AMMONIA EMISSION FROM DANISH CUBICLE BARNS FOR DAIRY COWS - EFFECT OF FLOOR TYPE AND MANURE SCRAPING

PETER KAI, ANDERS P. S. ADAMSEN, MORTEN L. JENSEN, PERNILLE KASPER OG ANDERS FEILBERG

DCA REPORT NO. 110 · DECEMBER 2017

AARHUS UNIVERSITY
DCA - DANISH CENTRE FOR FOOD AND AGRICULTURE

Ammonia Emission from Danish cubicle barns for dairy cows

Supplementary information and clarifications (October 2019)

In an effort to ensure that this report complies with Aarhus University's guidelines for transparency and open declaration of external cooperation, the following supplementary information and clarifications have been prepared in collaboration between the researcher (s) and the faculty management at Science and Technology:

In the colophon, Peter Kai and Anders P. Adamsen are noted as having two employers. At the start of the project, Anders P. Adamsen was employed at AU and changed job to SEGES. Anders P. Adamsen was overall project leader during data collection. He has not been involved in the project after the change to SEGES except for commenting on the report.

Peter Kai was employed at the Danish Technological Institute, Agrotech, at the start of the project. After the data collection, Peter Kai changed job to AU. At AU, Peter Kai was the main author of the report.

AU was overall project responsible and participated in the data collection with gas measuring instruments. AU carried out data treatment and analysis and was responsible for the reporting.

DTI-Agrotech was responsible for the measuring system including a mobile measuring lab and further participated in the data collection in collaboration with AU-ENG. In addition, DTI-Agrotech supplied the report template based on the VERA test protocol for livestock Housing and management systems version 2.

SEGES was responsible for communication with the test farms, collection of production data, and descriptions of the barns to the report.

SEGES and the Danish Technological Institut-Agrotech has commented on the understanding and language in the report.

AMMONIA EMISSION FROM DANISH CUBICLE BARNS FOR DAIRY COWS - EFFECT OF FLOOR TYPE AND MANURE SCRAPING

DCA REPORT NO. 110 · DECEMBER 2017

AARHUS UNIVERSITY
DCA - DANISH CENTRE FOR FOOD AND AGRICULTURE

Peter Kai[2,1], Anders P. S. Adamsen[1,3], Morten L. Jensen[3], Pernille Kasper[1] og Anders Feilberg[1]

Aarhus University
Department of Engineering[1]

Danish Technological Institute, AgroTech[2]

SEGES[3]

TEKNOLOGISK INSTITUT

AARHUS UNIVERSITET

SEGES

AMMONIA EMISSION FROM DANISH CUBICLE BARNS FOR DAIRY COWS - EFFECT OF FLOOR TYPE AND MANURE SCRAPING

Series:	DCA report
No.:	110
Authors:	Peter Kai, Anders P. S. Adamsen, Morten L. Jensen, Pernille Kasper og Anders Feilberg
Publisher:	DCA - Danish Centre for Food and Agriculture, Blichers Allé 20, PO box 50, DK-8830 Tjele. Tel. 8715 1248, e-mail: dca@au.dk, web: www.dca.au.dk
Commissioned	
by:	The study was funded by the Milk Levy Fund (Mælkeafgiftsfonden), the Danish Agricultural Agency and the Danish Environmental Agency.
Photo:	Frontpage: DCA foto.
Print:	www.digisource.dk
Year of issue:	2017
	Copying permitted with proper citing of source
ISBN:	Printed version 978-87-93643-16-1, elektronic version 978-87-93643-17-8
ISSN:	2245-1684

Reports can be freely downloaded from www.dca.au.dk

Scientific report
The reports contain mainly the final reportings of research projects, scientific reviews, knowledge syntheses, commissioned work for authorities, technical assessments, guidelines, etc.

1 Foreword

This study was conducted to update the ammonia emissions from typical Danish dairy housing systems, and to quantify the ammonia reduction effects of scraping of floors. Detailed descriptions of the studied housing and scraping systems are shown in section 2.3.

The study was executed in accordance to the prescriptions of the VERA test protocol for Livestock Housing and Management Systems version 2 (2011-29-08) (VERA, 2011).

The study was planned, initiated, and organized in collaboration between Aarhus University, the Danish Technological Institute – AgroTech, SEGES, Cattle, and the owners of the involved test farms.

The study was funded by the Milk Levy Fund (Mælkeafgiftsfonden), the Danish Agricultural Agency, and the Danish Environmental Agency.

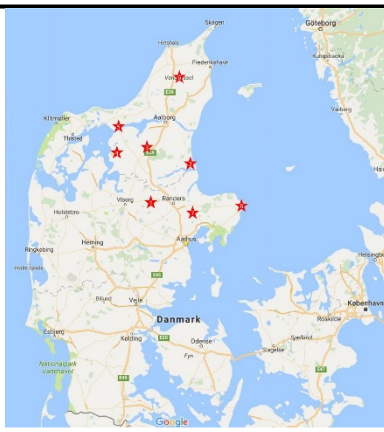
1. Contact addresses

1.1.1 Test farms

The study took place at eight representative commercial dairy farms. The addresses and contact info of the test farms are shown in table 1. Details about the individual farms is presented in section 3.

Table 1. Location of the eight test farms.

Farm id	*Location*
CB 1	Tjele
CB 2	Hadsund
CB 3	Skørping
CB 4	Farsø
CB 5	Løgstør
CB 6	Tårs
CB 7	Auning
CB 8	Grenå



1.1.2 Contributing institutes

The study was carried out in a collaboration between Aarhus University, Department of Engineering (AU-ENG), Danish Technological Institute, AgroTech (TI-AgroTech), and SEGES, Cattle (SEGES). TI-AgroTech is an authorized technological service institute offering impartial consultancy and technological services. SEGES is an agricultural R&D centre owned by the Danish farmers.

1.1.3 Test responsible

Associate Professor Anders Feilberg, Department of Engineering, Aarhus University, Hangøvej 2, 8200 Aarhus N, Denmark, email: af@eng.au.dk, Phone: +45 3089 6099.

1.1.4 Technical experts

The technical experts assigned to this test and responsible for review of test plan and test report includes:

Peter Kai, TI-AgroTech, Agro Food Park 13, 8200 Aarhus N. Current position:
Department of Engineering, Aarhus University, Hangøvej 2, 8200 Aarhus N, Denmark, email: peter.kai@eng.au.dk, Phone: +45 9350 8622

Anders Peter S. Adamsen, Department of Engineering, Aarhus University, Hangøvej 2, 8200 Aarhus N, Denmark. Current position: SEGES, Anlæg & Miljø, Agro Food Park 15, 8200 Aarhus N, Denmark, email: apa@seges.dk, Phone: +45 3339 4928 / +45 2974 4090.

Morten Lindgaard Jensen, SEGES, Anlæg & Miljø, Agro Food Park 15, 8200 Aarhus N, Denmark, email: mlj@seges.dk, Phone: +45 2493 0884.

1.1.5 Technicians

Søren G. Rasmussen, TI-AgroTech, Agro Food Park 15, Skejby, DK-8200 Aarhus N. Phone: +45 7220 3316. email: sras@teknologisk.dk.

Sune Petersen, TI-AgroTech, Agro Food Park 15, Skejby, DK-8200 Aarhus N. Phone: +45 7220 3315. email: spet@teknologisk.dk

Janni Ankerstjerne, Aarhus University, Department of Engineering, Hangøvej 2, DK-8200 N. Phone: +45 9350 8007. E-mail: jaas@eng.au.dk

Heidi Grønbæk Christiansen, Aarhus University, Department of Engineering, Hangøvej 2, DK-8200 N. Phone: +45 2012 0567. E-mail: heidig.christiansen@eng.au.dk

1.1.6 Data treatment and statistics

Pernille Kasper, Aarhus University, Department of Engineering, Hangøvej 2, DK-8200 N. E-mail: peka@eng.au.dk

1.1.7 Test period

The study took place between August 2015 and October 2016.

Table of contents

2 Introduction

This test report summarizes the methods and results of the emission survey from Danish dairy houses with different floor and manure handling systems. The test farms and the manure handling and scraping systems are described in detail in section 2.3.

2.1 Verification protocol reference

The study was performed according to the test requirements defined by the VERA Test Protocol for Livestock Housing and Management Systems, version 1 2011-29-08 (VERA, 2011).

2.2 Background and aim

Denmark has an intensive dairy production, which considerable contribute to the national emission of ammonia.

Dairy production is therefore like other Danish husbandry production systems holding more than 75 livestock units (number of livestock animals associated with 100 kg nitrogen ab manure storage) regulated by an Environmental Approval Act for Livestock Holdings. The approval act gives the frame for approval of projects for livestock holdings and has a national minimum requirement for environmental protection. The ammonia emission from dairy barns is therefore regulated of the environmental approval act when planning of new or enlarged production systems. Updated ammonia emission factors from dairy barns is therefore important in relation to planning and regulation of future dairy productions.

The aims of the project were:

1. to generate updated knowledge regarding the emission of ammonia from two common types of Danish dairy barns, and
2. to get improved knowledge regarding the abatement effects of manure scraping.

1.3 System description

2.3.1 Description of the housing systems involved in the study

The measurement of ammonia emission took place in eight cubicle dairy barns; the most common type of dairy barn in Denmark. The barns constituted the following two common subgroups, which differs in terms of floor profile:

Subgroup 1: Cubicle barns with slatted floor on interconnected manure channels is a common type dairy barn in Denmark. The excreted manure is collected beneath the slatted floor covering interconnected slurry channels, which are connected to an external pit with a pump, thus allowing daily mixing and recirculation of the slurry, hence the common term "**ring channel system**" (Figure 1, D). The height of slurry in the slurry channels ranges between 0.4 m and 0.8 m. A part of the stored slurry is typically transferred to an out-door storage tank on a weekly or monthly basis. Manure on the slatted floor is often removed by scraping by use of a robotic scraper or manure scrapers to reduce ammonia emission, and to reduce foulness of the cows and their udders.

Subgroup 2: Cubicle barns with various types of solid floors with sloped floor, grooves, or reduced slotted area is another common type of dairy barn The floor allows the urine to be continuously drained of the floor surface leaving the dry matter rich faeces that requires mechanically scraping towards transversely slurry channels, typically located at the ends of the alleys. From there the manure is transferred to external out-door storage facilities. Compared to barns with slatted floor, barns with solid drained floor is believed to be associated with a lower ammonia emission (Braams et al., 1997). In Denmark, subgroup 2 barns are labelled **solid drained floor** (Figure 1A, B, and C). The three variations of solid drained floor is described in the following:

A: Precast concrete floor with grooves typically covering a slurry channel. The perforations in the groves allows the urine to drain into the slurry channel. The dry matter rich manure is scraped to the end of the walking alley from where it is transferred to an external slurry storage tank. The floor requires frequent cleaning by means of a scraper equipped with fingers that cleans the grooves. Dairy barn No. 7 was equipped with this floor system.

B: Precast slatted floor equipped with slots consistent with an opening area of maximum 5 % to allow the urine to drain to an underlying slurry channel. The dry matter rich manure is removed from the floor 12 times per day using a scraper. Dairy Barn No. 6 was equipped with this floor system.

C: Solid V-shaped floor towards a urine gutter in the middle of the walking alley. The dry matter rich manure is scraped to the end of the walking alley from where it is transferred to an external slurry storage tank. Dairy Barns No. 5 and 8 were equipped with this floor system.

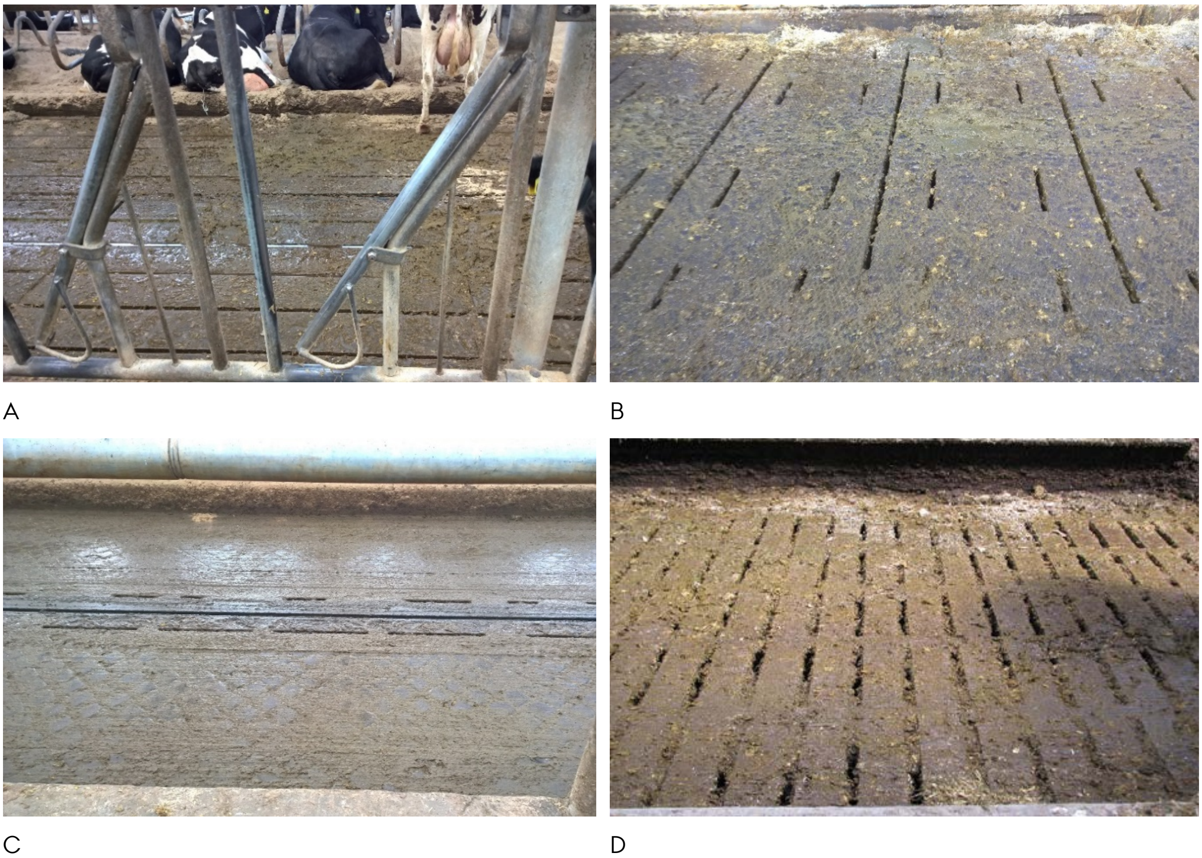


Figure 1. Pictures of the floor system in the dairy barns involved in the study. All housing system were naturally ventilated loose housing systems with different types of floor systems. The pictures A, B and C show different types of solid drained floor constituting subgroup 2, where the urine is continuously drained and the solid fraction is removed by scraping using either a manure scraper or a robotic scraper. Picture D shows a traditional slatted floor system covering a slurry channel.

The floor system of the involved test farms is described in section 0 and in Table 2.

2.3.2 Functional description of the manure scrapers

Solid drained floors require frequent scraping to remove the solid fractions of the manure that are not drained by the liquid manure gutters. A regular and efficient scraping is requested to provide cows a clean and comfortable place to walk, to keep their hoofs clean and healthy, and to avoid carrying manure on the hoofs to the cubicles with the risk of contaminating the udder. Likewise, regular scraping of walking alleys is important to reduce the ammonia emission from dairy barns (Braam et al., 1997). The scraping of the walking alleys can be performed manually using tractor-mounted scrapers during periods when the cows are in the milking parlour, however to increase the scraping frequency the scraping is often performed by either built-in scraper systems or robotic scrapers (Figure 2).

Figure 2. Pictures of different slurry scraper systems. The left picture shows a mobile scraper robot (CB 6). The right picture shows manure scraping by a built-in manure scraper system (CB 7).

3 Materials and methods

The emission of ammonia from Danish dairy barns with different floor and manure handling systems were measured on eight commercial dairy barns during a 12-month period from August 2015 to October 2016, covering all seasons in a year.

3.1 Test farms

3.1.1 Characterization of the test farms

The test took place at eight commercial dairy farms. All farms had conventional dairy production systems in typical naturally ventilated dairy housing systems. Aerial views of the test farms and test sections are shown in Figure 3.

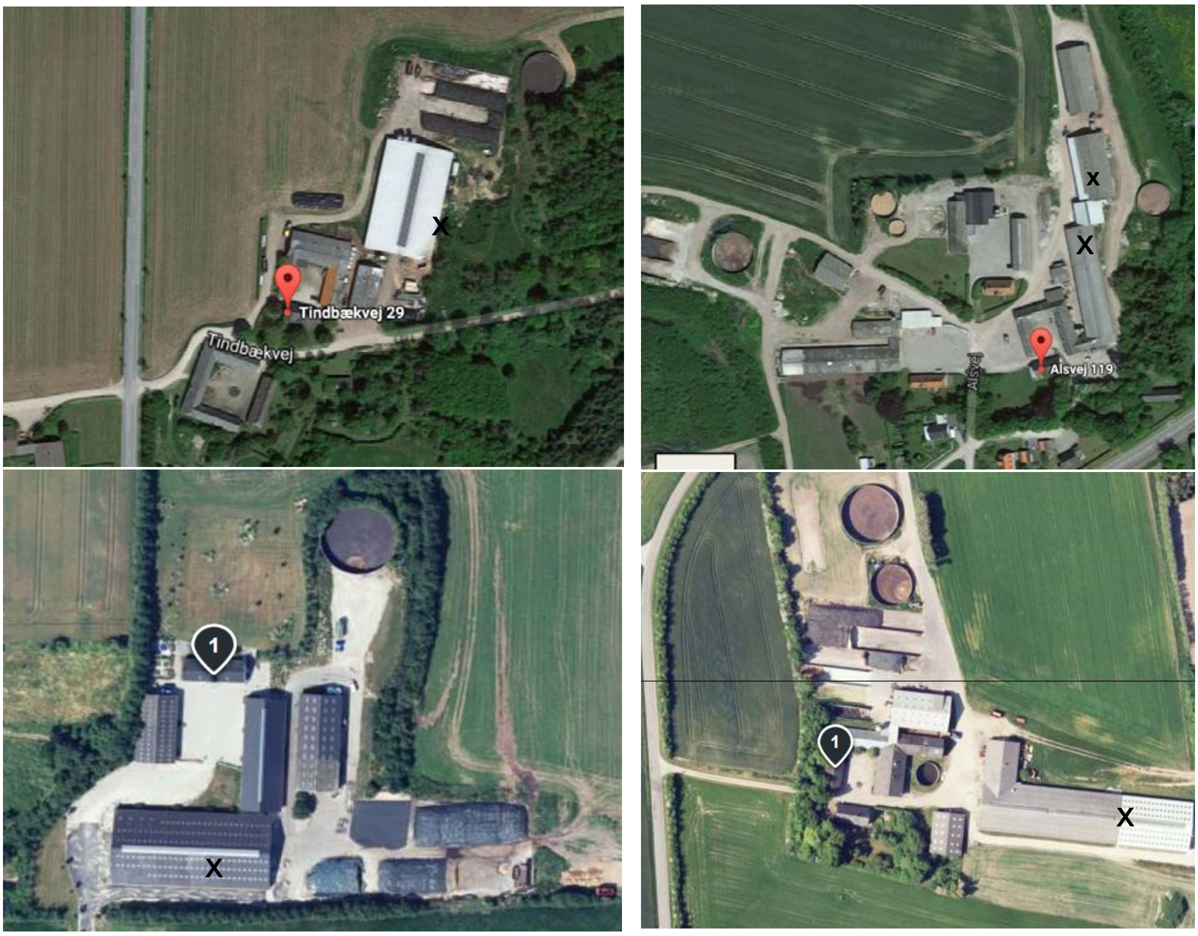


Figure 3. Aerial views of test farms. The actual test barns are denoted X (also indicates approximate location of center of sampling area.

The characteristics of the test farms are summarized in Table 2.

Table 2. Key characteristics of the eight test farms involved in the study.

	Key characteristics test farms							
Parameter	**Farm 1**	**Farm 2**	**Farm 3**	**Farm 4**	**Farm 5**	**Farm 6**	**Farm 7**	**Farm 8**
Number of cattle per test unit Number of Lactating cows per test unit Number of dry cows Number of heifers (6 to 27 month)	249-292 150-159 15-27 104-110	211-219 211-219 13-29 0	224-232 201-209 0 0	268-284 145-165 15-16 104	464-506 536-573 0 0	222-240 251-268 21-66 0	331-348 388-396 37-70 0	196-214 171-191 20-33 140-175
Average weight lactating cows (kg cow^{-1}) Average weight dry cows (kg cow^{-1}) Weight range (kg heifer^{-1})	600 600 275-600	675 675 -	600 - -	675 675 180-600	675 - -	600 600 -	700 700 -	627 627 180-600
Dimension test barns (l, w, h (ridge), m	59.0, 36.5, 8.0	131.0, 16.5, 6.4	62.0, 30.0, 5.9	108.0, 24.0, 7.3	121.0, 42.5, 12.0	63.0, 35.5, 8.1	134.0, 36.0, 10.8	138.0, 34.0, 10.5
Barn orientation (°)	12	349	92	96	245	70	29	90
Air volume test barns, m^3 barn^{-1}	12,275	11,186	11,441	13,349	40,883	12,524	35,698	32,375
Air volume per animal, m^3 animal^{-1}	41.6	51.5	48.5	49.1	74.5	47.4	89.5	85.6
Ventilation system	Naturally ventilated with adjustable curtains in the facades							
Heating system	No heating system							
Gross area of test barns (inside), m^2	2144	2132	1661	2455	4760	2271 + unused space 960	4648	4306
Animal occupied area[1], m^2	1444	1456	1196	1653	3820	1695	3343	3227
Animal occupied area, m^2 animal^{-1}	5.2	6.7	5.7	6.1	8.2	6.4	8.4	8.7
Area of walking alleys, m^2	942	936	683	1020	2640	1139	2272	2175
Area of walking alleys, m^2 animal^{-1}	3.4	4.3	3.2	3.8	5.6	4.3	5.7	5.9
Pens with deep litter, m^2	0	111	96	77	0	0	0	239
Floor system	Slatted floor	Slatted floor	Slatted floor	Slatted floor	Solid drained floor type C	Solid drained floor type B	Solid drained floor type A	Solid drained floor type C
Manure scraper system	Stationary scraper (6 day^{-1})	Manually operated scraping device / scraper robot[2]	Scraper robot (6 day^{-1})	Scraper robot (6 day^{-1})	Stationary scraper (12 day^{-1})	Scraper robot (12 day^{-1})	Stationary scraper (12 day^{-1})	Stationary scraper (12 day^{-1})
Bedding material lactating cows	Mattress + straw	Straw + chalk	Straw + chalk	Mattress + straw + chalk	Mattress + saw dust	Mattress + straw	Sand	Mattress + straw
Milking system	Milking parlour	Milking parlour	Milking parlour	Milking parlour	Automated milking system (AMS)	Milking parlour	AMS	AMS
Feeding	Concentrates (46% of total DM in feed) and roughage in compound feed.	Concentrates (30% of total DM in feed) in milking parlour, roughages in compound feed	Concentrates (44% of total DM in feed) and roughage in compound feed	Concentrates and roughage in compound feed	Concentrates in AMS, roughages in compound feed	Concentrates (41% of total DM in feed) and roughage in compound feed	Concentrates (46% of total DM in feed) in AMS[4] and in compound feed	Concentrates (36% of total DM in feed) in AMS[4] and in compound feed
Feed analysis and composition	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples	DMS[3] + N, P, K, and DM in feed samples
Water system, cows	Drinking tub	Drinking tub	Drinking tub	Drinking tub	Drinking tub	Drinking tub	Drinking tub	Drinking tub

1. *Animal occupied area defined according to Kai & Adamsen (2017) is the total animal accessible areal inside a barn including the walking alleys and the cubicles measured from rear curb to neck rail.*
2. *The scraper robot was only applied during defined test periods at a frequency of 6 day^{-1}. The slatted floor was scraped manually 1 day^{-1} in the control periods.*
3. *Dairy control and management system.*

3.2 Test procedure

3.2.1 Test parameters

Ammonia was the primary parameter. In addition, a number of conditional parameters was measured throughout the test periods.

Primary parameter

The primary analytical parameter was ammonia. The analytical method is presented in *Table 3*.

Dust and odour was not included as primary parameters in the current test because the primary aim of the test was to establish new ammonia emission factors for two subgroups of cubicle barns.

Table 3. Primary test parameters and corresponding analytical methods and detection limits

Parameter	Analytical method	Number of samples	Sampling time/period	Limit of detection	Uncertainty
Ammonia	Cavity ring-down spectroscopy (Picarro, G 2103 NH3 analyzer)	Six measuring periods, i.e. approx. one period every two months.	Min. (6 · 24 hours = 144 hours)	<1 ppbv	±5%

Conditional parameters

The conditional parameters are listed in Table 4. The conditional parameters are parameters, which may influence the emission level of the primary environmental pollutants. In addition, the table includes additional secondary environmental pollutants.

Table 4. Conditional parameters, involved analytic methods and detection limits

Parameter	Analytical method	No of measuring periods	Sampling time/period	Limit of detection	Uncertainty
Carbon dioxide (CO_2)	Photo acoustic multigas analyzer (INNOVA, 1412)	6	Continuous	2.5 mg/m^3	15 % RSD[1]
Carbon dioxide (CO_2)	NDIR (GMP 343 Carbon Dioxide Probe, Vaisala, Finland)	6	Continuous	30 ppm	±(5 ppm + 1 % of reading)[2]
Air exchange	Calculated based on the CO_2 balance	6	Continuous	-	-
Air Temperature	Testo 174H	6	Continuous	ND	±0.5 °C (-20 to +70 °C)
Relative air humidity	Testo 174H	6	Continuous	ND	±3 %RH (2 to 98 %RH)
Manure parameters	Accredited standard laboratory analyses				
- DM (%)	DIN EN 12880	6			
- Total N	DIN 19684-4	6			
- NH_4-N	DIN 38406-5-2	6			
- Total P	DIN 38406-5-2	6			
- Total K	DIN 38406-5-2	6			
Wind direction and speed (m/s)	Climatic data delivered by the Danish Meteorological Institute (DMI)	6	Continuous		

1. *RSD: Relative standard deviation*
2. *With temperature compensation*

3.3 Test activities

The test activities were undertaken by Aarhus University and TI-AgroTech Test Centre. All activities were performed according the principles of DS/EN ISO 9001. The ISO 9001 certification includes tests of environmental technologies and bioenergy technologies.

The test activities included quantification of the ammonia emission levels from traditional dairy housing systems and determination of the potential ammonia abating effect of frequent removal of the manure from the floor in walking alleys by means of scraping.

3.4 Test schedule

The measurement campaign was carried out over a year in eight dairy cattle barns starting August 2015 and ending October 2016. The annual ammonia emission from each dairy barn was based on six measurement periods. The six measuring periods in each barn were distributed over approximately 12 months to incorporate seasonal effects. Each test period was scheduled to last seven days. In barns 1 and 2 the measurement periods were extended in order to carry out an additional on-off case control test of the effect of scraping of the floors in the walking alleys. See Table 5 for details.

Table 5. The test schedule for the sampling periods at the individual test farms. Coloured squares signifies planned measuring periods.

2015 – Week no.

	Scraber test	Farm id	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Slatted floor	+	1	1 (Y)	6 (Y)	6 (Y)							6 (Y)	1 (Y)	6 (Y)								
	+	2				6 (Y)	0 (Y)	6 (Y)								6 (G)	0 (G)	6 (G)				
	-	3							(Y)										(G)			
	-	4								(Y)										(G)		
Solid drained floor	-	5														(Y)						
	-	6															(Y)	(Y)				
	-	7																	(Y)			
	-	8																		(Y)		

2016 – Week no.

	Scraber test	Farm id	1	2	3	4	5	6	7	8	9	10	11	12	13
Slatted floor	+	1			6 (G)	1 (G)	6 (G)						6 (Y)	1 (Y)	6 (Y)
	+	2						6 (G)	0 (G)	6 (G)	0 (G)				
	-	3										(Y)			
	-	4										(G)			
Solid drained floor	-	5			(Y)								(G)	(G)	
	-	6				(Y)									(G)
	-	7					(Y)								
	-	8						(Y)							

2016 – Week no.

	Scraber system	Farm id	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Slatted floor	+	1							6 (G)	1 (G)	6 (G)							
	+	2		6 (G)	0 (G)	6 (G)								6 (Y)	0 (Y)	6 (Y)	0 (Y)	
	-	3					(Y)											
	-	4						(Y)										
Solid drained floor	-	5							(Y)									
	-	6								(Y)	(Y)							
	-	7	(Y)									(Y)						
	-	8		(Y)									(Y)					

2016 – Week no. (continued)

	Scraber system	Farm id	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Slatted floor	+	1				6 (Y)	1 (Y)	6 (Y)										
	+	2							6 (G)	0 (G)	6 (G)							
	-	3		(Y)								(G)						
	-	4			(Y)								(G)					
Solid drained floor	-	5			(G)				(Y)	(Y)								
	-	6				(G)					(Y)	(Y)	(Y)					
	-	7					(G)							(Y)				
	-	8						(G)							(Y)			

Yellow weeks: CO_2 concentrations measured using INNOVA 1412.
Green weeks: CO_2 concentrations measured using Vaisala GMP343 CO_2 probe.
Farm 1 and 2: numbers indicate planned scrapings day^{-1} in specific weeks.

3.5 Test design and sampling methods

The overall principle for quantification of emissions from housing systems is to quantify the concentration of gas in the air entering and leaving the housing system and the air exchange (ventilation) of the housing system. As the ventilation rate, cannot be measured directly in naturally ventilated housing systems, the air exchange was measured indirectly using a tracer gas method (Demmers et al., 2001). The tracer gas method is briefly described in section 3.6.

The concentration of tracer gas was quantified by continuously sampling and analyses of air drawn from test sections (indoor air) and air sampled from outside the test section (outdoor air). During the sampling periods the indoor air was drawn to the sampling equipment through polytetrafluoroethylen (PTFE) tubing connected to 20 m long perforated PFTE tubes situated along the two facades and below the ridge of the test section (Figure 4). Outdoor air was drawn through PFTE tubing from two outdoor sampling points situated ca. 1 meter above ground level and ca. 2 meters away from the test sections (Figure 4).

3.5.1 Air sampling system

Sample air was continuously drawn from three 20-m sampling lines made of 6 mm (O.D.) PTFE (polytetrafluoroetylen) located inside and from two sampling points outside the cattle barns. Inside the barns one sampling line was located approximately 0.5 meter below the roof ridge (sampling line 3) and a sampling line where located along each side of the barns close to the opening (sampling lines 2 and 4, respectively).

Each 20-m sampling line consisted of four 5-m tubes assembled using T-connections. The sampling lines had 20 uniformly distributed perforations with a diameter of 1 mm made to ensure uniform airflow in all perforations in the sample line. Outside the barns, background air was sampled in two measuring points; one located on each side of the barn (sampling points 1 and 5).

The sample air was drawn continuously to the measurement system in 6 mm (I.D.) PFTE tubes at a rate of > 5 litres per minute using diaphragm pumps with PTFE membrane and valves (Charles Austen Capex L2). The sample air transfer tubes were insulated using polyethylene pipe insulation and was heated using a heating cable at 20 W m^{-1} to ensure a temperature well above the dew point temperature of the air in order to avoid vapour condensation in the tubes and measuring system.

The principal sampling area and points are shown in Figure 4.

Two gas monitoring systems was applied during the measuring periods. In the first system the sample air was split in two flows; one delivering sample air to an NH_3 analyser (Picarro G2103, Santa Clara, California), and another delivering sample air to an multigas monitor (Innova 1412, LumaSense Technologies, Ballerup, Denmark) to measure the CO_2 concentration, respectively (Figure 4C). In the second monitoring system the sample air was delivered at a rate of 1.0 L $minute^{-1}$ to a flow-through CO_2-sensor (GMP343 Carbon Dioxide Probe, Vaisala Oyj, Helsinki, Finland) and a NH_3 analyser installed in sequence (Figure 4D). The connection between the five sampling air lines/points and the gas analysers was controlled by either a multiposition valve made of polyphenylene sulphide (Cheminert low pressure valve model C25, VICI AG International, Schenkon, Switzerland) or a Innova Multipoint Sampler 1303 (LumaSense Technologies, Ballerup, Denmark).

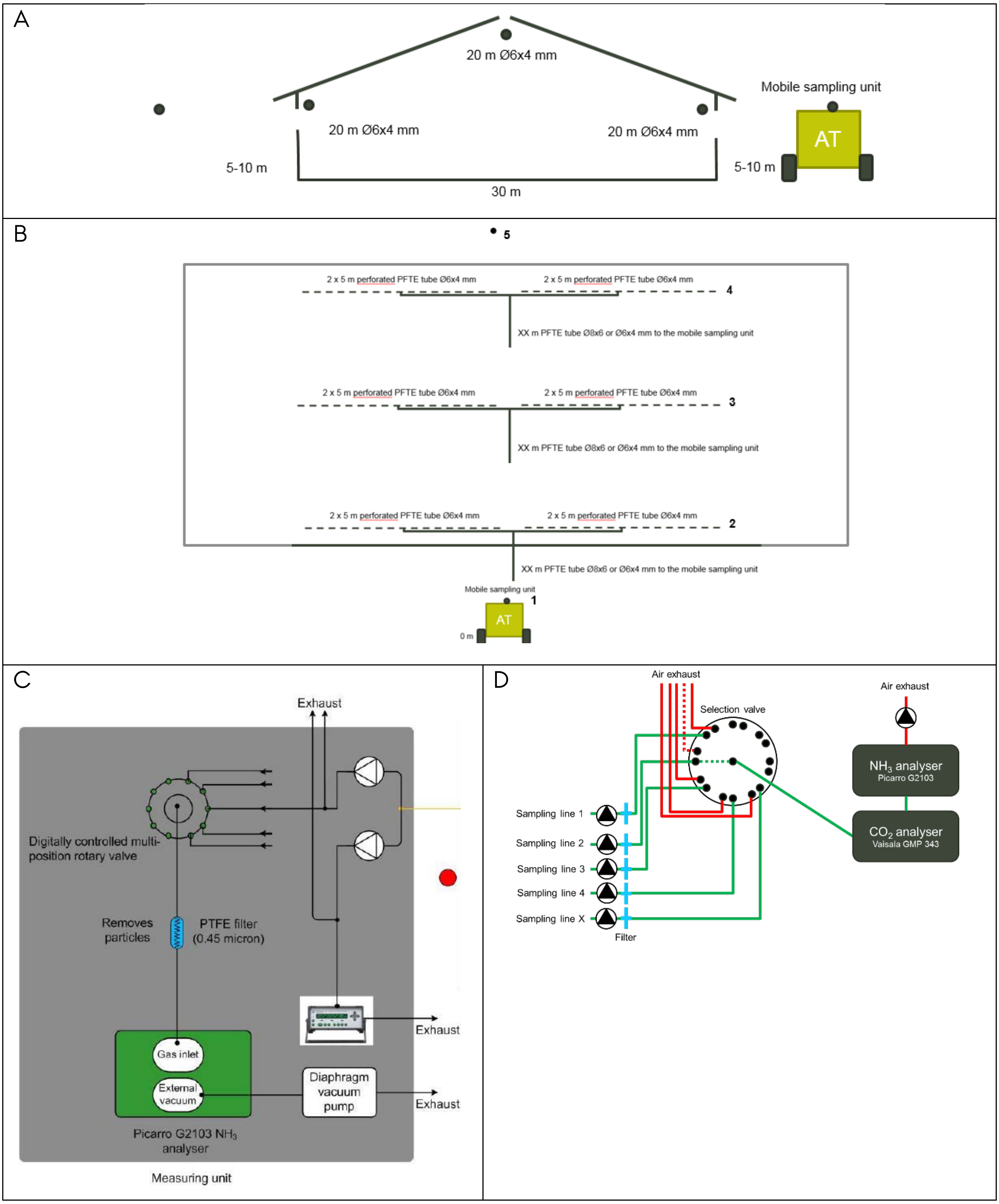


Figure 4. Schematic drawing of sampling points and measurement equipment at the test farms. The air sampling took place by drawing in-house air via insulated and heated PFTE tubes from 20 (4x5) m perforated air-sampling tubes placed below the ridge (sampling line 3) and along both sides of the barn (sampling line 2 and 4), and from background air at both side of the barn (sampling point 1 and 5). The sampled air was drawn by pumps to the measurement equipment situated inside the sampling unit (AT). Figure A shows the locations of the air sampling tubes in the barn, while figure B shows the locations of the sampling tubes seen from above. In the sampling unit (AT), the air from the indifferent sampling points was sequentially drawn towards one of two gas monitor systems (C and D).

3.5.2 Quantification of gas concentrations

The concentration of the primary gas ammonia was measured using *cavity ring down spectroscopy* (CRDS, PICARRO G2103, PICARRO Inc., Santa Clara, California, USA), while carbon dioxide which served as tracer gas was analysed using *photo acoustic spectroscopy* (PAS, Innova 1412, LumaSense Technologies, Ballerup, Denmark), or non-dispersive infrared spectroscopy (NDIR, Vaisala CARBOCAP® Carbon Dioxide Probe GMP343 (flow-through model), VAISALA, Finland). The instruments are described briefly in the following.

Cavity ring-down spectroscopy (CRDS)

A Picarro G 2103 NH_3 analyser was used to measure the ammonia concentration in the sample air in both sampling systems, i.e. all barns. The analytical method is based on cavity ring-down spectroscopy (CRDS) which is a direct absorption technique using light from a tuneable diode laser at with a narrow bandwidth of 1827 nm and is based the principle of measuring the rate of decay of light intensity inside an optical cavity. The observed ring-down time is used to calculate the concentration of the absorbing substance (here NH_3) in the gas mixture in the cavity (measuring chamber). The application of a light source with a narrow bandwidth strongly minimizes possible cross-interferences from other constituents of the air sample, including H_2O, CO_2, CH_4 and N_2O. However, although the cross-interferences are very low, the instrument still correct for cross-interferences from CO2 and H2O (Martin et al., 2016). The light source, the cavity and the detector system is precisely temperature controlled in order to improve accuracy of the instrument. The cavity pressure is precisely controlled at 185 kPa in order to reduce broadening of the absorbance peaks.

The Picarro G 2103 NH_3 analyser was applied using the following setup:

- Sample air flow: 2.0 L min^{-1}
- Cavity pressure: 185 kPa
- Cavity temperature: 45.00 °C
- Sampling frequency: 0.57 s^{-1}
- Sampling time per cycle: 4 min.

Photo Acoustic Spectroscopy (PAS)

The CO_2 concentrations of air inside and outside the barns was quantified by use either photo acoustic spectroscopy (PAS) using a 1412 Field Gas-Monitor (Lumasense Technologies, Ballerup, Denmark) coupled to a Innova 1309 multipoint sampler (Lumasense Technologies, Ballerup, Denmark). By use of the PAS analyser system the CO_2 concentration were automatically and quasi continuously sampled and logged during the measuring periods.

The Innova Field Gas-Monitor was applied using the following setup:

- Filters:
    - NH_3: UA0973
    - CO_2: UA0982
    - CH_4: UA0969
    - N_2O: UA0985
    - Water vapour: SB0527
- Sample integration time (CO_2, N_2O, NH_3, CH_4, water vapour): 5 s
- Compensate for Water vapour interference: yes
- Compensate for Cross interference: yes (for the gasses mentioned above)

- Chamber flushing time: 8 s
- Tube flushing time: 5 s
- Flushing mode: fixed
- Tube length: 1 m[1].
- Number of sampling events per cycle: 4.

The PAS Field Gas-Monitor was calibrated annually by Lumasense Technologies. The equipment was last calibrated the 5th of February 2016.

NDIR Carbon Dioxide Probe

In periods where two barns according to the schedule had to be sampled simultaneously, the Innova Field Gas-Monitor system was supplemented with a monitoring system where the CO_2 concentration was measured using non-dispersive infrared spectroscopy (NDIR) using a Vaisala CARBOCAP® Carbon Dioxide Probe GMP343 (VAISALA, Finland). The probe was calibrated at VAISALA immediately before initiation of the current project.

3.5.3 Onsite validation of measurement systems

The onsite check of the measurement systems was performed before every measurement period.

The calibration of each gas analyser was checked prior to the start of each measurement period. The validation was performed to check for drift, technical failures, or blockage of filters. The onsite check was performed by comparing the concentration measured by the measurement system and the gas concentration in standard gas. To check the calibration certified standard gases was applied containing either 10 ppm NH_3 with N_2 as the balancing gas or 1500 ppm CO_2 and 100 ppm CH_4 mixed standard gas with the N_2 as balancing gas.

If deviations (> 20 %) between sampling results or technical problems regarding the measuring system were observed, the problem was identified and repaired. If the problems were related to the measuring system, the system was sent for repair and recalibration and the scheduled measurements were instead performed by use of similar measuring system.

[1] *the air pumps delivering a constant airflow to the sampler were placed next to the sampler.*

3.6 Determination of ammonia emission

Determination of the ammonia emission from the dairy barns was established using the **tracer gas ratio method** using CO_2 as tracer gas (Ogink et al., 2013). The method and its preconditions is described in detail by Ogink et al. (2013), but a brief description will be given in the following.

The calculation of the ventilation by the tracer gas method is based on the release of natural CO_2 tracer gas inside the housing systems and its dilution. The release of CO_2 from livestock animals is depending on size, production level and activity of the animals. Due that, the CO_2 release is related to the heat produced by the animals. In the present study, the emission of the tracer gas CO_2 from the housed cattle was determined on previous estimation of the CO_2 emission from livestock cattle and from livestock manure stored inside the cattle barn (Pedersen et al., 2008).

The heat production of cattle depends on the body weight, milk yield, and the days of pregnancy, and on degradation of manure dry matter (Pedersen & Sällvik, 2002; Pedersen et al., 2008). The following equations were used to calculate the heat production of the cattle inside the test barns.

Lactating and dry cows: $\phi_{tot} = 5.6 \cdot m^{0.75} + 22 \cdot Y_1 + 1.6 \cdot 10^{-5} \cdot p^3$

Heifers: $\phi_{tot} = 7.64 \cdot m^{0.69} + Y_3 \cdot (23/M - 1) \cdot (57.27+0.302 \cdot m) / (1 - 0.0171 \cdot Y_3)) + 1.6 \cdot 10^{-5} \cdot p^3$

where

ϕ_{tot} = Total heat production per animal, W

m = body weight

Y_1 = milk yield (kg day^{-1} animal^{-1})

P = days of pregnancy (average: 160 days)

M = Energy content of the diet (MJ (kg dry matter)$^{-1}$; average: 10 MJ kg-1)

Y_3 = weight gain (kg day^{-1})

The CO_2 production from livestock animals is related to the total heat production by the following equation (Pedersen et al., 2008):

$$ECO_{2,a} = 0.180 \cdot \phi_{tot}$$

where

$ECO_{2,a}$ = CO_2 production associated with animal heat production (L h^{-1} W^{-1}).

Pedersen et al. (2008) recommend adding 10 % CO_2 production for animal houses in houses where the manure is stored for up to 3 weeks. The total CO_2 production from cattle and stored manure is therefore:

$$P_{CO2} = \sum_{i}^{i=2} N_i(ECO_{2,a,i} + ECO_{2,m,i})$$

where

P_{CO2} = Total CO_2 production inside the animal house, l CO_2 h^{-1} animal house^{-1}

i = animal type (lactating cow, dry cow, heifer)

N = number of animals within each category

$ECO_{2,a}$ = CO_2 production related to animal heat production (L CO_2/W; standard value: 0.18)

$ECO_{2,m}$ = CO_2 production from manure stored inside the barn (L CO_2/W; slatted floor: 0.02; solid drained floor: 0).

In barns with solid drained floor, the manure was removed from the barn at a frequency of 12 day^{-1} leaving very little manure in the barns to produce CO_2. Therefore, contribution of CO_2 by the manure was omitted for this barn type.

The total barn ammonia emission was calculated for each barn (*i*), at sampling day (*j*) at time interval (*k*) using the following equation:

$$E_{NH3_{ijk}} = P_{CO2_{ijk}} \times \frac{C_{NH3\_in_{ijk}} - C_{NH3\_out_{ijk}}}{C_{CO2\_in_{ijk}} - C_{CO2\_out_{ijk}}} \times \varrho_{NH3}$$

Where

E_{NH3} = emission of ammonia, *g h^{-1} barn^{-1}*

P_{CO2} = the production of trace gas in m^3 h^{-1} barn^{-1}

C_{CO2_in} - C_{CO2_out} = the difference in concentrations of CO_2 in ppmv in inside and outside air, respectively

C_{NH3_in} – C_{NH3_out} = the difference in concentrations of NH_3 in ppmv in inside and outside air, respectively

ρ_{NH3} = is the density of ammonia in g m^{-3}.

Each sampling line and point was measured three times per hour. The mean of the three samples per hour was used to calculate the hourly ammonia emission. Only the two sampling lines associated with the highest CO_2 concentrations inside the test barns was used. The third sampling line with the lowest CO_2 concentration was the one closest to the windward side of the barn, i.e. the primary air inlet. The outside sampling point in the windward side of the barn was chosen as representative for air entering the barn. The windward side of the barn was identified using meteorology data (hourly mean wind direction) relative to the barn orientation. If e.g. a barn was oriented north-south (i.e. bearing 0°-180°), the sampling point east to the barn was assumed representative for wind directions between 0° and 180° relative to the barn orientation, and the sampling point west to the barn was assumed representative for wind directions between 180° and 360° relative to the barn orientation.

For each barn, the daily ammonia emission was calculated as the sum of hourly ammonia emissions calculated for each 24-h measuring day. The time from midnight to midnight constituted one measuring day. Measuring days with less than 80% valid emission data i.e. NH_3 and CO_2 concentration measurements, were excluded, including transit days, i.e. days where the monitoring system was moved from one barn to the next.

For each barn, the mean daily ammonia emission per cow was calculated as the mean of daily ammonia emissions in the measuring period divided by the number of cows.

Barns 1, 4, and 8 housed heifers in the same barn as the cows. In these barns, the total number of cows was calculated as the total CO_2 production from cows and heifers divided by the mean CO_2 production per cow.

For each barn, the mean annual ammonia emission per animal was calculated as the mean of the measuring periods. For each subgroup of barns, the mean annual ammonia emission was calculated as the mean annual emission of the four barns belonging to each subgroup.

The same procedure was applied to calculate the mean annual ammonia emission per m^{-2} production area in the barns. The production area is defined in a report prepared by Aarhus University for the Danish Environmental Protection Agency (Kai & Adamsen, 2017) as the total barn area normally accessible to the animals. In dairy barns, the production area includes area of the cubicles measured from rear curb to the neck rail, the total area of the walking alleys, the collection area in front of the milking parlour or Automatic milking system (AMS), as well as calving pens and separation pens.

3.7 Determination of effect of frequent manure scraping in barns with slatted floor

The effect of frequent scraping of the slatted floor was investigated using a special case/control setup, where the case/control was separated in time instead of space, i.e. the same barn was used as case (6 scrapings day^{-1}) and control (0 or 1 scraping day^{-1}) only separated in time. Barn 1 and 2 belonging to the subgroup with slatted floor and recirculation manure system was used for the test. Each of six measurement periods was divided in three periods, i.e. case-control-case periods, respectively. The day following change of the scraping frequency was omitted from the data set in order to avoid carry over effect.

3.8 Indicative test of floor scraping frequency in dairy barns with solid drained floor

According to the environmental technology list of environmental technologies for livestock housing published by the Danish environmental Protection Agency it is required to remove the manure from the floor 12 times per day in dairy cubicle barns with solid drained floor for the barns to be considered low emission barns. To investigate the possible effect of manure removal frequency on the ammonia emission, the scraping frequency in two test barns was reduced from twelve to two times per day using the on-off test design, where a period with high manure removal frequency was followed by a period with low manure removal frequency. Each period lasted 48 to 72 hours and was carried out in barns 5 and 6 during measuring period 6 which was prolonged.

3.9 Determination of air temperature and air humidity

Air temperature and humidity of indoor and outdoor air were online measured during sampling periods by use of Testo 174 H temperature and air humidity data-logger sensors (Testo Inc., Sparta, USA). The sensors were situated about 3 m above floor level centrally inside the barn and in 1 m height in the shadow outside the dairy barns.

3.10 Determination of manure composition

Representative samples of the cattle slurry were sampled in connection to the ammonia sampling periods. From each test barn, three manure samples were collected from the slurry produced by the housed cattle. To ensure homogenization of the stored slurry the stored slurry was thoroughly agitated 20 minutes by the barns slurry pumps before the manure sampling took place. As soon as possible (<4 hours) the samples were stored at −18°C before analysed for dry matter, total-N, ammonium-N, P, and K.

3.11 Determination of feed composition

At the start at each measuring period representative samples of the mixed compound feed were sampled at each test farm. The feed samples were collected in two 60 L PVC buckets placed at the feeding alley during the first feeding in the morning of the first day of each measuring period. Feed was automatically collected in the buckets following passage by the feed mixer wagons or robotic feeder (Figure 5).

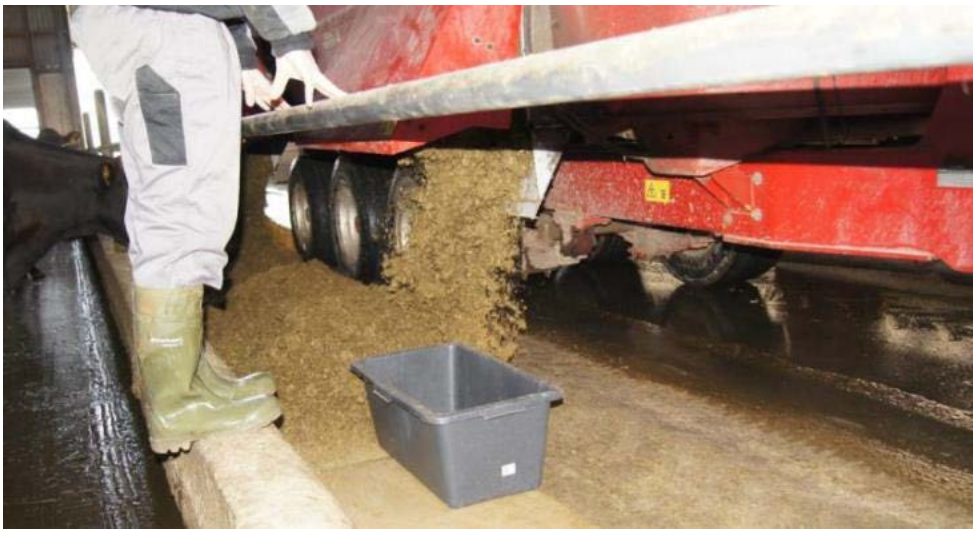


Figure 5. Sampling of feed samples directly from the feed alley (photo: Anon., 2014).

Representative feed samples were collected by 1) thoroughly mixing the feed from the two buckets, 2) making a pile of feed, 3) flatten the feed pile, 4) dividing the flatten pile of feed in four quadrants, 4) taking two diagonal quadrats and repeat 1-4 until a manageable sample size (ca. 1 kg) was obtained (Figure 6).

Figure 6. Feed sampling. Left: Feed sample mixed and divided in four quadrats. Right: remaining diagonal feed quadrats ready for further sampling (photo: Anon., 2014).

3.12 Preservation and storage of samples

3.12.1 Manure samples

Immediately after sampling manure samples were stored as cool as possible. Within 4 hours the samples were frozen (-18°C) until sent for analytical analyses.

3.12.2 Feed samples

Immediately after sampling the feed samples were stored as cool as possible. Within 4 hours the samples were frozen (-18°C) until sent for analytical analyses.

3.13 Analysis of manure and feed samples

The manure and feed analyses were analysed for dry matter, nitrogen, ammonium nitrogen, phosphorous, potassium, and pH. All analyses were carried out by Eurofins, Galten. The laboratory was accredited according chemical analyses of feed products and manure samples (DANAK, reg. no. 560, 2014).

3.14 Calculation of nitrogen excretion

For each test barn and measuring period the measured mean 24-h ammonia emission was related to the calculated excretion of total nitrogen (total-N) and total ammoniacal nitrogen (TAN). Total-N and TAN was calculated using the methodology described in Lund and Aaes (2016).

The total-N excretion was calculated using the following equation:

$$N_{excreted} = N_{feed} - (N_{milk} + N_{growth} + N_{foetus})$$

where $N_{excreted}$ is the amount of total nitrogen excreted per animal per day (g N day^{-1}), N_{feed} is the amount of nitrogen in feed per animal (g N day^{-1}), N_{growth} is the amount of nitrogen applied for growth (g N day^{-1}), and N_{foetus} is the amount of nitrogen in foetus per animal (g N day^{-1}).

The nitrogen content of the feed was calculated using:

$$N_{feed} = DM_{feed} \cdot P_{feed} / 6.25$$

where DM_{feed} is the consumed amount of feed dry matter per animal (kg day^{-1}), P_{feed} is protein content of the feed (g protein kg^{-1} feed), and 6.25 is a conversion factor used to calculate the nitrogen content of feed protein.

The nitrogen content of the milk produced per animal per day was calculated using:

$$N_{milk} = M \cdot P_{milk} / 6.38$$

Where, N_{milk} is produced amount of nitrogen in milk per animal (g day^{-1}), M is the mass of milk produced per animal (kg day^{-1}), P_{milk} is protein content of milk (g kg^{-1}), and 6.38 is a conversion factor used to calculate the nitrogen content of milk protein. Milk data was supplied by the Danish Registration and Milk Control (Registrerings- og YdelsesKontrollen, RYK).

$$N_{growth} = G \cdot 0.0256$$

Where, N_{growth} is the amount of nitrogen retained in the animal for growth (g day^{-1}), G is the growth rate per animal (kg day^{-1}), and 0.0256 is the amount of nitrogen in growth (g kg^{1}).

$$N_{foetus} = F \cdot 0.0296$$

Where, N_{foetus} is the amount of nitrogen retained in the animal for foetus growth (g day^{-1}), F is the growth of foetus per animal (kg day^{-1}), and 0.0296 is the amount of nitrogen in foetus growth (g kg^{-1}).

The amount of nitrogen in faeces from cows was calculated as:

$$N_{Faeces} = (0.04 \cdot N_{feed}) + (1.8 \cdot DM_{feed}^2 / 6.25) + (20 \cdot DM_{feed} / 6.25)$$

Where, N_{Faeces} is the amount of faeces nitrogen per animal (g day^{-1}).

The amount of nitrogen in faeces from heifers was calculated as:

$$N_{Faeces} = N_{feed} - DM_{feed} \cdot (0.93 \cdot P_{feed} - 30) / 6.25$$

The amount of nitrogen in urine was calculated as:

$$N_{urine} = N_{excreted} - N_{faeces}$$

Where, N_{urine} is amount of urinary nitrogen excreted per animal (g day^{-1}). By definition, N_{urine} is considered TAN following excretion.

3.15 Data management

3.15.1 Data storage, transfer and control

Data were either registered and reported at the test site, or collected by electronic means at the test site and sent via internet to electronic data storage (harddrive) at the test centres.

Results from external laboratories were sent electronically by email or in paper version by mail. A list of data compilation and storage is presented in Table 6.

Table 6. Data compilation and storage summary.

Data type	Data media	Data recorder	Recording of data	Data storage
Test plan and test report	Protected pdf-files.	Test responsible	When approved	Files and archives at test institutes
Data manually recorded at test site	Data recording forms	Test staff at test site	During collection	Files and archives at test institutes
Calculations	Excel files/MATLAB	Test responsible	After conclusion of data sampling	Files and archives at test institutes
Analytical reports	Paper / pdf-files	Test responsible	When received	Files and archives at test institutes

3.15.2 Statistical analysis

Within each test location *i* the proportional effect of the treatment was calculated for each measuring period *j* from the daily means of the case and control emissions (E_{case} and $E_{control}$) at measuring period *j*:

$$\frac{E_{controlij} - E_{caseij}}{E_{controlij}} \cdot 100\%$$

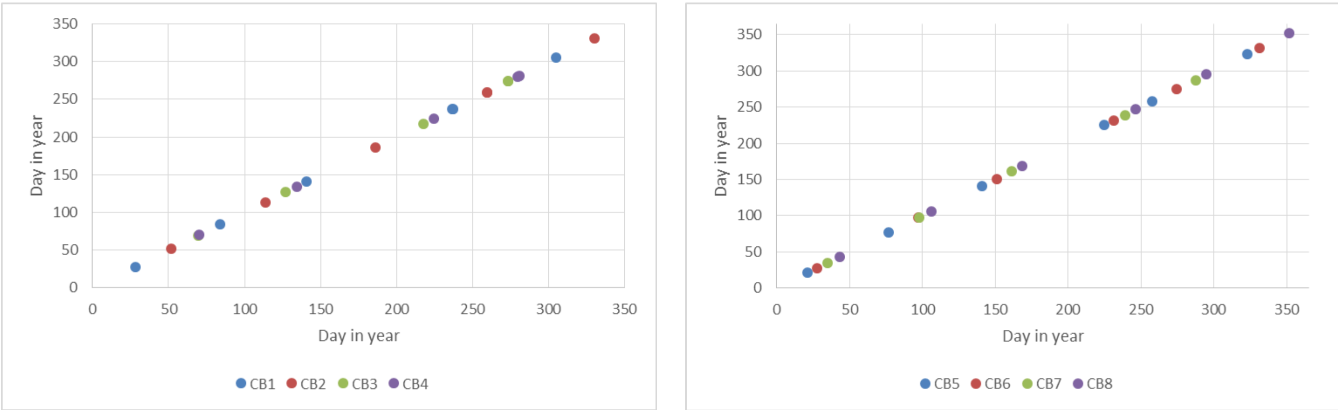
For each test location, the mean proportional effect, averaged over measuring periods, and the standard deviation of the mean is calculated and reported. The overall proportional effect was calculated as the average of both location means.

The difference between the two manure removal frequencies on each test barn were analysed using the paired t-test.

4 Results and discussion

4.1 Distribution of measuring periods

The VERA-protocol describes that for animal categories with a stable emissions pattern all test sites shall be measured minimum 6 times evenly distributed over a 12 months period in order to include measurement in all seasons. The distributed of the measuring periods for all test sites are depicted in Figure 7.

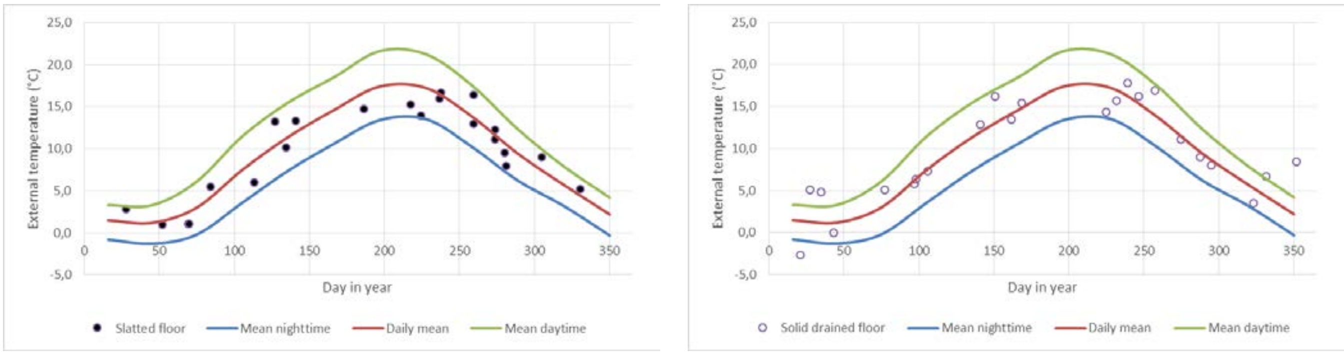


A

B

Figure 7. Distribution of measuring periods in cattle barns 1-4 with slatted floor (A) (n=22) and cattle barns 5-8 with solid drained floor (B) (n=23).

The mean outside temperatures recording in the measuring periods at the test sites are depicted in Figure 8. The mean outside temperature of all measuring days were 9.8 °C and 9.4 °C at test sites 1-4 with slatted floors and test sites 5-8 with solid drained floors, respectively. The annual mean outside temperatures recorded during the measuring periods were 0.6 - 1.0 °C higher than the decadal annual mean outside temperature in Denmark in the period 2001 to 2010 being 8.8 °C (www.dmi.dk). In cattle barns with solid drained floor, the outside temperature recorded during three wintertime measuring periods were somewhat higher than the decadal annual mean outside temperature in Denmark. This may have affected the ammonia emission. However, the limited number of deviating observations is considered to have little impact on the annual mean emission. The effect on the ammonia of the temperature differences between the two groups of cattle barns, and the current test and the decadal annual mean outside temperature in Denmark is assumed insignificant.



A

B

Figure 8. Outside temperature recorded in the measuring periods in (A) cattle barns 1-4 with slatted floor and (B) 5-8 with solid drained floor. The solid lines are decadal mean temperatures recorded in Denmark by DMI from 2001 to 2010.

For each test barn, the recorded climatic data for each measuring period is presented in Table 7. Three measuring periods (gas measurements) out of 48 planned periods were not carried out because of manning problems (illness), or because the data was discarded due to technical failure. Two of the missing periods were planned at test sites 3 and 4 (slatted floor), respectively, while the third missing period was planned at test site 7 (solid drained floor). In addition, indoor temperature and/or relative humidity data is missing in 4 measuring periods because of technical problems (data logger was not activated following battery change, data logger was destroyed by cow, data was unintentionally overwritten, and data logger was removed from barn area by service people).

Table 7. Climatic data (means) recorded during the different measuring periods at the eight test sites.

Sampling period					Indoor		Outdoor			
Barn id	Peri od	Floor system	dd-mm-yyyy	Median day in year	Tempe-rature (°C)	Relative humidity (%)	Tempe-rature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind directio n (°)
1	1	Slatted	17-08-2015 - 03-09-2015	237	16.7	78	15.9	78	4.4	155
1	2	Slatted	20-10-2015 - 15-11-2015	305	10.4	95	8.9	90	4.3	204
1	3	Slatted	19-01-2016 – 07-02-2016	28	6.5	89	2.8	89	5.7	239
1	4	Slatted	15-03-2016 – 03-04-2016	84	8.7	75	5.4	82	4.0	220
1	5	Slatted	14-05-2016 – 28-05-2016	141	16.3	76	13.3	75	3.5	169
1	6	Slatted	18-08-2016 – 02-09-2016	238	17.9	ND	16.7	80	3.5	200
2	1	Slatted	08-09-2015 – 27-09-2015	260	14.7	84	13.0	85	5.9	168
2	2	Slatted	18-11-2015 – 07-12-2015	331	5.8	91	5.2	87	6.8	203
2	3	Slatted	09-02-2016 – 06-03-2016	52	2.9	90	1.0	86	4.7	193
2	4	Slatted	14-04-2016 – 03-05-2016	114	8.3	80	6.0	79	5.8	208
2	5	Slatted	22-06-2016 – 14-07-2016	186	16.3	87	14.7	84	5.1	223
2	6	Slatted	08-09-2016 - 25-09-2016	260	16.9	84	16.4	76	3.8	148
3	1	Slatted	29-09-2015 - 04-10-2015	274	14.2	81	11.1	86	3.8	223
3	2	Slatted	09-12-2015 – 15-12-2015	346	ND	ND	ND	ND	ND	ND
3	3	Slatted	08-03-2016 – 13-03-2016	70	6.9	85	1.1	93	2.4	180
3	4	Slatted	04-05-2016 – 10-05-2016	127	16.5	63	13.3	62	3.4	131
3	5	Slatted	03-08-2016 – 08-08-2016	218	18.7	79	15.2	84	5.7	223
3	6	Slatted	28-09-2016 – 03-10-2016	274	15.4	87	12.3	81	5.4	152
4	1	Slatted	04-10-2015 – 10-10-2015	280	11.2	85	9.6	86	5.9	111
4	2	Slatted	12-12-2015 – 17-12-2015	349	ND	ND	ND	ND	ND	ND
4	3	Slatted	09-03-2016 - 13-03-2016	70	6.5	81	1.1	93	2.7	166
4	4	Slatted	12-05-2016 - 17-05-2016	135	ND	ND	10.2	69	5.8	232
4	5	Slatted	10-08-2016 - 15-08-2016	225	ND	ND	13.9	81	6.7	273
4	6	Slatted	05-10-2016 – 11-10-2016	281	10.4	82	7.9	79	5.1	46
5	1	Solid drained	17-11-2015 - 23-11-2015	323	8.4	88	3.5	88	5.2	156
5	2	Solid drained	20-01-2016 - 24-01-2016	21	3.9	80	-2.6	93	3.2	182
5	3	Solid drained	15-03-2016 - 21-03-2016	77	9.9	78	5.1	87	4.3	217
5	4	Solid drained	19-05-2016 - 23-05-2016	141	15.7	81	12.9	89	4.5	211

Sampling period					Indoor		Outdoor			
Barn id	Peri od	Floor system	dd-mm-yyyy	Median day in year	Tempe-rature (°C)	Relative humidity (%)	Tempe-rature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind directio n (°)
5	5	Solid drained	11-08-2016 – 15-08-2016	225	16.8	82	14.3	81	7.3	273
5	6	Solid drained	08-09-2016 – 21-09-2016	258	19.3	80	16.9	80	3.3	152
6	1	Solid drained	25-11-2015 – 02-12-2015	332	8.0	96	6.7	86	7.4	233
6	2	Solid drained	26-01-2016 – 31-01-2016	28	9.0	84	5.1	87	8.9	238
6	3	Solid drained	30-03-2016 – 12-04-2016	97	10.3	81	5.8	78	3.9	156
6	4	Solid drained	25-05-2016 – 06-06-2016	151	20.8	70	16.2	78	3.6	79
6	5	Solid drained	17-08-2016 – 22-08-2016	232	ND	ND	15.7	83	3.1	168
6	6	Solid drained	23-09-2016 - 10-10-2016	275	14.4	77	11.0	82	4.7	108
7	1	Solid drained	08-12-2015 – 14-12-2015	344	7.4	93	5.1	91	3.9	216
7	2	Solid drained	02-02-2016 – 08-02-2016	35	7.0	83	4.8	84	6.3	226
7	3	Solid drained	05-04-2016 – 11-04-2016	98	9.9	73	6.3	84	3.3	179
7	4	Solid drained	08-06-2016 – 13-06-2016	162	16.0	62	13.5	65	3.8	167
7	5	Solid drained	24-08-2016 – 30-08-2016	239	18.6	81	17.8	80	3.9	204
7	6	Solid drained	12-10-2016 – 17-10-2016	288	10.4	82	9.0	86	6.3	100
8	1	Solid drained	16-12-2015 – 21-12-2015	352	9.9	98	8.4	91	5.9	209
8	2	Solid drained	11-02-2016 – 15-02-2016	43	3.2	80	-0.1	76	3.8	170
8	3	Solid drained	13-04-2016 – 19-04-2016	106	9.0	80	7.3	82	6.0	190
8	4	Solid drained	15-06-2016 – 20-06-2016	169	9.0	81	15.4	81	5.0	214
8	5	Solid drained	01-09-2016 – 06-09-2016	247	17.1	77	16.2	82	4.2	193
8	6	Solid drained	19-10-2016 – 25-10-2016	295	9.7	91	8.0	90	5.0	89

4.2 Ammonia emissions

Based on the 24-h total ammonia emission the median and mean ammonia emission ± standard deviation (SD) was calculated for each measuring period and test barn. Further the ammonia emission per cow, livestock unit (1 LU = 500 kg live weight), heat producing unit (1 HPU = 1000 W free heat produced at 20 °C), and per m^2 production area and walking alley was calculated.

The emission per cow was calculated as the total ammonia emission divided by the number of cows present in each test barn during the measuring periods. In barns that in addition to cows housed heifers (barns 1, 4, and 8), the number of cows was calculated as the total daily barn CO_2 production divided by the average daily CO_2 production per dairy cow calculated for each test barn and measuring period. Detailed information on the calculation of the CO_2 production at barn level is provided in Appendix 7.3. The production area is defined in the Danish environmental approval act for livestock holdings (Husdyrgodkendelsesbekendtgørelsen Bilag C (BEK nr. 916 af 23/06/2017). The ammonia emissions per test barn and measuring period are presented in Appendix 0.

Calculated annual median and mean ± standard deviation (SD) ammonia emissions for each test barn calculated per cow, livestock unit (LU), heat producing unit (HPU), and m^2 production area is presented in Table 8.

Table 8. Median, mean ammonia emissions and standard deviations observed at the individual barns. The ammonia emission is calculated per cow, per livestock unit (LU = 500 kg live weight), per heat producing unit (1 HPU = 1000 W free heat produced at 20°C), and per m^2 of production area.

Barn id	*Floor type*	*No of periods*	kg NH_3-N cow^{-1} $year^{-1}$		kg NH_3-N LU^{-1} $year^{-1}$		kg NH_3-N HPU^{-1} $year^{-1}$		Kg NH_3-N m^{-2} $year^{-1}$	
			Median	*Mean ± std.dev.*	*Median*	*Mean ± std.dev.*	*Median*	*Mean ± std.dev.*	*Median*	*Mean ± std.dev.*
1	Slatted	6	10.0	9.8±1.9	7.6	7.5±1.5	7.8	7.7±1.6	1.5	1.5±0.3
2	Slatted	6	5.5	6.1±1.8	4.1	4.5±1.3	3.9	4.3±1.2	0.8	0.9±0.3
3	Slatted	6	6.4	6.2±1.8	4.7	4.6±1.3	4.8	4.7±1.5	1.1	1.1±0.3
4	Slatted	5	6.8	7.6±1.9	6.2	6.9±1.7	6.4	7.0±1.8	1.1	1.3±0.3
5	Solid drained	6	9.3	9.0±3.7	6.9	6.7±2.7	6.4	6.3±2.6	1.1	1.1±0.5
6	Solid drained	6	6.7	6.6±1.0	5.0	4.9±0.7	5.0	4.8±0.8	1.1	1.0±0.2
7	Solid drained	5	8.6	9.6±2.2	6.3	7.1±1.6	6.0	6.6±1.4	1.0	1.1±0.3
8	Solid drained	6	5.8	5.8±2.0	5.5	5.4±1.9	5.6	5.5±1.8	1.0	1.0±0.3

The standard deviations between measuring periods in barns with solid drained floor appears to be larger than observed in barns with slatted floor. This is likely an effect of a higher temperature dependency in barns with solid drained floor (R^2 = 0.5), whereas no correlation was found in barns with slatted floor (R^2 = 0.07) (Figure 9).

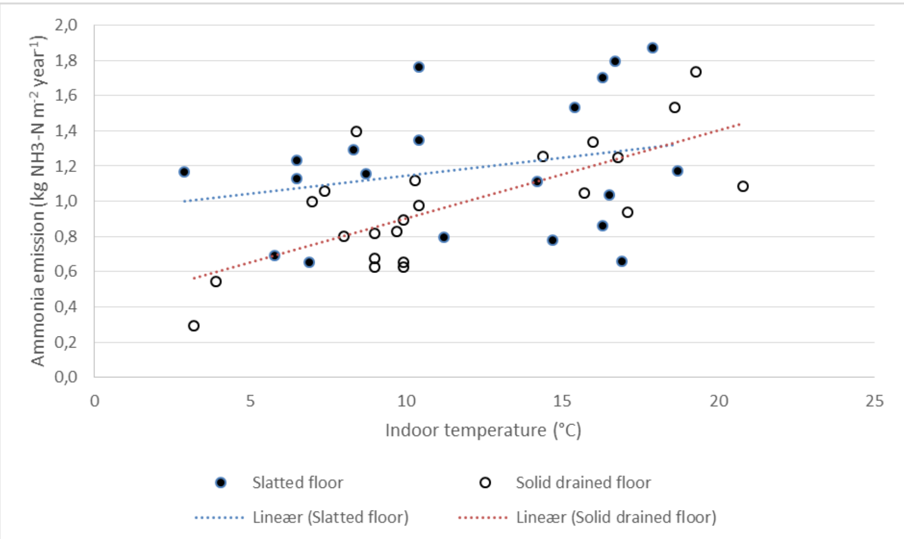
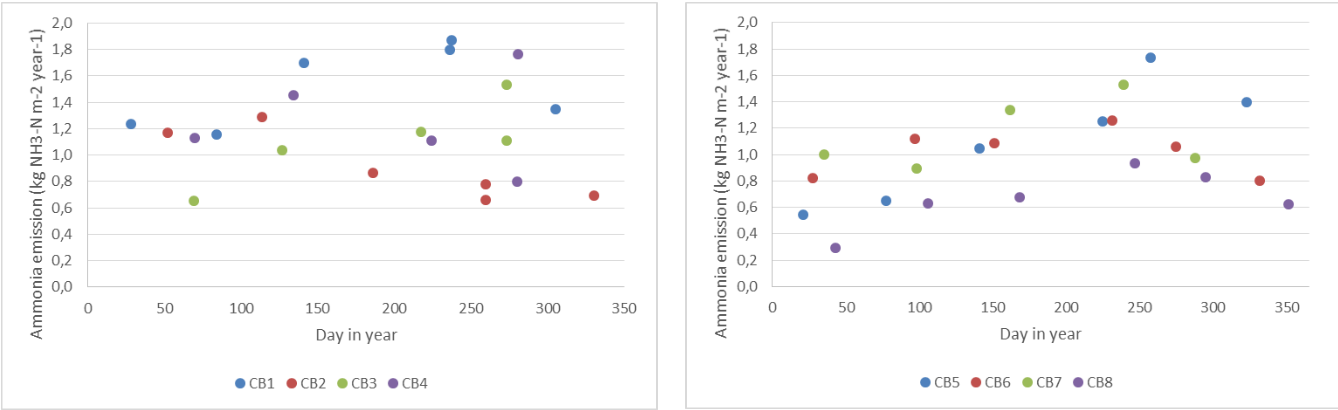


Figure 9. Ammonia emission and indoor temperature in barns with slatted floor (solid dots) and solid drained floor (open dots), respectively.

Figure 10 depicts the distribution of measured ammonia emissions per m^2 from (A) barns 1-4 with slatted floor and (B) barns 5-8 with solid drained floor. Whereas the ammonia emission from barns with solid drained floor appears to follow an annual cycle, i.e. suggesting a temperature dependency, the ammonia emission from barns with slatted floor is unaffected by temperature. The reason for this may be that the principal source of ammonia emission in barns with solid drained floor is the small amount of manure on the floor, whereas the ammonia emission from barns with slatted floor originates from the surface of the manure in the manure channels as well as the manure from the surface of the floors. The temperature in the manure channels is assumingly relatively stable because of the bulk amount of manure in the channels, and thus requires a large amount of energy to cause a change in the temperature.



A

B

Figure 10. Ammonia emissions (kg NH_3-N m^{-2} production area $year^{-1}$) measured in the different measuring periods in cattle barns 1-4 with slatted floor (A), and in cattle barns 5-8 with solid drained floor (B).

The median and mean ammonia emissions ± standard deviation (SD) between barns is presented in Table 9. The annual mean ammonia emission was not significantly affected by floor type. The mean ammonia emission measured in barns with slatted floor was **1.2 ± 0.3 kg NH_3-N m^{-2} $year^{-1}$** (mean ± SD), i.e. 10 % lower than the standard emission factor being 1.34 kg NH_3-N m^{-2} $year^{-1}$ for dairy cows and heifers (Kai & Adamsen, 2017).

The mean ammonia emission measured in barns with solid drained floor was **1.0 ± 0.2 kg NH_3-N m^{-2} $year^{-1}$** (mean ± SD). This is approximately 50 % higher than the standard emission factor being 0.67 kg NH_3-N m^{-2} $year^{-1}$ for dairy cows and heifers (Kai & Adamsen, 2017). Larger seasonal variation was observed for this barn type. This can in part be explained by a temperature dependency resulting in larger seasonal variation in the ammonia emission compared with barns with slatted floor which store liquid manure under the slatted floor to a much larger degree than do barns with solid drained floor where the manure is removed from the barns 12 times per day to an outdoor storage and thus stores very little manure in the barns. The Danish standard emission factor was established on basis of various studies on the effect of floor profiles on the ammonia emission. Swiestra et al. (1995) measured the ammonia emission from an experimental dairy cattle house with either slatted or solid floor with a central gutter and found that the emission from the compartment with solid floor and a central gutter was about 50 % of the emission from the compartments with slatted floors. Braam et al. (1997a) investigated ammonia emissions from a double-sloped solid floor scraped 12 times per day in a mechanically ventilated dairy cow house. The solid drained floor with under-floor manure storage reduced ammonia by about 50 % compared with the slatted floor. Braam et al. (1997b) compared the ammonia emissions from two solid floor systems with the emission from traditional slatted floor. The solid floor without a slope did not result in significant ammonia reduction while the solid floor with a 3% slope reduced ammonia emissions by 21 % compared to a slatted floor. Zhang et al. (2005) measured ammonia emissions from naturally ventilated dairy cattle buildings with different floor types and manure-handling systems and found that the lowest ammonia emission was from buildings with solid drained floors with smooth surface. With the exception of Zhang et al. (2005) all studies took place in relatively small experimental compartments with mechanical ventilation under strict experimental control. In contrast, the current study was carried out as a survey at production dairy cattle barns with no particular supervision or control during the measurement periods. As a result, the floors and scrapers were not new and may not have been maintained thoroughly prior to or during the measurement periods. This may have resulted in suboptimal performance of the scrapers and urine drains leading to higher ammonia emissions compared with the experimental studies.

Table 9. Median and mean ammonia emission ± standard deviation (SD) from dairy cows in dairy barns with slatted and partly slatted solid floors (solid floor). The ammonia emission is calculated per cow, per livestock unit (LU = 500 kg live weight) per heat producing unit (1 HPU = 1000 W free heat produced at 20°C), per m² production area, and per m² alley.

		kg NH_3-N cow^{-1} year^{-1}		kg NH_3-N LU^{-1} year^{-1}		kg NH_3-N HPU^{-1} year^{-1}		kg NH_3-N m^{-2} production area year^{-1}		kg NH_3-N m^{-2} alley year^{-1}	
Floor type	*No of farms*	Median	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD
Slatted	4	7.6	8.0±2.1	5.5	5.9±1.5	5.6	5.9±1.7	1.1	1.2±0.3	2.0	1.9±0.4
Solid drained	4	8.1	8.2±1.4	5.9	6.0±1.0	5.8	5.8±0.8	1.1	1.0±0.2	1.5	1.4±0.3
Mean ± SD of all barns									1.1±0.3		1.7±0.4

Only a few studies has been carried out in Danish dairy barns. Zhang et al. (2005) measured the ammonia emission from nine dairy barns with various floor types using the same tracer gas method as in the current study, while the ammonia concentration was measured using photoacoustic spectrometry (Innova gas monitor model 1312). Furthermore, the barns were only measured two or three times. The mean ammonia emission from four dairy barns with slatted floor and slurry recirculation or back flushing was 8.5±2.6 kg NH_3-N year^{-1} HPU^{-1}. Our study resulted in a mean ammonia emission of 5.9±1.7 kg NH_3-N HPU^{-1} year^{-1}, i.e. approximately 30 % lower compared with Zhang et al. (2005). This difference is probably a consequence of several factors. Our study was based on six measuring periods in each barn. We used a CRDS measuring principle, which is associated with better performance characteristics in terms of detection limit and specificity compared with the PAS measuring principle used by Zhang et al. (2005). This likely resulted in a higher accuracy than the study of Zhang et al. (2005). The variation coefficients observed in the two studies is however comparable, i.e. 29 % and 31 %, respectively.

Over the years, the feed efficiency has improved resulting in a decreasing TAN:total-N ratio leaving less ammonium to volatilize. In 2009, an average Danish cow of large race excreted 65.7 kg TAN in 22 tonnes of manure resulting in a theoretical manure TAN concentration of 3.0 kg TAN ton^{-1} (Poulsen et al., 2010). In 2016, an average Danish cow excreted 68.6 kg TAN in 26 tonnes of manure resulting in a theoretical TAN concentration of 2.6 kg ton^{-1} (Poulsen et al., 2017) (Table 10). The manure samples collected in the test barns in each measuring period contained a mean concentration of 4.2 kg total-N ton^{-1} and 2.7 kg TAN ton^{-1} (Table 16), i.e. significantly less total-N than expected according to the normative figures but a comparable TAN concentration.

Table 10. Normative figures for nitrogen and mass of manure excreted per cow per year in 2009 and 2016 according to the Danish normative system on livestock manure (Poulsen et al., 2010 and 2017).

	Year	
	2009	**2016**
Total-N (kg cow^{-1} year^{-1})	140.9	150.7
TAN (kg cow^{-1} year^{-1})	65.7	68.6
Manure (tonnes cow^{-1} year^{-1})	22	26
Total-N concentration (kg ton^{-1})	6.4	5.8
TAN concentration (kg ton^{-1})	3.0	2.6

4.3 Ammonia emission related to the nitrogen excretion

In order to calculate the ammonia emission in relation to the TAN excretion, the total TAN excretion was calculated based on the TAN excretion from each animal category. In addition to cows, three barns also housed heifers. For comparison with the corresponding normative figures, the annual nitrogen intake, excretion, and milk production per cow (weighted mean of lactating and dry in each herd) is tabulated in Table 11. The dry matter intake, milk production, and faecal nitrogen excretion were at the same level as the corresponding normative figures.

The annual feed-N, total-N excretion, and TAN excretion were slightly higher than the normative figures. Barns 3 and 5 deviated because the barns housed lactating cows only. The figures therefore represent cows that, from a calculation point of view, lactated 365 days per year. Lactating cows consumes much more feed and excretes more nitrogen than dry cows.

Table 11. Annual nitrogen excretion from cows in barns 1-8. Milk production is per dairy cow at each farm. Heifers are not included in the table.

Barn ID	Feed dry matter intake (kg year^{-1} cow^{-1})	N in feed (kg year^{-1} cow^{-1})	Milk production (kg year^{-1} cow^{-1})[2]	Total nitrogen excretion (kg N year^{-1} cow^{-1})	Faecal nitrogen excretion (kg N year^{-1} cow^{-1})	Urinary N excretion (kg TAN year^{-1} cow^{-1})
1	7573	212	9407	159	78	81
2	8116	202	10822	144	81	63
3[1]	8249	229	10314	163	87	76
4	8037	215	10422	168	89	79
Mean (1-4)	**7893**	**213**	**10241**	**159**	**84**	**75**
SD (1-4)	490	12	598	10	5	8
5[1]	8322	235	10757	174	86	88
6	7459	202	11066	144	74	70
7	7032	225	10610	166	77	89
8	7819	198	10311	142	83	59
Mean (5-8)	**7658**	**215**	**10686**	**157**	**80**	**77**
SD (5-8)	547	18	314	15	5	15
Mean (1-8)	**7826**	**215**	**10464**	**158**	**82**	**76**
SD (1-8)	444	14	502	12	5	11
Norm 2017/18[2]	**7851**	**209**	**10410[3]**	**150.7**	**82.1**	**68.6**

[1] Lactating cows only.
[2] Poulsen et al. (2017). Based on 2016 feed and production.
[3] Kg energy corrected milk (ECM) = kg milk · ((383 · % fat + 242 · % protein + 783.2)/3140) (Lund & Aaes, 2010).

Table 12 and Table 13 tabulates the calculated total-N and TAN excretion from each barn, animal category and measuring period as well as the ammonia emission in percent of the TAN excretion. Detailed information on the calculation of nitrogen excretions is provided in Appendix 7.3.

In barns with slatted floor, 5% ± 1 % (mean ± SD) of the calculated total-N excretion or **10 % ± 2 %** of the calculated TAN excretion was lost as ammonia in the barns. This is 38 % lower than the emission value being 16 %, which is currently applied in the Danish normative system.

In barns with solid drained floor, 5% ± 1 % (mean ± SD) of the calculated total-N excretion or **11 % ± 1 %** of the calculated TAN excretion in the barns. This figure is 38 % higher than the emission value being 8 % of excreted TAN, which is currently applied in the Danish normative system.

Table 12. Ammonia emission and the relation to the total-N and urinary nitrogen (TAN) excretion in dairy barns with slatted floor.

		Lactating cows			Dry cows			Heifers			Excretion		Ammonia emission		
Barn ID	Measuring period	No of animals (a)	Total-N ($g\ d^{-1}\ a^{-1}$)	TAN ($g\ d^{-1}\ a^{-1}$)	No of animals	Total-N ($g\ d^{-1}\ a^{-1}$)	TAN ($g\ d^{-1}\ a^{-1}$)	No of animals	Total-N ($g\ d^{-1}\ a^{-1}$)	TAN ($g\ d^{-1}\ a^{-1}$)	**Total-N** (kg TAN d^{-1})	**Total TAN** (kg TAN d^{-1})	(kg NH_3-N d^{-1})	% of total-N	% of TAN
1	25-08-2015	149	499	243	21	230	143	104	163	117	96	51	7.1	7%	14%
1	02-11-2015	153	490	271	16	230	143	105	163	117	96	56	5.3	6%	10%
1	28-01-2016	145	445	220	26	230	143	107	163	117	88	48	4.9	6%	10%
1	24-03-2016	155	494	252	15	230	143	107	163	117	97	54	4.6	5%	9%
1	21-05-2016	151	448	229	19	230	143	105	163	117	89	50	6.8	8%	14%
1	25-08-2016	149	468	218	27	230	143	110	163	117	83	49	7.4	9%	15%
1	**Annual mean**													**7%**	**12%**
2	17-09-2015	186	450	211	29	202	127	0	0	0	89	43	3.1	3%	7%
2	27-11-2015	201	437	199	17	202	127	0	0	0	91	42	2.8	3%	7%
2	22-02-2016	199	390	153	19	202	127	0	0	0	81	33	4.7	6%	14%
2	23-04-2016	190	398	161	24	202	127	0	0	0	80	34	5.1	6%	15%
2	05-07-2016	204	404	167	13	202	127	0	0	0	85	36	3.4	4%	10%
2	16-09-2016	190	424	186	33	202	127	0	0	0	87	40	2.6	3%	7%
2	**Annual mean**													**4%**	**10%**
3	01-10-2015	193	409	170	0	0	0	0	0	0	79	33	3.6	5%	11%
3	12-12-2015	202	404	173	0	0	0	0	0	0	82	35	ND	ND	ND
3	10-03-2016	217	460	217	0	0	0	0	0	0	100	47	2.1	2%	5%
3	07-05-2016	213	458	219	0	0	0	0	0	0	98	47	3.4	3%	7%
3	05-08-2016	221	466	233	0	0	0	0	0	0	103	51	3.8	4%	7%
3	30-09-2016	216	483	244	0	0	0	0	0	0	104	53	5023	5%	10%
3	**Annual mean**													**4%**	**8%**
4	08-10-2015	150	481	223	15	203	121	104	156	105	91	46	3.7	4%	8%
4	11-03-2016	155	500	240	14	203	121	104	156	105	96	50	5.2	5%	10%
4	14-05-2016	149	478	240	16	203	121	104	156	105	91	49	6.7	7%	14%
4	12-08-2016	151	480	242	14	203	121	104	156	105	92	49	5.1	6%	10%
4	08-10-2016	160	482	244	15	203	121	104	156	105	96	52	8.1	8%	16%
4	**Annual mean**													**6%**	**12%**
1-4	**Annual mean**													**5%**	**10%**
1-4	**Std. dev.**													**1%**	**2%**

Table 13. Ammonia emission and the relation to the total-N and urinary nitrogen (TAN) excretion in dairy barns with solid drained floor.

		Lactating cows			Dry cows			Heifers			Excretion		Ammonia emission		
Barn ID	Measuring period	No of animals (a)	Total-N (g d^{-1} a^{-1})	TAN (g d^{-1} a^{-1})	No of animals	Total-N (g d^{-1} a^{-1})	TAN (g d^{-1} a^{-1})	No of animals	Total-N (g d^{-1} a^{-1})	TAN (g d^{-1} a^{-1})	**Total-N** (kg TAN d^{-1})	**Total TAN** (kg N/d)	(kg NH_3-N d^{-1})	% of total-N	% of TAN
5	20-11-2015	451	478	225	0	0	0	0	0	0	219	101	14.6	7%	14%
5	22-01-2016	451	432	196	0	0	0	0	0	0	201	94	5.7	3%	6%
5	18-03-2016	483	449	219	0	0	0	0	0	0	227	109	6.8	3%	6%
5	21-05-2016	470	469	231	0	0	0	0	0	0	227	117	11.0	5%	9%
5	13-08-2016	478	517	267	0	0	0	0	0	0	256	128	13.1	5%	10%
5	14-09-2016	476	517	267	0	0	0	0	0	0	246	127	18.2	7%	14%
5	**Annual mean**													**5%**	**10%**
6	28-11-2015	222	483	260	29	223	140	0	0	0	114	62	3.7	3%	6%
6	28-01-2016	227	526	278	31	223	140	0	0	0	105	67	3.8	4%	6%
6	07-04-2016	240	334	140	21	223	140	0	0	0	85	37	5.2	6%	14%
6	31-05-2016	235	406	174	33	223	140	0	0	0	103	46	5.1	5%	11%
6	19-08-2016	234	479	208	39	223	140	0	0	0	113	54	5.8	5%	11%
6	01-10-2016	206	416	208	66	223	140	0	0	0	104	52	4.9	5%	9%
6	**Annual mean**													**5%**	**10%**
7	11-12-2015	327	442	276	70	201	126	0	0	0	180	99	ND	ND	ND
7	05-02-2016	336	493	262	54	201	126	0	0	0	181	99	9.2	5%	10%
7	08-04-2016	339	487	256	55	201	126	0	0	0	183	94	8.2	4%	9%
7	10-06-2016	346	485	254	54	201	126	0	0	0	186	95	12.2	7%	13%
7	27-08-2016	368	501	269	39	201	126	0	0	0	194	104	14.0	7%	13%
7	14-10-2016	368	488	231	37	201	126	0	0	0	194	99	8.9	5%	9%
7	**Annual mean**													**6%**	**11%**
8	18-12-2015	171	438	200	25	145	79	175	112	68	98	48	5.5	6%	11%
8	13-02-2016	175	411	180	33	145	79	175	112	68	96	46	2.6	3%	5%
8	16-04-2016	178	387	170	30	145	79	175	112	68	93	44	5.5	6%	12%
8	17-06-2016	190	445	185	20	145	79	140	112	68	90	46	6.0	7%	13%
8	03-09-2016	185	430	166	26	145	79	140	112	68	102	42	8.3	8%	19%
8	22-10-2016	191	433	179	23	145	79	175	112	68	105	48	7.3	7%	15%
8	**Annual mean**													**6%**	**13%**
5-8	**Annual mean**													**5%**	**11%**
5-8	**Std. dev.**													**1%**	**2%**

4.4 Confounding effect of barn type and area

The average production area per animal in barns with slatted floor was 5.9 ± 0.6 m^2 (mean ± SD). In barns with solid drained floor, the average production area per cow was 7.9 ± 1.0 m^2, i.e. on average 34 % higher production area per animal (Figure 11). In terms of the walking alleys, the barns with slatted floor had on average 40 % more floor area per animal compared with the barns with solid drained floor (4.0 vs. 5.6 m^2 animal). Therefore, barn type and production area may be considered confounders.

In 2010 new recommendations for the design of dairy barns were published (Anonym, 2010). These includes wider and longer cubicles, and wider walking alleys and passages between rows of cubicles than before. Therefore, barns built after 2010 will likely comply with these recommendations resulting in a larger animal occupied space than barn built before 2010. The recommendations were more or less incorporated into a decree on housing of dairy cattle and their offspring (www.retsinfo.dk: Bekendtgørelse om hold af malkekvæg og afkom af malkekvæg). All new or renovated barns must comply with the act after 2014.

Due to the requirements in the environmental approval act on livestock production (Lov om miljøgodkendelse mv. af husdyrbrug), dairy farmers are required to reduce the emission of ammonia when they built new barns or renovate old barns. The requirements can be met either by building low emission barns or by using environmental technology. Thus, since the mid 2010's, most new dairy barns have been built with solid drained floor, which has been considered a low emission system, while before that the preferred floor type was slatted floor.

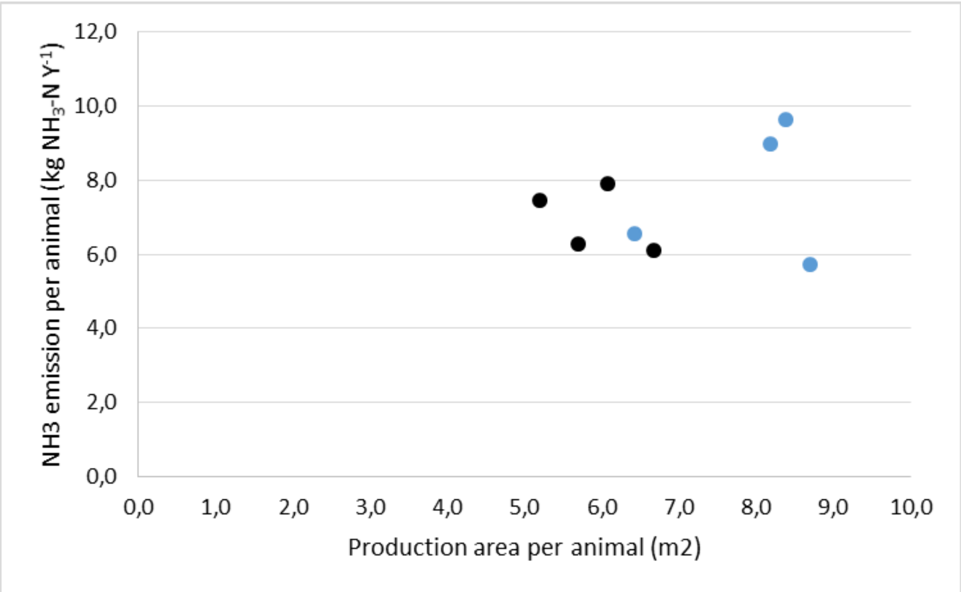


Figure 11. Distribution of production area and ammonia emission per animal. Black dots represent barns with slatted floor and blue dots represent barns with solid drained floor.

4.5 Effect of scraping of the slats in dairy barns with slatted floor

The effect on the ammonia emission of frequent manure removal from the slats was investigated in test barns 1 and 2 with slatted floors over approximately one year. The frequency of manure removal from the slats was reduced from six to either one (barn 1) or zero (barn 2) per day over a period lasting between four to nineteen days within each of the measuring periods. The observed ammonia emission as affected by the manure removal frequency is shown in Table 14. Measuring period 2 in CB2 was an extreme value, i.e. proportional effect = -94 %. To determine whether the extreme value was an outlier, an analysis using Grubbs' test was carried out. The analysis determined that it could be considered an outlier ($P<0.05$) and was excluded from further analysis.

Correcting for the extreme value, frequent scraping numerically increased the ammonia emission by 0.1 ± 1.0 kg NH_3-N per year per cow (mean ± 95% C.I) or 3% ± 10% (mean ± 95% C.I.) compared with 0 or 1 scraping per day. The observed effect was not statistically significantly different from 0 ($P=0.93$). Thus, it cannot be concluded that scraping of the slats 6 times per day by means of either a manure scraper (pulled by a chain, robe, or wire) or a robotic manure scraper affected the ammonia emission.

4.6 Indicative effect of scraping of the floor in dairy barns with solid drained floor

To provide an indication of the effect of manure removal frequency on the ammonia emission test barns 5 and 6 equipped with solid drained floor was reduced from twelve to two times per day over periods lasting between two and three days carried out during a prolonged measuring period.

The observed effect on the ammonia emission of the manure removal frequency in the two barns with solid drained floor is shown in Table 15. Although only indicative for the effect, the ammonia emission was not affected by the manure scraping frequency. However, the farmers at both farms reported increased problems with soiling of the laying area on days with only two scrapings per day. This was likely due to the increased accumulation of manure on the floor because of the low manure removal frequency. Data is however too limited to make a scientifically based conclusion regarding scraping frequency in barns with solid drained floor.

Table 14. Effect of slat scraping frequency on the ammonia emission in two dairy barns with slatted floor.

				Low scraping frequency, kg NH_3-N cow^{-1} year^{-1}				High scraping frequency, kg NH_3-N cow^{-1} year^{-1}				Reduction by high scraping frequency	
Farm ID	*Period*	*Floor type*	*Scraper system*	*No of scrapings d^{-1}*	*Length of period, days*	*Median*	*Mean ± 0.95 CI*	*No of scrapings d^{-1}*	*Length of period, days*	*Median*	*Mean ± 0.95 CI*	kg NH_3 *cow^{-1} year^{-1}*	*% of low frequency*
1	1	Slatted	Traditional	1	6	11.3	10.7±1.4	6	11	13.4	13.5±1.1	-2.7	-25
1	2	Slatted	Traditional	1	6	8.2	8.4±1.0	6	19	9.5	9.7±0.8	-1.3	-15
1	3	Slatted	Traditional	1	6	9.3	9.8±2.3	6	12	7.6	7.7±1.4	2.1	22
1	4	Slatted	Traditional	1	6	7.9	8.2±0.9	6	12	7.8	7.7±0.7	0.5	6
1	5	Slatted	Traditional	1	6	11.1	11.4±1.6	6	7	11.2	11.5±1.6	-0.1	-1
1	6	Slatted	Traditional	1	6	11.9	13.4±4.4	6	8	11.3	11.6±1.3	1.8	13
2	1	Slatted	Robot	0	6	3.6	3.4±1.1	6	6	7.3	6.6±2.8	-3.2	-94 [1]
2	2	Slatted	Robot	0	20	6.9	7.7±0.8	6	6	8.4	8.5±1.3	-0.8	-11
2	3	Slatted	Robot	0	6	8.5	8.9±3.3	6	12	8.2	8.6±1.1	0.2	3
2	4	Slatted	Robot	0	13	5.6	5.7±1.2	6	3	5.8	5.9±3.4	-0.2	-3
2	5	Slatted	Robot	0	4	4.1	3.9±3.0	6	13	5.7	4.5±1.5	-0.6	-15
Mean ± 0.95 C.I.												**-0.1±1.0**	**-3±10**

[1] Outlier determined using Grubbs' test (P>0.05).

Table 15. Tentative effect of floor scraping frequency on the ammonia emission in two dairy barns with solid drained floor.

				Manure scraping frequency, kg NH_3 cow^{-1} year^{-1}				High slurry scraping frequency, kg NH_3 cow^{-1} year^{-1}				Reduction by high scraping frequency	
Farm ID	*Period*	*Floor type*	*Scraper system*	*No of scrapings d^{-1}*	*Length of period, days*	*Median*	*Mean ± 0.95 CI*	*No of scrapings d^{-1}*	*Length of period, days*	*Median*	*Mean ± 0.95 CI*	kg NH_3 *cow^{-1} year^{-1}*	*% of low frequency*
5	6	Solid	Stationary	2	4		14.2±2,3	12	4		13.9±2.6	0.3	2
6	6	Solid	Robot	2	7		6.9±1.2	12	9		6.9±1.0	0.0	0
Mean													**1**

4.7 Manure composition

Table 16 and Table 17 tabulates the nutrient content of the manure as well as the indoor air temperature and relative humidity of the air measured in the individual barns and measuring periods. Floor type did not significantly affect any of the measured manure constituents. However, slatted floor was associated with numerically higher concentrations of the constituents suggesting that manure in barns with solid drained floor in general was mere dilute than in barns with slatted floor.

In general, the manure content of manure collected in barns with slatted floor was comparable with Danish national normative values (manure following 9 months storage). The ammonium concentration was somewhat lower than the normative value (1.9 vs. 2.7 g N/kg). This may be explained by more dilute manure in our study compared with the norm, but also mineralisation of organic nitrogen during storage of the manure will result in a shift in the TAN:N ratio in stored manure.

Also the total-N content was lower than expected compared with the normative values (3.7 vs. 4.6 g N/kg). This too, may be explained by more dilute manure or that more nitrogen than expected is lost through volatilization as ammonia or other nitrogen-containing gases.

Table 16. Composition of manure from barns 1 – 4 with slatted floor.

		Sampling day	Manure						Indoor air	
Barn id	*Period*	*dd-mm-yyyy*	*Dry matter %*	*Total N g N kg^{-1}*	*NH_4-N g N kg^{-1}*	*Phosphorous g P kg^{-1}*	*Potassium g K kg^{-1}*	*pH*	*Temperature °C*	*Humidity % RH*
1	1	25-08-2015	10.3	4.7	2.0	0.66	3.3	7.0	16.8	78
1	2	02-11-2015	9.4	4.8	2.4	0.75	3.6	7.2	10.4	95
1	3	28-01-2016	ND	ND	ND	ND	ND	7.3	6.5	89
1	4	24-03-2016	10.5	4.5	2.2	0.67	3.8	7.1	8.7	75
1	5	21-05-2016	9.8	4.4	1.9	0.65	3.8	6.9	16.3	76
1	6	25-08-2016	8.9	3.7	1.8	0.67	4.1	6.9	ND	ND
1		**Mean**	**9.8**	**4.4**	**2.1**	**0.68**	**3.7**	**7.1**	**12.8**	**83**
2	1	17-09-2015	7.6	3.4	1.6	0.59	3.4	6.7	14.7	84
2	2	27-11-2015	7.9	4.0	1.7	0.72	3.3	7.0	5.8	91
2	3	22-02-2016	8.6	4.0	2.0	0.68	4.3	7.2	2.9	90
2	4	23-04-2016	9.0	3.9	2.1	0.65	4.1	6.9	8.3	80
2	5	05-07-2016	ND	ND	ND	ND	ND	6.9	16.3	87
2	6	16-09-2016	9.2	4.2	1.8	0.79	3.3	7.0	16.9	84
2		**Mean**	**8.5**	**3.9**	**1.8**	**0.69**	**3.7**	**6.9**	**10.8**	**86**
3	1	01-10-2015	12.9	5.3	1.5	0.97	2.8	6.7	14.2	81
3	2	12-12-2016	6.6	3.7	1.8	0.58	2.5	7.0	ND	ND
3	3	10-03-2016	8.7	3.6	2.0	0.53	2.9	7.0	6.9	85
3	4	07-05-2016	12.8	5.6	2.4	0.96	3.6	6.8	16.5	63
3	5	05-08-2016	9.3	4.0	2.1	0.59	2.7	6.9	18.7	79
3	6	30-09-2016	12.6	5.0	2.1	0.91	2.7	6.8	15.4	89
3		**Mean**	**10.5**	**4.5**	**2.0**	**0.76**	**2.9**	**6.9**	**14.4**	**79**
4	1	08-10-2015	7.3	4.0	1.7	0.74	2.8	6.9	11.2	85
4	2	15-12-2015	ND	ND	ND	ND	ND	ND	ND	ND
4	3	11-03-2016	7.7	3.8	2.0	0.71	3.5	7.1	6.5	81
4	4	14-05-2016	8.7	4.0	2.2	0.74	4.0	7.0	ND	ND
4	5	12-08-2016	6.9	3.3	1.7	0.58	2.9	7.1	ND	ND
4	6	08-10-2016	7.8	3.9	2.1	0.71	3.2	7.3	10.4	82
4		**Mean**	**7.7**	**3.8**	**1.9**	**0.70**	**3.3**	**7.1**	**9.4**	**83**
1-4		**Mean**	**9.1**	**4.2**	**1.9**	**0.71**	**3.4**	**7.0**	**11.8**	**83**
1-4		**SD**	**1.3**	**0.4**	**0.1**	**0.04**	**0.4**	**0.1**	**2.2**	**3**
Norm[1]		2016/17	8.0	4.2	2.7	0.68	3.3	-	-	-

[1]Normative values representative for dairy manure following 9 months storage outside barns with slatted floor and recirculation manure channels (ring-channel).

Table 17. Composition of manure from barns 5 – 8 with solid drained floor.

		Sampling day	Manure						Indoor air	
Barn id	*Period*	*dd-mm-yyyy*	*Dry matter %*	*Total N g N/kg*	*NH_4-N g N/kg*	*Phosphorous g P/kg*	*Potassium g K/kg*	*pH*	*Temperature ˚C*	*Humidity % RH*
5	1	20-11-2015	7.3	3.9	1.9	0.71	2.5	7.6	8.4	88
5	2	22-01-2016	ND	ND	ND	ND	ND	ND	3.9	80
5	3	18-03-2016	10.0	4.3	2.0	0.83	4.1	7.2	9.9	78
5	4	21-05-2016	10.7	4.5	2.1	0.89	4.1	6.7	15.7	81
5	5	13-08-2016	10.1	4.1	1.8	0.83	2.7	6.9	16.8	82
5	6	14-09-2016	3.9	1.8	1.0	0.32	1.4	7.3	19.3	80
5		**Mean**	**8.4**	**3.7**	**1.7**	**0.71**	**3.0**	**7.1**	**12.3**	**81**
6	1	28-11-2015	7.9	4.3	2.0	0.75	3.0	7.1	8.0	96
6	2	28-01-2016	6.5	3.4	1.7	0.52	3.2	7.0	9.0	84
6	3	07-04-2016	7.2	4.0	2.1	0.62	3.5	6.8	10.3	81
6	4	31-05-2016	7.1	3.7	2.0	0.58	3.3	6.8	20.8	70
6	5	19-08-2016	9.0	4.6	2.5	0.80	3.3	6.9	ND	ND
6	6	01-10-2016	6.9	3.7	2.0	0.63	3.1	6.9	14.4	77
6		**Mean**	**7.4**	**3.9**	**2.1**	**0.65**	**3.3**	**6.9**	**12.5**	**82**
7	1	11-12-2015	12.7	3.4	1.6	0.61	2.2	8.3	7.4	93
7	2	05-02-2016	11.3	3.9	2.2	0.58	3.3	7.7	7.0	83
7	3	08-04-2016	5.8	2.9	1.6	0.47	2.5	7.4	9.9	73
7	4	10-06-2016	7.5	2.6	1.4	0.39	2.0	7.2	16.0	62
7	5	27-08-2016	12.4	3.3	1.8	0.54	1.9	7.2	18.6	81
7	6	14-10-2016	19.3	4.1	2.0	0.76	2.5	7.0	10.4	82
7		**Mean**	**11.5**	**3.4**	**1.8**	**0.56**	**2.4**	**7.5**	**11.6**	**79**
8	1	18-12-2015	8.5	3.6	2.1	0.49	3.1	7.2	9.9	98
8	2	13-02-2016	8.1	3.5	1.9	0.58	2.8	7.2	3.2	80
8	3	16-04-2016	7.4	3.5	1.8	0.49	2.7	7.0	9.0	80
8	4	17-06-2016	7.4	3.5	1.9	0.50	2.7	6.9	9.0	81
8	5	03-09-2016	7.0	3.6	2.1	0.53	2.9	6.9	17.1	77
8	6	22-10-2016	9.0	4.2	2.3	0.65	3.4	6.9	9.7	91
8		**Mean**	**7.9**	**3.7**	**2.0**	**0.54**	**2.9**	**7.0**	**9.7**	**85**
5-8		**Mean**	**8.8**	**3.7**	**1.9**	**0.62**	**2.9**	**7.1**	**11.5**	**82**
5-8		**SD**	**1.8**	**0.2**	**0.2**	**0.08**	**0.3**	**0.3**	**1.3**	**2**
Norm[1]		2016/17	8.0	4.6	2.8	0.68	3.3	-	-	-

[1]Normative values representative for dairy manure following 9 months storage outside dairy barns with solid drained floor (Normtal 2016/17; Poulsen et al., 2016).

4.8 Uncertainties

The uncertainty of the calculated ammonia emissions cannot easily be calculated due to the complexity of the system. In terms of calculating the ammonia emission based on the constant injection method using metabolically produced CO_2 as tracer, the tracer gas method benefits from the natural spacial distribution of CO_2 by the animals throughout the building, providing a better mixing of the tracer and air than can normally be achieved by artificial injection systems at reasonable costs (Ogink et al., 2013). According to the tracer gas method, the ammonia emission is proportional to the CO_2 production, thus the accuracy of this method depends on the accuracy of the concentration measurement of CO_2 and NH_3 (Table 3 and Table 4) as well as the estimation of the CO_2 production of the animals, which varies with animal breed, weight, activity, productivity and pregnancy (Ogink et al., 2013). To calculate the number of heat producing units (HPUs) from cows and heifers, respectively, the models devised by Pedersen and Sällvik (2002) was used. These models include animal weight, feed energy intake, milk production and days in pregnancy. The uncertainty of the heat production from animals is estimated 10% (Zhang et al., 2010).

Furthermore, we used the hourly CO_2 production per HPU for dairy cattle including manure (24-h average: 180 + 20 L h^{-1} HPU^{-1}) [1] as devised by Pedersen et al. (2008). This is in agreement with Wang et al. (2016) who estimated a 24-h average CO_2 production of 178 L h^{-1} HPU^{-1} based on a comparison of the barn CO_2-balance and a direct method to determine the air exchange rate (AER) in a dairy barn.

The eight barns included in the current study was selected from a list of approximately 100 dairy barns provided by SEGES and considered representative for Danish cubicle barns. As representatives for each barn type sampling four barns is a relatively small sample size. The individual barn emission therefore strongly affects the barn type means. However, due to high measurement costs, increasing the number of barns was not applicable. Furthermore, the current number of barns is in line with the requirement in the VERA protocol for livestock housing and management.

Feed data was primarily based on the DMS system and to a lesser degree on direct measurements during barn visits and feed plans. The DMS system relies on the quality of data from the farmers and advisors including feed analysis of the feed ingredients (roughage and concentrates). The N excretions were in general higher than the normative figures, but that may be explained by the animals housed in the barns, e.g. some barns only housed lactating cows, whereas others in addition to lactation cow also housed dry cows and heifers. The algorithms which were used to calculate the distribution between TAN and organic nitrogen are the same as the ones which are used to calculate the national normative figures. New digestibility experiments are currently being undertaken by Dept. of Animal Science at Aarhus University to provide new data as basis for a revision of the algorithms (Peter Lund, pers. comm., Dec. 2017). This will likely not affect the total-N excretion, however, the experiments may change the distribution of excreted TAN and organic nitrogen and thus the ammonia emission value in terms of TAN excretion.

[1]Manure CO_2 production was excluded in barns with solid drained floor because of frequent manure removal.

5 Conclusion

The objectives of this study were:

1. to provide updated ammonia emissions values for the two most common types of dairy barns, i.e. cubicle barns with slatted floor and with solid drained floor, and

2. to document the effect of frequent removal of the manure by scraping of the floor in dairy barns with slatted floor.

The study was generally designed in accordance with the "VERA protocol for livestock housing and management systems" (Version 2 / 2011-29-08).

The measurements were carried out in four dairy barns equipped with slatted floor and recirculated manure channels, and four dairy barns equipped with solid drained floor as defined in general terms in Kai et al. (2014) and exemplified in Anon. (2012). In each barn, six measurement periods lasting from one to three weeks have been performed spread over a year. In addition, the efficacy of manure scraping by means of a mechanical manure scraper or a robotic scraper was documented in two dairy barns with slatted floor by means of an on-off test approach, which is characterized by alternating the case (6 scrapings per day) and control (0 or 1 scraping per day) within the same barn within a short timeframe (1 week).

The ammonia emission was measured using an indirect constant tracer gas method applying the natural production of carbon dioxide from the dairy cows as tracer gas. The carbon dioxide concentration was measured using Photoacoustic Spectroscopy (PAS) and Non-Dispersive Infrared Spectroscopy (NDIR). The ammonia concentration was measured using Cavity Ring-Down Spectroscopy (CRDS).

Dairy barns with slatted floor and recirculated manure channels emitted on average 1.2 ± 0.3 kg NH_3-N year^{-1} m^{-2} of production area (mean ± SD) or 1.9 ± 0.4 kg NH_3-N year^{-1} m^{-2} walking alley (mean ± SD). The ammonia emission equal to 5 % ± 1 % of excreted total-N or 10 % ± 2 % of excreted TAN (mean ± SD).

Dairy barns with solid drained floor with was scraped 12 times per day emitted on average 1.0 ± 0.2 kg NH_3-N year^{-1} m^{-2} of production area (mean ± SD) or 1.4 ± 0.3 kg NH_3-N year^{-1} m^{-2} walking alley (mean ± SD). The ammonia emission was equal to 5 ± 1 % of excreted total-N or 11 ± 2 % of excreted TAN (mean ± SD).

The mean production area per animal in barns with solid drained floor was 34 % larger than the mean production area per animal in in barns with slatted floor. Since both area and floor profile affect the ammonia emission, production area and barn type are confounders. Therefore, barns with slatted floor would likely have emitted more ammonia per cow and per kg TAN excreted, if the production areas were comparable to the barns with solid drained floor.

Removing the manure from the slats six times per day by use of manure scraper or robotic scraper increased numerically the ammonia emission by 3 % ± 10 % (mean ± 95% C.I.) compared with zero or one manure removal per day. The effect was not significant (P=0.93), thus it cannot be concluded that scraping in the current study affected the ammonia emission from the cattle barns.

Although only indicative for the effect, the ammonia emission was not affected by the manure scraping frequency in two barns with solid drained floor. The farmers at both farms reported increased problems with soiling of the cubicles on days with low scraping frequency. This was likely due to the increased accumulation of manure on the floor because of the low manure removal frequency. Data is however too limited to make a scientifically solid conclusion regarding scraping frequency in barns with solid drained floor.

6 References

Anonymous. 2012. Videnskatalog over kvægstaldgulve med 4 % ammoniakfordampning. Version 5 / 25/10 2012. Videncenter for Landbrug, Kvæg. 40 pp.

Anonymous, 2014. KMP-fuldfoder. Kvægbrugets forsøgslaboratorium. SEGES og RYK i samarbejde med DLBR. SEGES, Skejby, Denmark.

Braam, C. R., and C. J. Van den Hoorn. 1996. Concrete floors for animal houses with low ammonia emission (in Dutch, with English summary). IMAD–DLO Rapport 96–12. Wageningen, The Netherlands.

Braam, C. R., M. C. J. Smits, H. Gunnink, and D. Swierstra. 1997a. Ammonia emission from a double–sloped floor in a cubicle house for dairy cows. J. Agric. Eng. Res. 68(4): 375–386.

Braam, C. R., J. J. M. H. Ketelaars, and M. C. J. Smits. 1997b. Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. Netherlands J. Agric. Sci. 45(1): 49–64.

Special Issue: Emissions from naturally ventilated livestock buildings. Biosystems Engineering 116 (2013): 297-308.

DANAK, 2014. Accreditation report EuroFins Agro Testing Denmark. Registration No. 560 05-0560. 22th December 2014.

Demmers T.G.M., Phillips V.R., Short L.S., Burgess L.R., Hoxey R.P., Wathes C.M. 2001. Validation of Ventilation Rate Measurement Methods and the Ammonia Emission from Naturally Ventilated Dairy and Beef Buildings in the United Kingdom. *J. agric. Engng Res.* 79:(1), 107 – 116.

Kai, P. and Adamsen, A.P.S. 2017. Fra produktionsbaseret til arealbaseret emissionsberegning. Del 2: Emissionsfaktorer. BCE Technical Report, Institut for Ingeniørvidenskab, Aarhus Universitet, BCE-TR-12, 78 pp.

Kai, P., Tybirk, P., Jensen, M.L., Elvstrøm, J., Bækgaard, H. 2014. Kapitel 8. Tab fra stalde. I: Kvælstof, fosfor og kalium I husdyrgødning – normtal 2014, 30-147.

Laussmann, D., Helm, D. 2011. Air change measurements using tracer gases. In: Chemistry, emission control, radioactive pollutin and indoor air quality. Ed. Mazzeo N.

Lund, P., Aaes, O. 2016. Normtal for mængde og sammensætning af fæces og urin samt udskillelse af N, P og K i fæces og urin hos kvæg (2016/2017). Aarhus Universitet.

Ogink, N.W.M., Mosquera, J., Calvet, S., and Zhang, G. 2013. Methods for measuring gas emissions from naturally ventilated livestock buildings: Developments over the last decade and perspectives for improvement. Review. Special Issue: Emissions from naturally ventilated livestock buildings. Biosystems Engineering 116 (2013): 297-308.

Pedersen S., Sällvik K. 2002. Climatization of Animal Houses. Heat and moisture production at animal and house levels. 4th report of working group. Int. commission of agricultural Engineering, section II.

Pedersen S., Blanes-Vidal V., Joergensen H., Chwalibog A., Haeussermann A., Heetkamp M.J.W., Aarnink A.J.A. 2008. Carbon dioxide production in animal houses: A literature review. Agricultural Engineering International: CIGR Ejournal Vol X.

Swierstra, D., M. C. J. Smits, and W. Kroodsma. 1995. Ammonia emission from cubicle houses for cattle with slatted and solid floors. J. Agric. Eng. Res. 62(2): 127–132.

Swierstra, D., Braam, C.R., and Smits, M.C. 2001. Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. Appl. Engng in Agric. 2001 17(1): 85-90.

Wang, X., Ndegwa, P.M., Joo, H., Neerackal, G.M., Stöckle C.O., Liu, H., and Harrison, J.H. 2016. Indirect method versus direct method for measuring ventilation rates in naturally ventilated dairy houses. Biosystems Engng 144(2016): 13-25.

Zhang, G., Strøm, J.S., Li, B., Rom, H.B., Morsing, S., Dahl, P., Wang, C. 2005. Emission of Ammonia and Other Contaminant Gases from Naturally Ventilated Dairy Cattle Buildings. Biosystems Engng 92(3): 355–364.

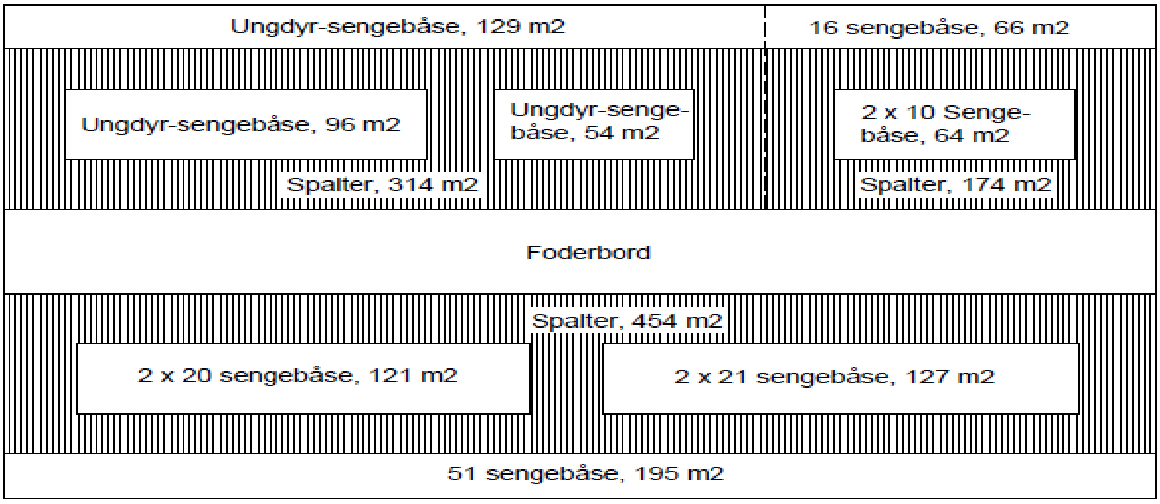
Zhang, G., Pedersen, S., & Kai, P. (2010). Uncertainty analysis of using CO2 production models by cows to determine ventilation rate in naturally ventilated buildings. In Proceedings of the CIGR XVIIth world congress - Québec City, Canada, Paper No. 100542.

7 Appendixes

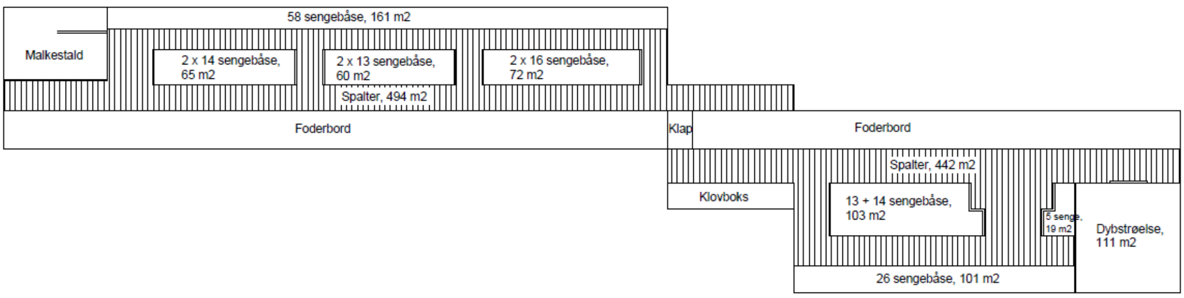
7.1 Layout of test barns

The layout of the individual test barns is described below.

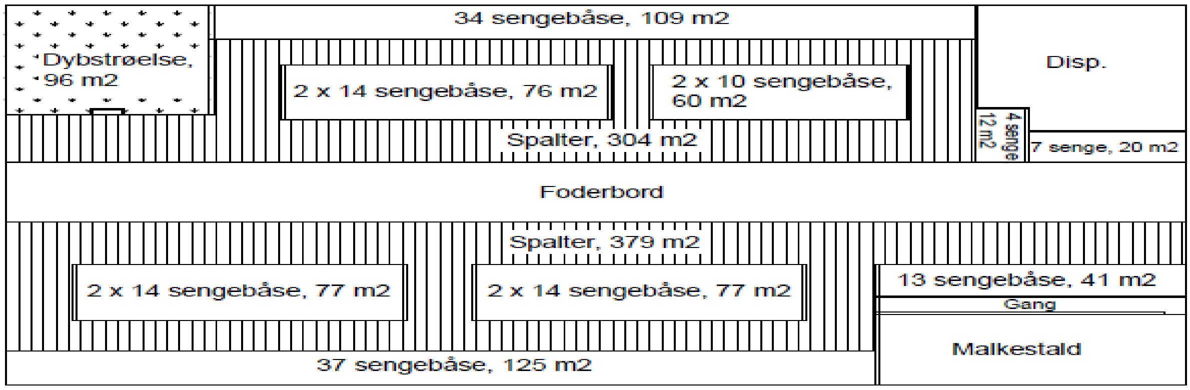
Total animal accessible area: total animal accessible area including total area of the cubicles and the walking alleys. Net animal accessible area: animal accessible area including area of the cubicles measured from rear curb to neck rail, and the total area of the walking alleys.



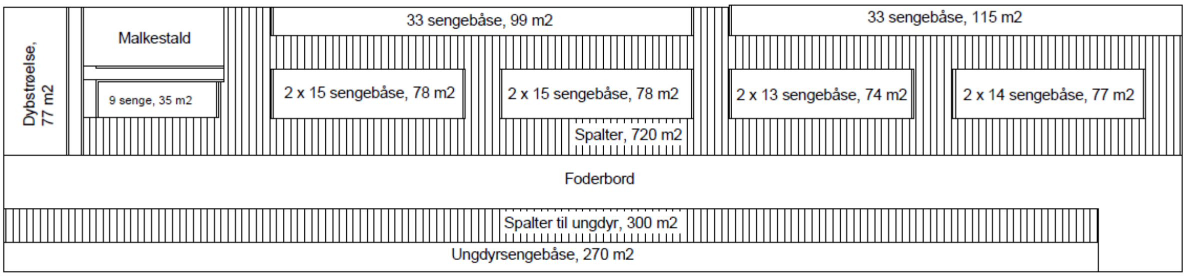
Cattle barn 1: Total animal accessible area: 1794 m^2; production area: 1445 m^2; total area of walking alleys: 942 m^2.



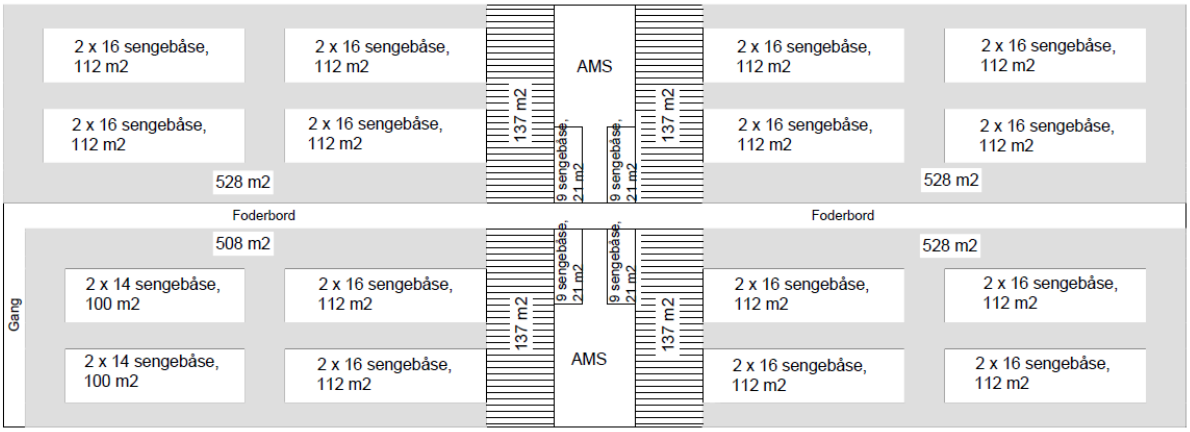
Cattle barn 2: Gross animal accessible area: 1517 m^2; production area: 1456 m^2; total area of walking alleys: 936 m^2.



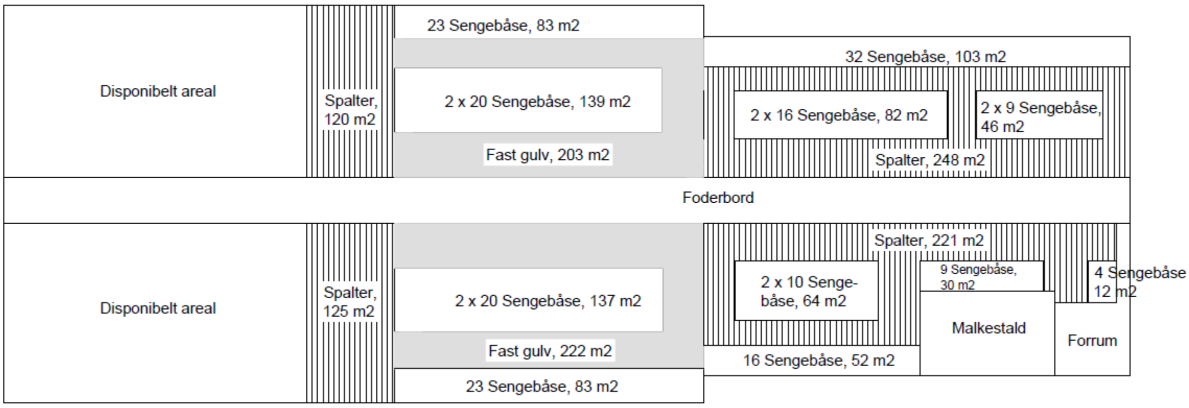
Cattle barn 3. Total animal accessible area: 1280 m^2; production area: 1196 m^2; total area of walking alleys: 683 m^2



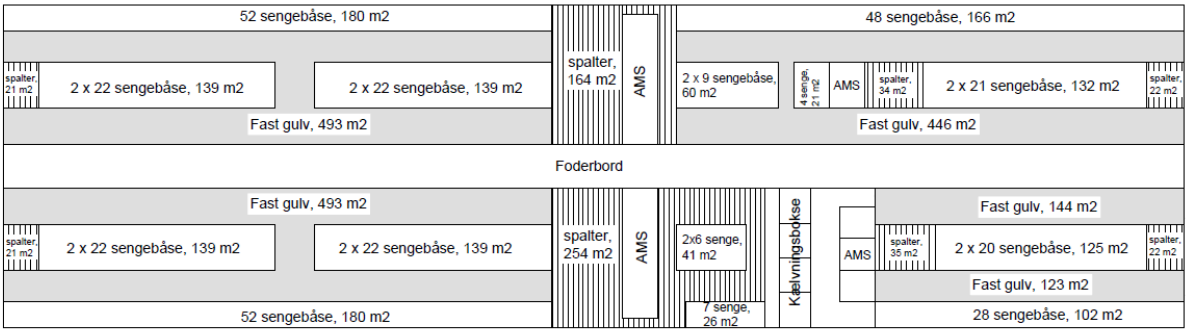
Cattle barn 4. Total animal accessible area: 1846 m^2; production area: 1653 m^2; total area of walking alleys: 1020 m^2.



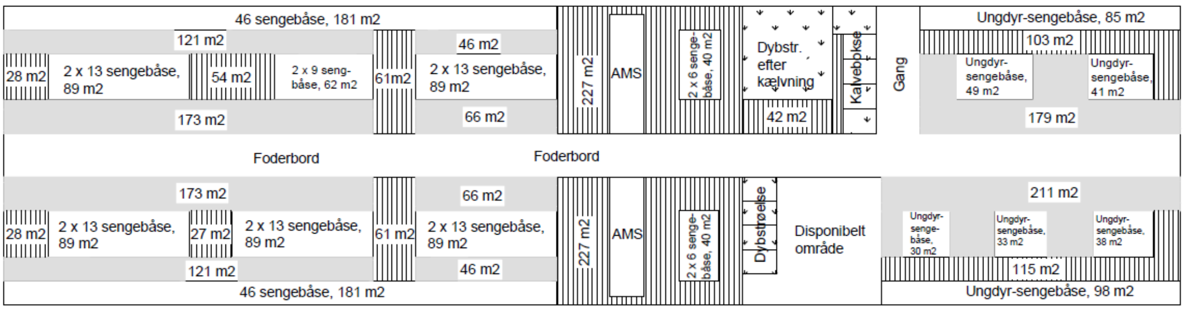
Cattle barn 5. Total animal accessible area: 4516 m^2; production area: 3820 m^2; total area of walking alleys: 2640 m^2.



Cattle barn 6. Total animal accessible area: 1970 m^2; production area: 1695 m^2; total area of walking alleys: 1139 m^2.



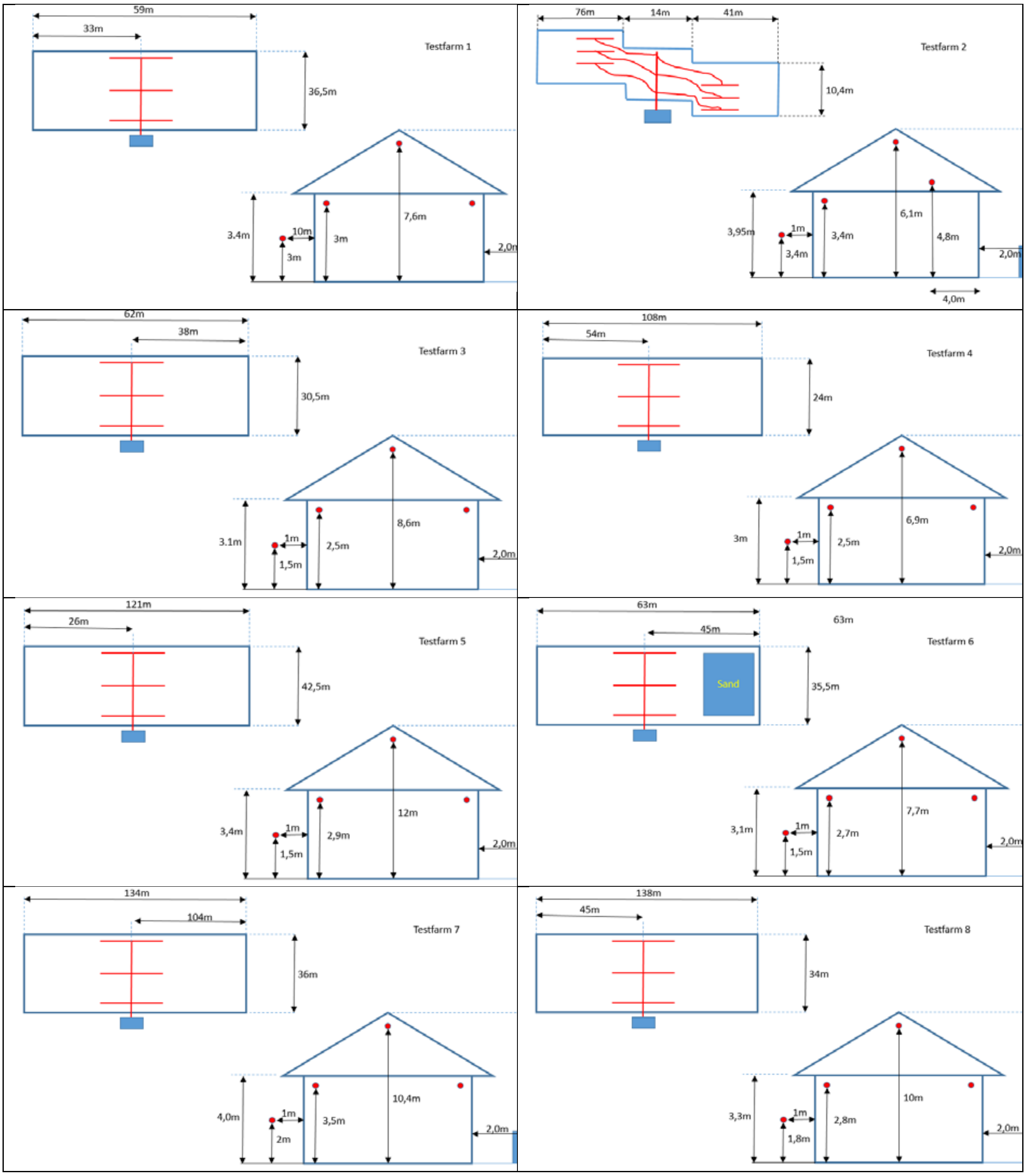
Cattle barn 7. Total animal accessible area: 3861 m^2; production area: 3343 m^2; total area of walking alleys: 2272 m^2.



Cattle barn 8. Total animal accessible area: 3498 m^2; production area: 3227 m^2; total area of walking alleys: 2175 m^2.

7.2 Description of the individual test farms and placement of sampling tubes

This appendix contains description of the air-sampling layout of the individual test barns. The location of the individual sampling tubes is shown in red. The location of the mobile sampling unit is shown as a blue square.



7.3 Input data used for calculation of the total barn CO_2 production

		Lactating + dry cows				Heifers				HPU			CO_2 production		
Barn ID	Measuring period	No of animals (a)	Weight (kg a^{-1})	Milk production (kg ECM d^{-1} a^{-1})	Heat production (W a^{-1})	No of animals (a)	Weight (kg a^{-1})	Daily gain (kg d^{-1} a^{-1})	Heat production (W a^{-1})	Cow	Heifers	Total	Animals (L h^{-1})	Manure (L h^{-1})	Total (L h^{-1})
1	25-08-2015	170	600	24.9	1271	104	334	0.63	553	216	58	274	49231	5470	54701
1	02-11-2015	169	600	25.1	1275	105	334	0.63	553	215	58	274	49236	5471	54706
1	28-01-2016	171	600	24.6	1264	107	334	0.63	553	216	59	275	49555	5506	55061
1	24-03-2016	170	600	28.5	1350	107	334	0.63	553	229	59	289	51953	5773	57726
1	21-05-2016	170	600	25.4	1282	105	334	0.63	553	218	58	276	49667	5519	55186
1	25-08-2016	176	600	23.8	1246	110	334	0.63	553	219	61	280	50434	5604	56038
2	17-09-2015	215	675	28.3	1408	0				303		303	54493	6055	60548
2	27-11-2015	218	675	31.8	1485	0				324		324	58275	6475	64750
2	22-02-2016	218	675	30.6	1459	0				318		318	57239	6360	63599
2	23-04-2016	214	675	29.0	1423	0				305		305	54833	6093	60926
2	05-07-2016	217	675	30.3	1452	0				315		315	56719	6302	63021
2	16-09-2016	223	675	26.5	1368	0				305		305	54931	6103	61035
3	01-10-2015	193	593	27.0	1311	0				253		253	45539	5060	50599
3	12-12-2015	202	594	27.6	1325	0				268		268	48173	5353	53526
3	10-03-2016	217	610	30.0	1391	0				302		302	54343	6038	60381
3	07-05-2016	213	619	32.3	1449	0				309		309	55572	6175	61747
3	05-08-2016	221	608	26.7	1317	0				291		291	52389	5821	58210
3	30-09-2016	216	594	26.2	1294	0				280		280	50315	5591	55905
4	08-10-2015	165	675	29.3	1430	104	400	0.68	636	236	66	302	54385	6043	60427
4	11-03-2016	169	675	27.0	1379	104	400	0.68	636	233	66	299	53875	5986	59861
4	14-05-2016	165	675	27.8	1397	104	400	0.68	636	230	66	297	53405	5934	59338
4	12-08-2016	165	675	27.0	1379	104	400	0.68	636	228	66	294	52882	5876	58758
4	08-10-2016	175	675	27.3	1386	104	400	0.68	636	243	66	309	55573	6175	61748

		Lactating + dry cows				Heifers				HPU			CO_2 production		
Barn ID	Measuring period	No of animals (a)	Weight (kg a^{-1})	Milk production (kg ECM d^{-1} a^{-1})	Heat production (W a^{-1})	No of animals (a)	Weight (kg a^{-1})	Daily gain (kg d^{-1} a^{-1})	Heat production (W a^{-1})	Cows	Heifers	Total	Animals (L h^{-1})	Manure (L h^{-1})	Total (L h^{-1})
5	20-11-2015	451	675	27,5	1390	0				627		627	112881	0	112881
5	22-01-2016	451	675	27,9	1399	0				631		631	113595	0	113595
5	18-03-2016	483	675	29,8	1441	0				696		696	125289	0	125289
5	21-05-2016	470	675	29,6	1437	0				675		675	121545	0	121545
5	13-08-2016	478	675	30,4	1454	0				695		695	125128	0	125128
5	14-09-2016	476	675	28,2	1406	0				669		669	120457	0	120457
6	28-11-2015	251	600	29,9	1381	0				347		347	62375	0	62375
6	28-01-2016	258	600	30,4	1392	0				359		359	64626	0	64626
6	07-04-2016	261	600	32,1	1429	0				373		373	67134	0	67134
6	31-05-2016	268	600	31	1405	0				376		376	67767	0	67767
6	19-08-2016	273	600	28,6	1352	0				369		369	66437	0	66437
6	01-10-2016	272	600	23,6	1242	0				338		338	60808	0	60808
7	11-12-2015	397	700	24,8	1352	0				537		537	96586	0	96586
7	05-02-2016	390	700	27,9	1420	0				554		554	99670	0	99670
7	08-04-2016	394	700	28,3	1429	0				563		563	101317	0	101317
7	10-06-2016	400	700	30	1466	0				586		586	105552	0	105552
7	27-08-2016	407	700	30,8	1484	0				604		604	108689	0	108689
7	14-10-2016	405	700	29,5	1455	0				589		589	106070	0	106070
8	18-12-2015	196	625	25,7	1310	175	425	0.68	663	257	116	372	67099	0	67099
8	13-02-2016	208	626	25,6	1308	175	425	0.68	663	272	116	388	69872	0	69872
8	16-04-2016	208	621	29	1378	175	425	0.68	663	287	116	403	72500	0	72500
8	17-06-2016	210	618	30,6	1411	140	394	0.68	629	296	88	384	69206	0	69206
8	03-09-2016	211	635	29,2	1394	140	394	0.68	629	294	88	382	68815	0	68815
8	22-10-2016	214	634	28.0	1368	175	425	0.68	663	293	116	409	73584	0	73584

7.4 Ammonia emissions calculated for the different measuring periods at the eight test barns

Barn id	Period	Floor system	Sampling period dd-mm-yyyy	Median Date	Median day in year	NH_3 emission Total g NH_3-N d^{-1}	Cow^{-1} (kg NH_3-N $year^{-1}$)	LU^{-1} (kg NH_3-N $year^{-1}$)	HPU^{-1} (kg NH_3-N $year^{-1}$)	m^{-2} production area (kg NH_3-N $year^{-1}$)
1	1	Slatted	17-08-2015 - 03-09-2015	25-08-2015	237	7113	11.7	8,9	9,2	1,8
1	2	Slatted	20-10-2015 - 15-11-2015	02-11-2015	305	5346	8.8	6,7	6,9	1,3
1	3	Slatted	19-01-2016 – 07-02-2016	28-01-2016	28	4888	8.0	6,1	6,3	1,2
1	4	Slatted	15-03-2016 – 03-04-2016	24-03-2016	84	4585	7.6	5,7	5,6	1,2
1	5	Slatted	14-05-2016 – 28-05-2016	21-05-2016	141	6739	11.1	8,4	8,6	1,7
1	6	Slatted	18-08-2016 – 02-09-2016	25-08-2016	238	7425	11.7	8,9	9,3	1,9
2	1	Slatted	08-09-2015 – 27-09-2015	17-09-2015	260	3111	5.3	3.9	3.8	0.8
2	2	Slatted	18-11-2015 – 07-12-2015	27-11-2015	331	2757	4.6	3.4	3.1	0.7
2	3	Slatted	09-02-2016 – 06-03-2016	22-02-2016	52	4660	7.8	5.8	5.3	1.2
2	4	Slatted	14-04-2016 – 03-05-2016	23-04-2016	114	5149	8.8	6.5	6.2	1.3
2	5	Slatted	22-06-2016 – 14-07-2016	05-07-2016	186	3446	5.8	4.3	4.0	0.9
2	6	Slatted	08-09-2016 - 25-09-2016	16-09-2016	260	2626	4.3	3.2	3.1	0.7
3	1	Slatted	29-09-2015 – 04-10-2015	01-10-2015	274	3646	6.9	5.1	5.3	1.1
3	2	Slatted	09-12-2016 – 15-12-2015	12-12-2015	346	ND	ND	ND	ND	ND
3	3	Slatted	08-03-2016 – 13-03-2016	10-03-2016	70	2140	3.6	2.7	2.6	0.7
3	4	Slatted	04-05-2016 – 10-05-2016	07-05-2016	127	3398	5.8	4.3	4.0	1.0
3	5	Slatted	03-08-2016 – 08-08-2016	05-08-2016	218	3849	6.4	4.7	4.8	1.2
3	6	Slatted	28-09-2016 – 03-10-2016	30-09-2016	274	5023	8.5	6.3	6.6	1.5
4	1	Slatted	04-10-2015 – 10-10-2015	08-10-2015	280	3674	4.9	4.4	4.4	0.8
4	2	Slatted	12-12-2015 - 17-12-2015	11-03-2016	349	ND	ND	ND	ND	ND
4	3	Slatted	09-03-2016 - 13-03-2016	14-05-2016	70	5200	6.8	6.2	6.3	1.1
4	4	Slatted	12-05-2016 - 17-05-2016	12-08-2016	135	6706	9.0	8.1	8.3	1.5
4	5	Slatted	10-08-2016 - 15-08-2016	08-10-2016	225	5129	6.8	6.2	6.4	1.1
4	6	Slatted	05-10-2016 – 11-10-2016	08-10-2015	281	8132	10.4	9.4	9.6	1.8
5	1	Solid drained	17-11-2015 - 23-11-2015	20-11-2015	323	14820	11.8	8.7	8.5	1.4
5	2	Solid drained	20-01-2016 - 24-01-2016	22-01-2016	21	5887	4.6	3.4	3.3	0.5
5	3	Solid drained	15-03-2016 - 21-03-2016	18-03-2016	77	7142	5.2	3.8	3.6	0.7
5	4	Solid drained	19-05-2016 - 23-05-2016	21-05-2016	141	11307	8.5	6.3	5.9	1.0
5	5	Solid drained	11-08-2016 – 15-08-2016	13-08-2016	225	13552	10.0	7.4	6.9	1.3
5	6	Solid drained	08-09-2016 – 21-09-2016	14-09-2016	258	18899	13.9	10.3	9.9	1.7
6	1	Solid drained	25-11-2015 – 02-12-2015	28-11-2015	332	3723	5.4	4.0	3.9	0.8
6	2	Solid drained	26-01-2016 – 31-01-2016	28-01-2016	28	3806	5.4	4.0	3.9	0.8
6	3	Solid drained	30-03-2016 – 12-04-2016	07-04-2016	97	5198	7.3	5.4	5.1	1.1
6	4	Solid drained	25-05-2016 – 06-06-2016	31-05-2016	151	5051	6.9	5.1	4.9	1.1
6	5	Solid drained	17-08-2016 – 22-08-2016	19-08-2016	232	5826	7.8	5.8	5.8	1.3
6	6	Solid drained	23-09-2016 - 10-10-2016	01-10-2016	275	4921	6.6	4.9	5.3	1.1
7	1	Solid drained	08-12-2015 – 14-12-2015	11-12-2015	344	ND	ND	ND	ND	ND
7	2	Solid drained	02-02-2016 – 08-02-2016	05-02-2016	35	9153	8.6	6.3	6.0	1.0
7	3	Solid drained	05-04-2016 – 11-04-2016	08-04-2016	98	8178	7.6	5.6	5.3	0.9
7	4	Solid drained	08-06-2016 – 13-06-2016	10-06-2016	162	12220	11.2	8.3	7.6	1.3
7	5	Solid drained	24-08-2016 – 30-08-2016	27-08-2016	239	14022	12.6	9.3	8.5	1.5
7	6	Solid drained	12-10-2016 – 17-10-2016	14-10-2016	288	8921	8.0	6.0	5.5	1.0
8	1	Solid drained	16-12-2015 – 21-12-2015	18-12-2015	352	5528	5.4	5.1	5.4	0.6
8	2	Solid drained	11-02-2016 – 15-02-2016	13-02-2016	43	2588	2.5	2.3	2.4	0.3
8	3	Solid drained	13-04-2016 – 19-04-2016	16-04-2016	106	5549	5.3	5.0	5.0	0.6
8	4	Solid drained	15-06-2016 – 20-06-2016	17-06-2016	169	5996	6.3	5.9	5.7	0.7
8	5	Solid drained	01-09-2016 – 06-09-2016	03-09-2016	247	8277	8.6	8.0	7.9	0.9
8	6	Solid drained	19-10-2016 – 25-10-2016	22-10-2016	295	7311	6.9	6.3	6.5	0.8

7.5 Nitrogen excretion

This appendix contains detailed data on the basis for calculation of the nitrogen excretion at each test barn and at the individual sampling periods.

Test barn 1. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control. Data shown in green was measured by AU.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
Lactating cows															
1	27-08-2015	23.6	172	649	27.7	3.3	142	150	4	142	4	499	256	**243**	49%
1	04-11-2015	21.3	189	644	27.2	3.6	153	-87	-2	142	4	490	218	**271**	55%
1	27-01-2016	21.8	187	652	28.6	4.4	199	175	4	142	4	445	224	**220**	49%
1	23-03-2016	22.8	179	653	28.5	3.4	150	175	4	142	4	494	242	**252**	51%
1	04-05-2016	21.9	189	662	29.5	3.3	152	175	4	142	4	501	228	**273**	54%
1	13-06-2016	20.9	168	560	28.7	3.5	157	175	4	142	4	394	208	**186**	47%
1	12-09-2016	23.3	171	636	29.4	3.5	160	175	4	142	4	468	250	**218**	47%
Dry cows															
1	27-08-2015	11.8	126	238	0	0	0	175	4	142	4	230	87	**143**	62%
Heifers															
1	27-08-2015	6.9	165	182	0	0	0	700	18	44	1	163	46	**117**	72%

Dry cows and heifers: Feed control data was only available in the first measuring period. The calculated excretion of N per head from the single feed control was used to calculated N excretion in the other measuring periods assuming that the error is relatively small due to the relative small contribution of dry cows and heifers to the total N excretion from the barn.

Test barn 2. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control. Data shown in green was measured by AU.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
2	11-08-2015	23.7	164	623	32.5	3.26	166	110	3	142	4	450	239	**211**	47%
2	27.11.2015	23.7	164	623	32.7	3.49	179	110	3	142	4	437	238	**199**	46%
2	23-04-2016	23.7	151	573	31.3	3.43	168	110	3	142	4	398	237	**161**	40%
2	05-07-2016	23.7	151	573	31.5	3.29	162	110	3	142	4	404	237	**167**	41%
2	16-09-2016	23.7	155	589	30.1	3.34	158	110	3	142	4	423	238	**186**	44%
	Dry cows														
2	11-08-2015	10.7	122	209	0	0	0	110	3	142	4	202	75	**127**	63%

Test barn 3. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control. Data shown in green was measured by AU.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
3	16-09-2015	22.8	163	594	32.4	3.5	178	140	4	142	4	409	239	**170**	42%
3	26-11-2015	22.3	164	584	31.0	3.55	172	140	4	142	4	404	231	**173**	43%
3	22-03-2016	22.9	177	648	33.0	3.49	181	130	4	142	4	460	242	**217**	47%
3	06-06-2016	22.5	177	637	32.3	3.43	173	130	4	142	4	456	236	**220**	48%
3	12-08-2016	22.3	178	637	30.7	3.39	163	130	4	142	4	466	233	**233**	50%
3	04-11-2016	22.6	181	655	29.5	3.57	165	130	4	142	4	483	239	**244**	51%

Test barn 4. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control. Data shown in green was measured by AU.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
4	08-10-2015	23.8	174	662	30.8	3.59	173	110	3	142	4	481	259	**223**	46%
4	10-03-2016	23.8	174	662	27.3	3.63	155	110	3	142	4	500	259	**240**	48%
4	13-04-2016	22.6	179	646	28.6	3.59	161	110	3	142	4	478	239	**240**	50%
4	27-07-2016	22.6	179	646	28.2	3.6	159	110	3	142	4	480	239	**242**	50%
4	05-10-2016	22.6	179	646	27.4	3.66	157	110	3	142	4	482	239	**244**	51%
	Dry cows														
4	Norm	11.4	115	210	0	0	0	110	3	142	4	203	82	**121**	60%
	Heifers														
4	Norm	8.0	137	175	0	0	0	700	18	44	1	156	51	**105**	68%

Test barn 5. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
5	08-12-2015	23.5	174	654	30.6	3.50	168	150	4	142	4	478	253	**225**	47%
5	07-01-2016	22.6	169	611	31.5	3.46	171	150	4	142	4	432	237	**196**	45%
5	17-02-2016	22.1	176	622	30.3	3.49	166	150	4	142	4	449	229	**219**	49%
5	29-04-2016	22.6	179	647	32.4	3.34	170	150	4	142	4	469	238	**231**	49%
5	12-08-2016	23.2	186	690	31.0	3.40	165	150	4	142	4	517	250	**267**	52%

Test barn 6. Calculation of the nitrogen excretion per animal per day. Data from DMS feed control. Data shown in green was measured by AU.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
6	22-11-2015	20.1	190	611	29.9	3.58	168	-46	-1	142	4	440	198	**242**	55%
6	04-12-2015	23.1	190	702	30.0	3.58	168	130	3	142	4	526	249	**278**	53%
6	05-04-2016	20.1	164	527	32.6	3.63	185	145	4	142	4	334	194	**140**	42%
6	10-08-2016	24.5	168	659	31.1	3.53	172	133	3	142	4	479	270	**208**	43%
6	22-09-2016	20.8	175	582	29.1	3.48	159	130	3	142	4	416	208	**208**	50%
6	22-12-2016	23.3	166	619	31.1	3.70	181	89	2	142	4	432	248	**184**	43%
	Dry cows														
6	22-11-2015	11.4	126	230	0	0	0	110	3	142	4	223	83	**140**	63%

Test barn 7. Calculation of the nitrogen excretion per animal per day. Data from feed plans.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
7	08.12.2015	22.1	191	676	29.6	3.48	162	155	4	142	4	507	232	**275**	54%
7	19-01-2016	22.1	191	676	31.6	3.49	173	155	4	142	4	496	231	**264**	53%
7	16-03-2016	22.1	191	676	32.8	3.46	178	155	4	142	4	491	231	**260**	53%
7	18-05-2016	22.1	191	676	34.3	3.43	185	155	4	142	4	484	231	**253**	52%
7	13-07-2016	22.1	191	676	33.9	3.43	182	155	4	142	4	486	231	**255**	52%
7	11-10-2016	22.1	191	676	31.9	3.61	180	155	4	142	4	488	231	**257**	53%
	Dry cows														
7	17-01-2017	10.7	122	209	0	0	0	155	4	142	4	201	75	**126**	63%

Test barn 8. Calculation of the nitrogen excretion per animal per day.

Barn ID	Date	Feed (kg dm)	CP (g/kg dm)	Feed N (g/d)	Milk (kg/d)	Milk protein (%)	Milk N (g/d)	Growth (g/d)	N ingrowth (g/d)	Foetus (g/d)	N in foetus (g/d)	Total-N excreted (g/d)	Faecal N (g/d)	Urine N (g/d)	Urine N (% of total N)
	Lactating cows														
8	19-11-2015	26.4	165	599	27.5	3.56	154	127	3	142	4	438	239	**200**	46%
8	24-02-2016	25.9	162	578	29.2	3.50	160	113	3	142	4	411	231	**180**	44%
8	16-03-2016	26.4	165	562	29.2	3.50	160	64	2	142	4	396	215	**181**	46%
8	09-05-2106	25.8	161	559	31.5	3.54	175	82	2	142	4	378	220	**158**	42%
8	30-06-2016	26.6	166	637	34.0	3.46	184	140	4	142	4	445	261	**185**	42%
8	12-09-2016	25.0	156	604	29.6	3.54	164	230	6	142	4	430	263	**166**	39%
8	06-10-2016	25.9	162	612	29.9	3.62	170	202	5	142	4	433	253	**179**	41%
8	25-11-2016	25.8	161	592	28.1	3.67	162	188	5	142	4	422	243	**179**	42%
	Dry cows														
8	19-11-2015	10	96	154	0	0	0	110	4	142	4	145	67	**79**	54%
	Heifers														
8	19-11-2015	7.2	114	131	0	0	0	700	18	44	1	112	44	**68**	61%

7.6 Climatic conditions during sampling periods

Table 18. Climatic conditions (mean of sampling periods) during sampling at test farms.

Barn ID	Period id	Date[1]	Out-door air temperature. °C	Radiation. MJ/m^2	Out-door air humidity. % RH	Windspeed. $m\ s^{-1}$	Wind dir. (°)
1	1	25-08-2015	15.91	0.59	78	4.39	154.8
1	2	02-11-2015	8.94	0.12	90	4.31	204.3
1	3	28-01-2016	2.78	0.09	89	5.65	239.2
1	4	24-03-2016	5.43	0.43	82	4.04	219.7
1	5	21-05-2016	13.27	0.80	75	3.52	169.0
1	6	25-08-2016	16.69	0.55	80	3.51	200.4
2	1	17-09-2015	13.0	0.43	85	5.9	168.3
2	2	27-11-2015	5.2	0.07	87	6.8	203.5
2	3	22-02-2016	1.0	0.22	86	4.7	193.4
2	4	23-04-2016	6.0	0.62	79	5.8	207.9
2	5	05-07-2016	14.7	0.69	84	5.1	223.1
2	6	16-09-2016	16.4	0.53	76	3.8	148.2
3	1	01-10-2015	11.15	0.41	86	3.81	222.9
3	2	12-12-2016	ND	ND	ND	ND	ND
3	3	10-03-2016	1.06	0.21	93	2.36	179.6
3	4	07-05-2016	13.26	1.07	62	3.44	130.9
3	5	05-08-2016	15.25	0.56	84	5.73	223.0
3	6	30-09-2016	12.29	0.27	81	5.39	151.5
4	1	08-10-2015	9.55	0.12	86	5.87	111.3
4	2	15-12-2015	ND	ND	ND	ND	ND
4	3	11-03-2016	1.10	0.21	93	2.74	166.4
4	4	14-05-2016	10.16	0.94	69	5.83	231.6
4	5	12-08-2016	13.89	0.60	81	6.68	272.7
4	6	08-10-2016	7.95	0.27	79	5.13	46.5
5	1	20-11-2015	3.53	0.09	88	5.19	156.0
5	2	22-01-2016	-2.63	0.11	93	3.24	182.5
5	3	18-03-2016	5.09	0.47	87	4.35	217.3
5	4	21-05-2016	12.86	0.45	89	4.54	211.2
5	5	13-08-2016	14.34	0.62	81	7.27	272.7
5	6	14-09-2016	16.86	0.52	80	3.34	151.6
6	1	28-11-2015	6.70	0.06	86	7.43	233.4
6	2	28-01-2016	5.10	0.08	87	8.86	238.3
6	3	07-04-2016	5.76	0.60	78	3.88	156.3
6	4	31-05-2016	16.20	0.96	78	3.59	79.3
6	5	19-08-2016	15.67	0.58	83	3.05	168.4
6	6	01-10-2016	11.04	0.35	82	4.66	108.0
7	1	11-12-2015	5.08	0.06	91	3.91	216.3
7	2	05-02-2016	4.84	0.10	84	6.27	226.3
7	3	08-04-2016	6.30	0.49	84	3.30	179.0
7	4	10-06-2016	13.51	1.04	65	3.79	167.2
7	5	27-08-2016	17.83	0.67	80	3.92	204.4
7	6	14-10-2016	8.98	0.11	86	6.31	100.0
8	1	18-12-2015	8.40	0.03	91	5.90	209.3
8	2	13-02-2016	-0.05	0.22	76	3.78	169.8
8	3	16-04-2016	7.30	0.45	82	5.98	189.9
8	4	17-06-2016	15.40	0.79	81	4.96	213.9
8	5	03-09-2016	16.20	0.55	82	4.20	193.2
8	6	22-10-2016	8.01	0.12	90	4.98	88.6

[1] *Median date of measuring period.*

DCA - National Centre for Food and Agriculture is the entrance to research in food and agriculture at Aarhus University (AU). The main tasks of the centre are knowledge exchange, advisory service and interaction with authorities, organisations and businesses.

The centre coordinates knowledge exchange and advice with regard to the departments that are heavily involved in food and agricultural science. They are:

Department of Animal Science
Department of Food Science
Department of Agroecology
Department of Engineering
Department of Molecular Biology and Genetics

DCA can also involve other units at AU that carry out research in the relevant areas.

SUMMARY

The mean annual ammonia emission was determined from eight naturally ventilated dairy cubicle barns. Four barns had slatted floor above slurry channels (SF), while four barns had solid drained floor (SDF). The manure was removed from the slatted floor 6 times per day and 12 times per day from solid drained floor.

Each barn was measured 6 times over a period of a year, each period lasting 1-3 weeks. The ammonia emission was measured using the constant tracer injection technique using carbon dioxide produced by the animals as tracer. The effect of manure removal from the slatted floor was tested in 2 SF barns applying an on-off test design, where a period of frequent manure removal was followed by a period of 0 or 1 manure removal per day. The on-off periods was repeated 6 times in each barn.

The SF barns emitted 1.2±0.3 kg NH_3-N year^{-1} m^{-2} production area (mean ± SD) or 5±1% of excreted total-N or 10±2% of excreted TAN. The SDF barns emitted 1.0±0.2 kg NH_3-N year^{-1} m^{-2} production area or 5±1% of excreted total-N or 11±2% of excreted TAN.

In SF barns, no significant difference in ammonia emission between periods with 6 manure removals per day or 0 or 1 manure removal per day was observed.