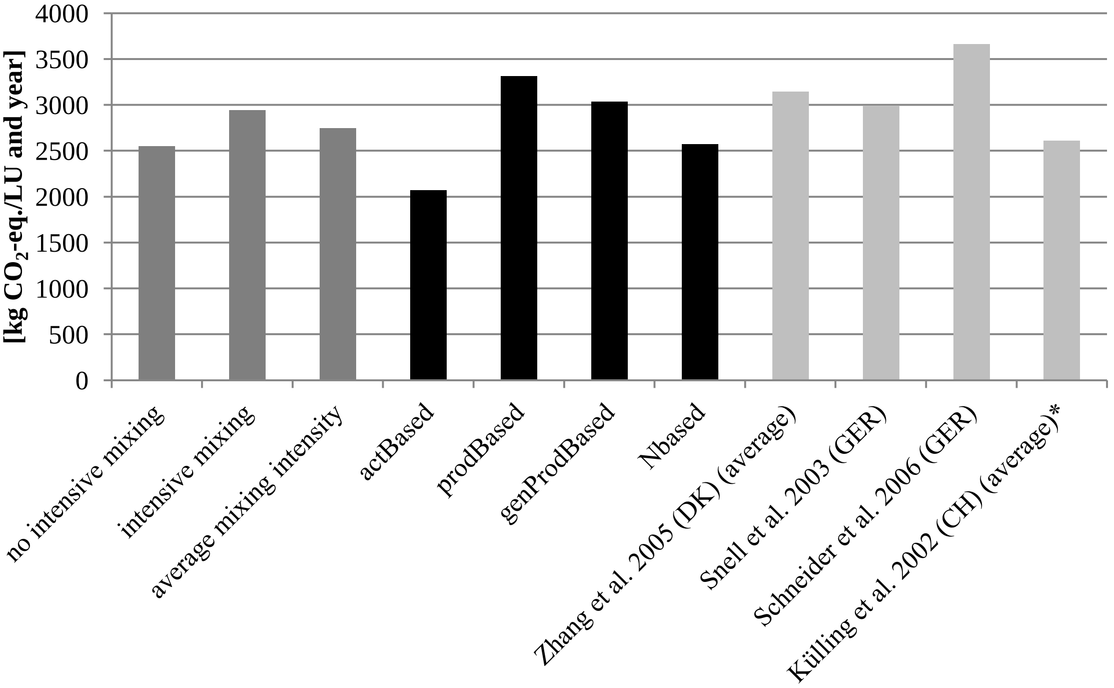

Figure 3.3 Visualization of model results compared to real measurements and literature findings for slatted floor conditions (measured and simulated emissions are rebased to emissions per LU (500 kg of live weight); DK: Denmark, GER: Germany, CH: Switzerland, *average is built over all investigated feeding strategies and according to measurements with 14-day manure storage time)

Model estimates by the actBased indicator lead to the lowest emission quantities, whereas the prodBased indicator scheme results in comparatively high estimates. By modeling the identical farm as presented by the experimental barn on Haus Riswick, the NBased indicator leads to CH_4 calculations near the ‘real world’ quantities.

3.4 Discussion

The results show that the range of model estimates for CH_4 emissions for the dairy barn on Haus Riswick is quite broad, varying between 18.8% below (actBased) the lower bound to 12.6% above (prodBased) the upper bound.

The overestimation of CH_4 by the prodBased indicator is a result of the construction of the indicator-specific emission parameter per kg of milk. The per kg emission parameter was derived by dividing the IPCC Tier 1 default value per cow by a potential milk yield of 6,000 kg per year. This routinely overestimates real emissions by multiplying the emission parameter by the actual milk yield level of 12,410 kg per barn place on Haus Riswick, assuming a constant per kg milk emission factor with increasing milk yield. Hence, approximation of CH_4 emissions, using the prodBased indicator, are quite inconsistent if dairy facilities are modeled that deviate from a 6,000 kg average milk yield potential per cow. Following the results in Table 3.3, using the actBased indicator (meaning default Tier 1 IPCC CH_4 parameters per animal) leads to underestimations for a farm with high milk yield potential, owing to the default emission parameters appropriate for a 6,000 kg milk yield potential. As further shown in Table 3.3, the genProdBased indicator derives good estimates in the case of the barn section with high manure homogenization rates. On average, the model CH_4 calculations, using the NBased indicator, produce the best proxy for actual measured CH_4 amounts, owing to recognition of higher manure removal frequencies, and adjustment to the real average feed digestibility. Not only the small underestimation of real emissions (-6.4% on average), but also the fact that its estimates lie between the measured upper- and lower-bound for high and low mixing intensity underlines the suitability of the most detailed indicator for CH_4 emission calculation in dairy barns. With regard to Figure 3.3, the NBased estimates also lead to per LU emissions comparable to results from KÜLLING et al. (2002) (only -1.3% deviation), which further underlines its accuracy and adaptability to other farm types, because experimental attributes of KÜLLING et al. are comparable to the specified model experiments (KÜLLING et al. investigated high lactating cows with a lactation of about 31.3 ± 5.1 kg milk d^{-1} and an average live weight of 635 ± 56 kg cow^{-1}).

As the actBased indicator falls back on the most aggregated process variables, and represents a default and very simple emission accounting, the emission approximation increases in accuracy compared to real measurements, when incorporating more detailed process variables into the indicator scheme.

This result is in line with findings from ELLIS et al. (2010), who compare GHG simulation equations with small-scale measurements on dairy cows. They state that the simple Tier 1 approach of IPCC, equivalent to our actBased indicator, leads to the worst emission estimates in contrast to the NBased one (comparable to Tier 2 methodology of IPCC), which was also valued as relatively adequate by these authors. Nevertheless, estimated errors are still rather high, but more detailed approaches have been missing up to now. As about 80% of the dairy barn CH_4 emissions stem from animal rumination it is obvious that indicators with detailed accounting of feeding patterns and milk output intensity (NBased) lead to more accurate CH_4 calculations (ELLIS et al. 2010). This divergence in GHG accounting accuracy between default and detailed indicators even increases the stronger farm characteristics deviate from attributes the simple default emission factors (actBased/Tier 1) are calibrated on.

The comparison of indicator-modeled CH_4 emissions with online measurements should lead to a validation of the DAIRYDYN model. Compared with findings of other studies, the model results - except when using the actBased and prodBased indicators - offer relatively moderate deviations (between -6.4 and 10.5%) from average actual CH_4 amounts. For example TALLEC and HENSEN (2011) underestimate real CH_4 emissions by about 25%.

However, it should be noted that the actual measurement results of Haus Riswick may also include minor measurement errors. For example, the CO_2 mass balance method for the estimation of the air exchange rate bears the risk of inaccuracy, since - beside the cows - there may be other minor CO_2 sources within the barn (e.g. manure, feed and/or machines). Furthermore, it has to be considered that Haus Riswick represents a well-managed demonstration farm, having very well-balanced feed rations and performing high-frequency cleaning of surfaces within the barn. It can be assumed that, in practice, not all farms are able to fulfill best agricultural practices, and that they may have slightly higher emissions. Unfortunately, up to this point, we were not able to quantify the portion of difference between measured and calculated CH_4 occurring from the modeling bias or the measurement error.

3.5 Conclusion

Concluding from the former sections, this study underlines that generally the CH_4 calculation schemes implemented into the model DAIRYDYN lead to good approximations of actual barn CH_4 release. The highest accuracy in CH_4 approximation for the experimental farm is given by the most detailed indicator (NBased).

Although the different indicator schemes within the model approach of DAIRYDYN may show adequacy in emission accounting to some degree, the usefulness for political GHG control instruments is not yet given. The validation of the model, using different GHG indicators in this study, is only representative of one specific lactation level and barn type. Hence, further research has to be done to compare modeling results for other intensity levels and barns. Therefore, our study underlines the advantage of using long-term measurements of a whole barn system for a high number of animals to ensure representative estimates including variability within the cow population and the influence of exogenous parameters over time (e.g. feed quality, temperature…). Special emphasis should therefore be placed on the use of long-term measurements for model validation instead of using small scale and short term results.

Furthermore, it has to be emphasized that management options are a relevant variable to include into modeling approaches. Limiting calculations to default and highly aggregated GHG calculation schemes may be inadequate for a broad range of dairy farm types due to the high heterogeneity in the actual farm population.

Certainly, adequate emission accounting is of great relevance (ELLIS et al. 2010). However, in the case of the enforcement and control of emission ceilings in agricultural dairy production, induced abatement strategies by the different indicators are of great interest, leading to different cost implications for the abatement of GHG amounts. Hence, further research has to be done in this field, capturing engineering costs at the farm level, as well as administrative costs for control and enforcement.

Also, the model approach has to be developed further to increase the level of detail (e.g. as done by BANNINK et al. (2011), implementing a more detailed IPCC Tier 3 approach for dairy cow CH_4 estimation). This is of special interest not only for ruminant CH_4 emissions but also for the emissions occurring from manure, as the diet composition also significantly impacts the CH_4 amount stemming from the animals´ excreta (HINDRICHSEN et al. 2005; KÜLLING et al. 2002).

The inclusion of more detailed information from the production process, in order to obtain less biased emission estimates, hence guarantees more reliable results for a more diversified range of dairy farms, especially if willing to use modeling results for more aggregated and political purposes.

In general, our study showed that the exchange between and the combination of modeling and measuring science is a valuable cooperation, offering the possibilities to improve the accuracy in modeling and to amend or partly replace the time and cost intensive measurements in the future.

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General Conclusions

The investigations presented within this thesis refer to the topic of gaseous emissions from naturally ventilated dairy barns. The thesis addresses the need for enhancement of methods for the measurement or calculation of air exchange rates and shall serve as a basis for future research activities in this field. Furthermore, emission modeling and measuring science is brought together in an interdisciplinary approach and discussed in detail. However, apart from the scientific objectives the thesis further contributes to the present discussion in practical dairy farming, specifically, which floor design and manure removal strategy in dairy barns causes least impact on the environment.

The following conclusions refer to the objectives of the study mentioned in the introductive part of this thesis.

1) Further development of methods for the measurement of gaseous emissions from naturally cross ventilated dairy barns:

a) Development of a building-specific air exchange model for the calculation of the air exchange rate

There is a great need for improving methods in the determination of air exchange rates of naturally ventilated buildings. Apart from necessary improvements in accuracy and feasibility, SF_6 has a high global warming potential and one can expect that its usage may be prohibited in several countries in the near future. Building specific models may help to reduce the required amount of tracer gases.

The developed method can be seen as a rough, but solid model to estimate the air exchange rate of the investigated building with minimal effort. Regarding the complexity of tracer gas measurements in naturally ventilated buildings this result is a step towards the simplifying the determination of the air exchange rate. However, there is major need for further development of the building specific air exchange model. In particular, in periods offering no cross ventilation, e.g. when curtains are closed or when the wind direction is not appropriate, the developed methodology is not applicable in the present form and has to be improved.

b) Development of a robust measurement system for the long-term measurement of CH_4, NH_3, and CO_2 outdoor and indoor concentrations.

The system for gas concentration measurement delivered reliable and precise results during long-term experiments. Although the tube distances within the barn were long and there were temperature differences between barn and the adjacent building, there were no problems with condensation or contamination. Unfortunately the gas concentration measurements were limited to CO_2, CH_4, and NH_3 and were not suitable for N_2O. The author's assumption for the problems occurred in N_2O concentration measurement in the own investigation is: In contrast to straw based systems, liquid manure systems are expected to generate only minimal N_2O emissions (MONTENY et al., 2006; THORMAN et al., 2007). Accordingly, with a very high ventilation rate of the barn (see chapter 1), the N_2O indoor concentrations are decreasing even more. Especially differences in concentrations of incoming and exhaust air are minimal and thus difficult to measure precisely.

With a high global warming potential, even slight N_2O emissions may affect the level of emissions in CO_2-equivalents significantly. But apart from this enormous weighting of even slight N_2O emissions in the calculation of CO_2-equivalents there is one more reason to emphasize the importance of N_2O measurements for future investigations: Interactions of N_2O with other gaseous emissions. For example, PETERSEN & SOMMER (2011) found that the reduction of NH_3 emissions may result in higher N_2O emissions. This interaction is of particular importance with regard to NH_3 or CH_4 reduction strategies.

2) Long-term measurement of CH_4 and NH_3 emissions from differently managed naturally ventilated dairy barns:

a) Comparison of the dairy cow housing systems: slatted floor with subfloor storage and solid floor with external storage

This objective includes the very 'hands-on' aspect which floor design and manure removal system is resulting in lowest gaseous emissions. In the own investigation emissions from slatted floor including storage with low intensity of homogenization led to lowest NH_3 and CH_4 emissions in all seasons. However, varying only one factor – slurry homogenization – emissions from slatted floor increased dramatically. Furthermore, the design of the external slurry tank from solid floor was affecting the balance. This underlines the close relationship between housing system and its management (objective 2a ↔ objective 2b)

Once more it must be emphasized that the whole system, barn and storage, has to be considered when assessing the emission level of dairy houses and manure management. This underlines the importance of an integrated approach in the development of mitigation measures (e.g. additives). Furthermore, there may be several mitigation options that shift the emission potential from one factor to another, e.g. when reduced emissions from storage are compensated by higher emissions in field application or by higher emissions of other gases (AMON et al., 2006; PETERSEN & SOMMER, 2011).

With a shared subfloor storage for liquid manure between the two slatted floor sections it was not possible to consider separate nutrition balances for the two barn sections. It is also apparent that there was an exchange of gases between the air above and beneath the slatted floor. This may have resulted in mixing air between the sections to an unknown extent but since there were large differences in gas concentrations and emissions between the sections, this did not strongly affect the own measurements. The shared liquid manure storage and the position of the mixer at the gable wall of the barn resulted in a higher homogenization of liquid manure in one of the slatted floor sections. This made it possible to determine the enormous influence of slurry mixing on emissions on the one hand, but it hampered the simultaneous comparison of feeding or cleaning procedures between the two sections on the other hand. However, since there was no opportunity to modify the slurry tank within the period of investigation, the problem was avoided by a reduced mixing frequency during specific investigations. Nevertheless, the author recommends the future separation of the slurry storages in order to ensure optimal conditions for research activities within the dairy barn.

b) Effect of manure management on CH_4 and NH_3 emissions

The effect of manure management in the own investigation on CH_4 and NH_3 emissions was evident (see chapter 2). One of the main conclusions of this thesis is that manure management is strongly affecting the level of emissions rather than the barn construction and the floor design itself (see objective 2a).

3) Validation of the dairy farm-level model DAIRYDYN with long-term measurement results.

The comparison of indicator-modeled CH_4 emissions with online measurements should lead to a validation of CH_4 accounting for the DAIRYDYN model. The interdisciplinary study showed the necessity of very detailed indicator schemes. Compared with findings of other studies the model results offered relatively moderate deviations. In general, the exchange between and the combination of modeling and measuring science is a valuable cooperation, offering the possibilities to (a) improve accuracy in modeling (chapter 3) and (b) to amend or partly replace the time and cost intensive measurements (chapter 2).

To sum up, reducing livestock sector emissions is an indisputable subject regarding the environmental impact and thus the sustainability of land use and food production. In order to receive precise sector- or farm-specific emission factors and to evaluate possible mitigation strategies, accurate measuring and modeling systems are of particular importance. There are several promising approaches of both, modeling and measuring science, successively demanding for further improvement in accuracy, consistency and effectiveness. The present work contributes to these approaches and may serve as a further piece of the puzzle within this complex topic. The investigated barn offers favorable conditions for future research activities. These future research activities should include N_2O measurements in order to reach the long-term objective in the environmental assessment of farming procedures, the calculation of CO_2-equivalents per product unit, in that case CO_2-eq per kg milk.

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