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Nutritional and Environmental Effects on Ammonia Emissions from Dairy Cattle Housing: A Meta-Analysis

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Abstract

Nitrogen excreted in dairy manure can be potentially transformed and emitted as NH_3, which can create livestock and human respiratory problems and be an indirect source of N_2O. The objectives of this study were to: (i) investigate environmental factors influencing NH_3 emissions from dairy housing; and (ii) identify key explanatory variables in the NH_3 emissions prediction from dairy housing using a meta-analytical approach. Data from 25 studies were used for the preliminary analysis, and data from 10 studies reporting 87 treatment means were used for the meta-analysis. Season and flooring type significantly affected NH_3 emissions. For nutritional effect analysis, the between-study variability (heterogeneity) of mean NH_3 emission was estimated using random-effect models and had a significant effect ($P < 0.01$). Therefore, random-effect models were extended to mixed-effect models to explain heterogeneity regarding the available dietary and animal variables. The final mixed-effect model included milk yield, dietary crude protein, and dry matter intake separately, explaining 45.5% of NH_3 emissions heterogeneity. A unit increase in milk yield (kg d^{-1}) resulted in a 4.9 g cow^{-1} d^{-1} reduction in NH_3 emissions, and a unit increase in dietary crude protein content (%) and dry matter intake (kg d^{-1}) resulted in 10.2 and 16.3 g cow^{-1} d^{-1} increases in NH_3 emissions, respectively, in the scope of this study. These results can be further used to help identify mitigation strategies to reduce NH_3 emissions from dairy housing by developing predictive models that could determine variables with strong association with NH_3 emissions.

Core Ideas

- Season and flooring type significantly affected NH_3 emission rates.
- Open lots had the highest emissions in this study but the lowest by USEPA.
- Crude protein and dry matter intake had positive impacts on NH_3 emissions.
- Milk yield had negative impacts on NH_3 emissions.

The environmental impact of livestock production is of concern because it generates greenhouse gases and NH_3 emissions, which contribute to air, water, and soil pollution (FAO, 2002). Ammonia emitted from animal operations is of particular concern because it can cause animal health hazards when concentrations reach critical levels in confined spaces (National Research Council, 2003) and contributes to the formation of fine particulate matter that is linked to human respiratory problems (Fu et al., 1999). Ammonia emissions can also cause regional degradation of terrestrial and aquatic ecosystems through acid deposition and eutrophication, and it represents a net loss of manure fertilizer value (Leytem and Dungan, 2014). In the United States, NH_3 emission is regulated by the USEPA in response to the Clean Air Act (USEPA, 1990), whereas in the European Union, capping of NH_3 emission is part of the National Emission Ceilings Directive 2001/81/EC (European Commission, 2001) currently being reviewed as part of the EU Clean Air Policy Package. Approximately 3.9 Tg of NH_3 were emitted in the United States in 2011, with 82% of emissions attributed to agriculture (USEPA, 2011). Similarly, in Europe 3.4 Tg of NH_3 were emitted in 2012, with 93% coming from agriculture (European Commission, 2013).

Nitrogen utilization in ruminants is relatively inefficient, with 50 to 80% of the N consumed excreted as urea-N and other organic N compounds in feces and urine (Moore et al., 2014). Manure from dairy farms has been recognized as a major source of NH_3 emission (Külling et al., 2001; Hristov et al., 2011). About 90% of the NH_3–N originates from urine N, with the remaining 10% found in feces. The amount of N in manure (defined here as urine plus feces) is related to dietary crude protein (CP) content, thus decreasing dietary CP is probably the most effective strategy to decrease NH_3 emissions from dairy manure due to reduced N substrate in the excreta (Frank et al., 2002; Frank and Swensson, 2002; Agle et al., 2010). Although the relationship between dietary CP content and NH_3 emissions is highly variable, it can be quantified using a meta-analytical approach. For example, Frank and Swensson (2002) reported a 45% reduction in NH_3 emissions when dietary CP was lowered from 17.0 to 13.5%.

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Abbreviations: BW, body weight; CP, crude protein; DMI, dry matter intake; SD, standard deviation.

Ammonia is volatilized after N excretion in manure under both confinement and grazing conditions (Fig. 1). Urea is excreted in urine and, when both urine and feces are well mixed, the urease enzyme present in the feces rapidly converts urea into an unstable complex of NH_3 and NH_4, resulting in volatilization of NH_3 (Powell et al., 2008). Large variation in urinary N excretion compared with N excretion in feces presents an opportunity to manipulate diets to reduce urinary N excretion. Although most of the N in urine is present in the form of urea-N (from 50 to well over 90% of total urine N), diet composition affects the level of various urinary N compounds and consequently susceptibility to losses after excretion (Dijkstra et al., 2013). Depending on environmental conditions (e.g., soil type, moisture, temperature, wind speed) and urine N composition, 25 to 50% of the N excreted in manure (Hristov et al., 2011) and 4 to 52% from urine patches (Oenema et al., 2008) may be lost as NH_3. The large variation in reported NH_3 emission estimates are mainly due to several environmental factors affecting measurement, time of day and year, in addition to the above-mentioned factors. For example, Hristov et al. (2011) calculated a daily average NH_3 emission rate of 59 g cow^{-1} based on a compilation of studies, with a large standard deviation of 65 g d^{-1}. When averaged over a year, NH_3 emissions measured at open-lot dairy housing systems in Idaho, Texas, and California were more consistent and ranged from 120 to 150 g cow^{-1} d^{-1} (Leytem et al., 2011). Emission rates at freestall and open-freestall dairies were found to be lower at 10 to 100 g cow^{-1} d^{-1} (Leytem et al., 2013).

This study was undertaken to collate and analyze published data on NH_3 emissions from dairy housing to provide more information on the factors affecting NH_3 emissions. The specific objectives were to: (i) investigate environmental factors that influence NH_3 emissions from dairy housing; and (ii) identify key explanatory variables in the prediction of NH_3 emissions from dairy housing using a meta-analytical approach.

Materials and Methods

Data Sources

A search was conducted for studies published up to April 2015 using Science Direct, CAB direct (CAB International), SCOPUS, and Web of Knowledge online databases with search terms *ammonia* or *NH_3*, *emission*, *dairy*, and *cows* or *livestock* or *cattle*. The searches collectively resulted in 266 articles. To be included in the data set, the studies were required to have the following characteristics: (i) in vivo dairy cow studies reporting emissions from dairy housing; (ii) published in English, (iii) reported mean NH_3 emissions in grams per cow per day or grams per livestock unit per day, with measures of sample size (*n*). If emissions were reported in a different unit, for example, grams per cow per year or grams per cow per month, the study was removed from the data set. Also, studies were required to report emissions from measurements taken for 24 h and from housing only. Thus, 73 studies were excluded because NH_3 emissions only from manure storage or lagoons were reported, and 29 studies were related to mathematical model development. An additional 25 studies were excluded because they did not include NH_3 emission data, and 33 studies were duplicates. In addition to mean NH_3 emissions (in grams per cow per day) and variability measures, the final data set included environmental information such as ambient air temperature, relative humidity, wind speed, season, and region, as well as housing characteristics, flooring and barn types, and manure management. A total of 25 studies were used for analysis. The main characteristics of each study are described in Table 1, and the summary statistics are given in Table 2.

A subset of the database was extracted to assess the impact of diet and animal characteristics on NH_3 emission. To be included in the subset, the studies were required to have additional information, i.e., report dietary CP content, milk yield, body weight (BW), and dry matter intake (DMI). A total of 11 studies met the criteria, with one study taken out because it was identified as an influential case. Influential cases are define as one or multiple studies leading to considerable changes in the fitted model if excluded from the analysis (Viechtbauer and Cheung, 2010). Publication bias denotes a tendency not to publish studies if findings are not statistically significant or if findings contradict prior expectations (Rothstein et al., 2005). Both influential cases and publication bias, in the collection of studies, can affect the validity and robustness of meta-analysis conclusions (Sutton et al., 2000; Viechtbauer and Cheung, 2010). Influential cases were identified using Cook's distance values and the estimates of τ^2 obtained when each study was removed from the data set as described previously (Viechtbauer, 2010). Cook's distance values are useful for identifying outliers in the predictor's variables as well as showing the influence of each observation on the fitted response values. An observation with a Cook's distance value larger than three times the mean Cook's distance might be an outlier.

The study descriptions and summary statistics are given in Tables 3 and 4. If CP content was not provided, it was calculated from DMI and N intake. If measures of variability other than the standard deviation (SD) were reported (such as standard error of

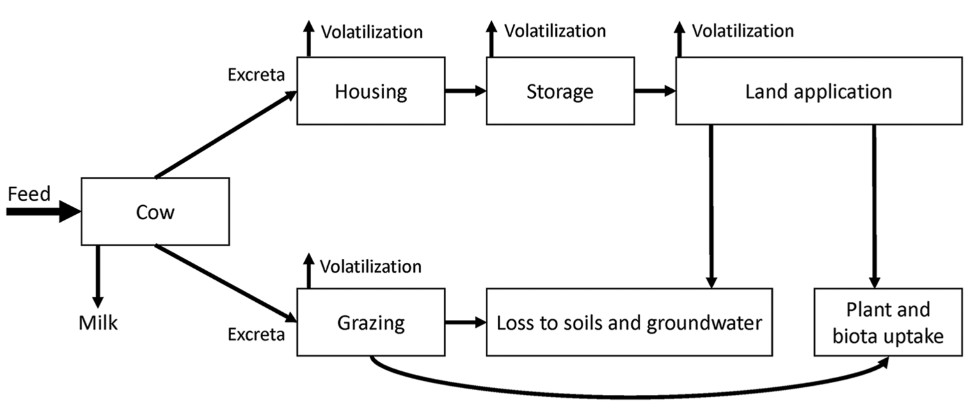

Fig. 1. Nitrogen flow through the animal and the environment.

Table 1. Description of the 25 studies included in data set for evaluation of environmental factors.

Reference	Region	Season	avg. temp.	Source type†	Flooring	Manure handling	Measurement method	*n*	Animals	Milk yield	Dry matter intake	Dietary crude protein	NH_3
			°C						no.	—— kg d^{-1}	——	%	g cow^{-1} d^{-1}
Aguerre et al. (2011)	Wisconsin	all	–	barn NV	solid floor	manure pack	mass balance	4	–	37.4	20.5	16.2	14.1
Amon et al. (2001)	Austria	all	15.8	barn MV	solid floor	manure pack	mass exchange	1	12	18.5	16.2	13.4	5.8
Bjorneberg et al. (2009)	Idaho	autumn, winter, spring	−4.8 to 15.3	open lot	open lot	stacked	mass exchange	4	700	–	–	–	116.3
Bluteau et al. (2009)	eastern Canada	all	–	barn MV	solid floor	scraped	mass balance	1	71	25.7		13	6.5
Cassel et al. (2005a)	California	winter	12.5	barn NV	solid floor	flush	mass exchange	2	4265 & 2342	–	–	–	54–106.3
Cassel et al. (2005b)	California	winter	–	open lot	open lot	flush	mass balance	1	–	–	–	–	50
Dore et al. (2004)	UK	winter	5.4	barn NV	solid floor	scraped	tracer	6	125	–	–	–	88
Gustafsson et al. (2005)	Sweden	all	15.4	barn NV	solid floor	scraped	mass exchange	2	42	–	–	–	20.3
Harper et al. (2009)	Wisconsin	summer, autumn, winter	–	barn NV	solid floor	flush (2), scraped (1)	inverse dispersion	3	902	–	–	–	33.2 (flush), 16.8 (scraped)
Jungbluth et al. (2001)	Germany	all	–	barn NV	slatted floor	pit	mass exchange	1	55	–	–	–	15
Kavolelis (2006)	Lithuania	all	8	barn NV	solid floor (2), slatted floor (1)	scraped (2), pit (1)	CO_2 balance	3	196–230	21.3	–	–	scraped (23), pit (29)
Leytem et al. (2011)	Idaho	all	−4 to 23.5	open lot	open lot	stacked	inverse dispersion	10	10,000	34	24	17.6	136.5
Leytem et al. (2013)	Idaho	all	−8.3 to 23.8	barn NV	solid floor	flush	inverse dispersion	10	10,000	34	24	17.6	87.7
Moore et al. (2014)	California	summer	26.5	open lot	open lot	scraped	inverse dispersion	2	950	–	25.2	18.4	140.7 (passive sampler), 186.0 (inverse dispersion)
Mosquera et al. (2006)	Netherlands	winter	6.4	barn NV	solid floor	manure pack	tracer	2	49 & 62	–	–	–	32
Ngwabie et al. (2009)	Sweden	spring (1), winter (4)	13.4	barn NV	slatted floor	scraped	mass balance	5	164–195	32.1	20.1	16.2	24.3
Pereira et al. (2010)	Portugal	all	14	barn NV	solid & slatted floor	scraped, pit, flush	passive sampler	3	15–74	24.5	16.9	17.2	30 (pit), 35.3 (flush), 65.8 (scraped)
Phillips et al. (1998)	UK	winter	9.5	barn NV	solid floor	scraped	passive sampler	1	96	–	–	–	7.4
Rong et al. (2014)	Denmark	summer, winter	–	barn NV	slatted floor	pit	mass exchange	2	350	32	21	14.2	12.2
Schrade et al. (2012)	Switzerland	summer (4), winter (2)	6.5–16.0	barn NV	solid floor	scraped	tracer	6	20–73	25.4	–	–	36.2
Todd et al. (2015)	New Mexico	summer	24.8	open lot	flush	hard surface	inverse dispersion	1	3492	29.2	22.5	16.64	304
van Duinkerken et al. (2005)	Netherlands	all	–	barn NV	solid floor	scraped	tracer	32	57	29.4	21	16.4	35.5
Wu et al. (2012)	Denmark	all	17	barn NV	slatted floor	scraped	mass balance	2	165 & 126	30.5	21.4	17.1	104–40
Zhang et al. (2005)	Denmark	autumn	13	barn NV	slatted floor	scraped (11), flush (2), pit (12)	CO_2 balance	25	105–282	28.2	–	–	35.7 (pit), 27.2 (flush), 31.8 (scraped)
Zhu et al. (2012)	China	spring, summer, winter	0.3–29.1	barn NV	solid floor	scraped	CO_2 balance	4	180	–	15	15.8	75.5

† MV, mechanically ventilated; NV, naturally ventilated.

Table 2. Summary statistics of the 25 studies included in data set for evaluation of environmental factors.

Parameter	Mean	SD	Min.	Max.	*n*
NH_3, g cow^{-1} d^{-1}	59.3	53.1	5.0	304	138
Wind speed, m s^{-1}	2.7	1.7	0.2	7.0	58
Relative humidity, %	66.2	12.1	41.0	82.0	17
Outside temperature, °C	10.2	9.3	−9.1	30.3	65
Inside temperature, °C	13.1	4.8	0.3	29.1	57

the mean or coefficient of variation), they were converted to SD and entered into the database.

Statistical Analysis

Physical Effects

To assess the impact of housing systems, flooring type, manure management, housing type, and season, mixed effect models were constructed for NH_3 emission data (g cow^{-1} d^{-1}) using the lme4 package (Version 1.1-10) in R statistical software (Version 0.98.1102, R Foundation for Statistical Computing). Study was considered a random effect and the categorical variables (housing systems, flooring type, manure management, housing type, and season) were used as fixed effects in the analysis. Nonsignificant variables were excluded step by step to avoid multicolinearity problems. The final mixed effect model included the significant categorical variables that had an impact on NH_3 emissions. Statistical significance was declared at $P < 0.05$, and a trend was discussed at $0.05 < P < 0.10$.

The following groups were made: (i) housing system: open lots vs. naturally ventilated barns (use forces of nature such as wind to cause air exchange) vs. mechanically ventilated barns (use fans for air exchange); (ii) flooring type: open lots (open floors comprised of soil) vs. solid concrete floor vs. slatted floor (concrete floors having openings through which manure falls into a subfloor or a pit); (iii) manure handling: five systems were compared, i.e., flush, scraped, stacked, pack, and pit, which

Table 3. Description of the 10 studies included in the subset for evaluation of dietary, animal, and environmental factors.

Reference	Region	Source type	Flooring (*n*)	Manure handling (*n*)	Measurement method	*n*	Animals	Milk yield	Dry matter intake	Dietary crude protein (CP)	Neutral detergent fiber	Mean NH_3 emission	SD	Highest NH_3 emission
							no.	— kg d^{-1} —		%	g kg^{-1}	g cow^{-1} d^{-1}		g cow^{-1} d^{-1}
Aguerre et al. (2010)	USA	on-farm	solid floor	scraped	mass balance	7	39	32.4	24.2	15–18.2	263.6	110.4	43.79	CP 17.7%, 178.0
Aguerre et al. (2011)	USA	chamber	solid floor	manure pack	mass balance	4	4	37.35	20.53	16.2	347.50	14.1	2.30	15.1
Arndt et al. (2015)	USA	chamber	solid floor	–	mass balance	4	4	40.68	24.63	16.6–18	277.25	15.7	2.34	CP 17.5%, 16.5
Burgos et al. (2010)	USA	chamber	solid floor	scraped	mass balance	4	3	30.23	23.25	15.1–20.7	223.50	102.7	8.61	CP 20.7%, 149.1
Leytem et al. (2011)	USA	on-farm	open-lot	stacked	inverse dispersion	10	10,000	34	24	17.6	–	136.5	58.47	185.4
Leytem et al. (2013)	USA	on-farm	solid floor	flush	inverse dispersion	11	10,000	34	24	17.6	–	87.7	42.32	138.9
Liu et al. (2012)	USA	chamber	solid floor	scraped	mass balance	6	4	33.9	21.1	15.3–16.5	–	29.5	4.35	CP 16.2%, 36.2
Ngwabie et al. (2009)	Europe	on-farm	slatted floor	scraped	mass balance	5	164–195	32.11	20.10	16.2	–	24.3	7.20	27.1
Pereira et al. (2010)	Europe	on-farm	solid (1); slatted floors (2)	scraped (1), pit (1), flush (1)	Passive sampler	3	74, 21, 15	23.03	16.88	17.2	462.30	47.2	39.65	solid floor, 65.8
van Duinkerken et al. (2005)	Europe	on-farm	solid floor	scraped	Tracer	32	48	29.3	20.9	14.1–18.9	–	35.5	5.52	CP 16.9%, 88.5 CP 18.2%, 83.8

Table 4. Summary statistics of the 10 studies included in the subset for evaluation of dietary, animal, and environmental factors.

Parameter	Mean	SD	Min.	Max.	*n*
NH_3, g cow^{-1} d^{-1}	60.1	49.3	7.8	213	87
Body weight, kg	616	32.7	500	649	87
Days in milk, d	166	43.3	73	223	58
Milk yield, kg d^{-1}	31.9	3.8	19.9	41.0	87
Dry matter intake, kg d^{-1}	22.2	2.6	14.6	25.0	87
Nitrogen intake, g d^{-1}	607	96.8	404	791	87
Crude protein content, %	16.8	1.4	14.1	20.7	87
Neutral detergent fiber content, %	32.4	8.2	22.0	48.3	28
Temperature, °C	13.6	7.0	−8.3	23.8	46
Wind speed, m s^{-1}	3.7	1.4	1.7	7.0	11
Relative humidity, %	59.6	15.2	46.5	80.0	11

correspond to categories used by the USEPA for the national emission inventories (barns with flush systems remove manure using water for flushing concrete aisles, and barns with scraped systems remove manure from concrete aisles or gutters using chains, tractors, or other devices; manure is scraped and stacked in open lots for storage (stacked system), while in pack systems, bedding is used and the manure and bedding accumulate before clean-out; pit systems use slatted floors where manure is transferred to a pit below the floor for storage); (iv) housing type: free-stall cubicle (partly restricted lying area, cubicle) vs. loose housing-barn (unrestricted area, non-cubicle) vs. tied stalls (constrained cubicle laying area) vs. loose housing lots (open-lot lying area); and (v) season: spring (March–May) vs. summer (June–August) vs. autumn (September–November) vs. winter (December–February). The season or date of 13 experiments was not reported. All open-lot related studies were considered to have hard surface beddings and stacked manure handling. The open-lot flooring type represents an outdoor facility where the area is devoid of vegetation, which is commonly used in the western United States.

Nutritional and Animal Effects

Meta-regression models describing the relationship between dietary nutrient composition (and weather condition), and NH_3 emission were developed using R (metafor package Version 1.9-5). The variability (heterogeneity) associated with NH_3 emission was first quantified using a random-effect model:

$$y_i = \mu + \mu_i + e_i \quad [1]$$

where y_i is the measured NH_3 emission related to the ith treatment; μ is the overall true effect size, μ_i is the random deviation from the overall effect size [$\mu i \sim N(0, \tau^2)$], which was estimated from the data; and e_i is the sampling error [$e_i \sim$ N(0, sampling variance)], assumed to be known and taken as the squared SD of the effect size. The term τ^2 indicates heterogeneity. To explain more of the heterogeneity in the data, the random-effect models were extended to mixed-effect models by including a fixed effect of the dietary, animal, and weather explanatory variables. The mixed-effect models are given by

$$\theta_i = \beta + \beta_1 x_{ij} + ... + \beta_{ip} x_{ip} + \mu_i \quad [2]$$

where θ_i is the true effect size in the ith treatment; β is the overall true effect size; x_{ij} is the value of the jth explanatory variable (j = 1, 2, ..., p) for the ith treatment; β_j is the change in the true effect per unit increase in the jth explanatory variable; and $\mu_i \sim N(0, \tau^2)$. Here τ^2 indicates the amount of heterogeneity not explained by the variables (Viechtbauer, 2010). The explanatory variables used include BW, days in milk, milk yield, DMI, dietary CP content, N intake, dietary neutral detergent fiber, temperature, wind speed, and relative humidity. The explanatory variables were centered on their means and then regressed individually against NH_3 emission. Centering variables allows interpretation of the regression effects in terms of changes in NH_3 emission for a unit change in an explanatory variable from its mean.

Publication Bias and Influence Diagnosis

Although 11 studies reporting 88 treatments means were initially chosen for the nutrition effect meta-analysis, the influence analysis removed one treatment mean reported in one study (Bluteau et al., 2009), leaving 10 studies reporting 87 treatment means for subsequent analysis. Bluteau et al. (2009) reported a low NH_3 emissions mean from 71 cows, with 6.3 g cow $^{-1}$ d^{-1} measured using the mass balance technique. Publication bias of the NH_3 emission was assessed using Egger's regression test for funnel plot asymmetry (Viechtbauer, 2010). Egger's regression test did not show a presence of significant publication bias in the data ($P > 0.05$) in all cases.

Model Fitting and Selection

The random-effect models were initially fitted using the restricted maximum likelihood method to estimate heterogeneity (τ^2). Statistical significances of τ^2 were obtained using chi-squared tests (Higgins and Thompson, 2002). Moreover, I^2 statistics were calculated expressing τ^2 as a percentage of the total variance ($I^2 = \tau^2$ + sample variance). Hence, the I^2 statistic represents the proportion of the total variation in the estimate of the treatment effect that is due to heterogeneity. The mixed-effect models were then constructed by including individual explanatory variables. Full mixed-effect models carrying all explanatory variables having effects ($P < 0.2$) when fitted individually were then fitted using the maximum likelihood method. Multicollinearity was considered when selecting variables for the models ($r > 0.6$). For example, dietary CP and N intake were not analyzed together because they were highly correlated ($r = 0.77$). Reduced models were selected via stepwise elimination of one variable at a time and fitted again using the maximum likelihood method. The final mixed-effect models were chosen by testing the reduced models vs. the full models using log-likelihood ratio tests. The parameter estimates of the final model were obtained by fitting the model using the restricted maximum likelihood method.

Results and Discussion

The variables having an impact on NH_3 emissions are given in Table 5 along with the mean NH_3 emission for the significant categorical variables. In this study, open lots had a significantly greater NH_3 emission, with 165.2 g cow^{-1} d^{-1}, compared with slatted and solid floor systems (40.4 and 47.7 g cow^{-1} d^{-1}, respectively; Table 5). Ammonia emission rates were reported to increase with temperature, which was highly dependent on floor type and manure system (Zhang et al., 2005). In open-lot housing systems, urine is deposited on soil, which has an abundant urease content (Montes et al., 2013), promoting rapid conversion to NH_3 and loss via volatilization, whereas in barns, urine is typically removed along with feces on a regular basis, which has been shown to decrease the NH_3 emissions generated from the housing (Leytem et al., 2013); however, this NH_3 can later be lost in storage or during land application if not properly managed. In addition, the open-lot soil surface is directly impacted by weather conditions such as wind, moisture, and ambient temperature, all of which are important factors that influence NH_3 emissions.

Similar to the study of Pereira et al. (2010), dairy barns with a solid floor had greater NH_3 emission than those with slatted floors (47.7 and 40.4 g cow^{-1} d^{-1}, respectively; $P > 0.05$). Urine and feces are mixed and stagnant on solid floors, whereas slatted

Table 5. Ammonia emission as affected by significant physical characteristics of the barn.

Characteristic	NH_3 emission	*n*	SEM	*P* value
	g cow^{-1} d^{-1}			
Housing system				>0.05
Flooring				
Open lot	165.2†	17		
Slatted floor	40.4	29	20.32	<0.001
Solid floor	47.7	92		
Manure management				>0.05
Housing type				>0.05
Season				
Winter	59.7	26		
Spring	92.1	22	24.68	<0.01
Summer	91.7	29		
Autumn	75.5	48		

† Within a column, means followed by different letters differ significantly ($P < 0.05$).

floor systems consist of narrow gaps, allowing for partial separation of urine and feces. Therefore, urease that is abundantly present in feces interacts less with urinary urea-N, resulting in a lower NH_3 emission. In addition, manure stored in a pit below the floor will probably have less air movement across the surface, thus reducing the potential emission of NH_3 compared with solid floors. It has been shown that air velocity above the surface of slurry in a pit plays a key role in NH_3 emission (Braam et al., 1997).

Manure handling systems and housing type did not have a significant impact on NH_3 emissions when analyzed together with the other variables (Table 5; $P > 0.05$); however, some differences were identified when analyzed separately. Stacked manure systems had the greatest emissions, which can be four times higher than the lowest emitting systems (flush system; data not shown). However, it is not an effect of housing systems per se, as manure handling, housing type, and flooring were confounded. Furthermore, loose-housing lots showed the greatest emission rate (145 g cow^{-1} d^{-1}; data not shown), and loose-housing barns released more NH_3 than tied stalls but not freestall cubicles. Monteny and Erisman (1998) also reported a greater NH_3 emission from loose-housing barns than tie-stall barns. The lack of mixed feces and urine in tie-stall barns compared with open lots or freestalls may have led to lower NH_3 emissions as well as the small surface exposure where dairy cows have reduced access to mixed floor space. Also, the enzyme urease is more likely to be released on surfaces that are frequently in contact with feces like loose-housing barn surfaces (Ketelaars and Rap, 1994).

Several studies showed a significant relationship between temperature in the barn and NH_3 emission (Van der Stelt et al., 2007; Powell et al., 2008; Dai and Karring, 2014) and seasonal variation (Saha et al., 2014). In the current study, a positive correlation trend was demonstrated between the outside air temperature and NH_3 emission (Fig. 2; $r = 0.39$). A significant impact of the outside temperature on the NH_3 emission ($P < 0.05$) was also shown in this study, whereas wind speed and relative humidity had no significant effects. The greatest average temperature occurred in the summer (21.2°C), which also corresponds with the period of greatest NH_3 emission (Table 5). Urease activity is optimum at 60°C and declines with decreasing temperature, as shown by Sahrawat (1984), thus high temperature would enhance NH_3 emissions. Also, in this analysis, seasonal variation significantly affected average NH_3 emission (Table 5; $P < 0.05$). The greatest NH_3 emissions were measured in spring and summer, with 92.1 and 91.7 g cow^{-1} d^{-1}, respectively, and were significantly greater than emissions in winter. The average reported NH_3 emission in winter and autumn accounted for 65.1 and 82.3%, respectively, of peak summer emissions, resulting in a reduction of about 35% of NH_3 emission in winter. Mukhtar et al. (2008) reported that NH_3 emission from an open lot in Texas was 53% less in winter than in summer.

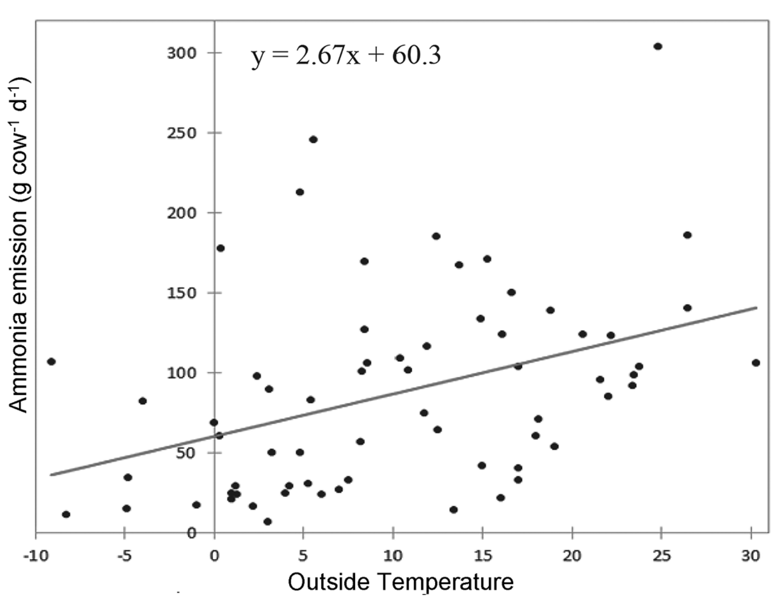

Fig. 2. Ammonia emission as affected by temperature outside the barn ($r^2 = 0.15$; $NH_3 = 60.3 + 2.67 \times$ outside temperature).

USEPA Ammonia Emission Inventories Comparison

National NH_3 inventories are reported by the USEPA (2011) based on emissions from cattle housing, manure storage, manure application to soil, grazing, and mineral N fertilizer. To calculate NH_3 emission, the USEPA and/or state agencies may use county-level emission factors derived from the Carnegie Mellon University (CMU) Ammonia Emissions Model in each state and for each animal population, but there is no consideration for seasonal variation in these factors. This could ultimately produce estimates that under- or overpredict actual emissions.

The emission factors reported in the CMU Ammonia Emissions Model vary from the on-farm data utilized for this study. The CMU emission factors are lower than those found in this study for the "scrape dairy barn" and "open-lot dairy stacked barn," were similar for "flush dairy barn," and were greater for "deep pit dairy barn." The CMU model had both flush and deep-pit barns producing 2.8 and 3.4 times more NH_3, respectively, than open-lot dairies. However, the on-farm data consistently showed that emissions from open-lot systems were much greater than other housing systems. Indeed, the NH_3 emission factor used for open-lot dairies is 720 g cow^{-1} mo^{-1}, whereas the mean NH_3 emission from the literature is 4350 g cow^{-1} mo^{-1} (Table 6). This suggests that the USEPA and states

Table 6. Livestock emission factors reported by the CMU Ammonia Emission Model and average NH_3 emission in this study.

Type of barn	CMU emission factor	Avg. NH_3 emission in this study†
	——— g cow^{-1} mo^{-1} ———	
Deep pit dairy barn	2420	930
Open-lot dairy (stacked)	720	4350
Flush dairy barn	2000	2100
Scrape dairy barn	720	1386

† Monthly NH_3 emission rates in the study were multiplied by 30 d to obtain the monthly NH_3 emission rate as given by the USEPA.

using the CMU Ammonia Emission Model may need to revise NH_3 emission factors based on current published studies of emissions from production facilities.

Nutritional Effects on Ammonia Emission

The overall average NH_3 emission from the subset of data used for analysis was 60.1 g cow^{-1} d^{-1} with a high variation (Table 4; SD = 49.3). The highest emission was 213 g cow^{-1} d^{-1} compared with the lowest, which was 7.8 g $cow^{-1}d^{-1}$. The overall NH_3 emission rate found in this study is in agreement with that stated in a review by Hristov et al. (2011) at 59 g cow^{-1} d^{-1}. In addition, it was reported in that review that NH_3 emissions varied from 0.82 to 250 g cow^{-1} d^{-1}.

Because N excretion is the major source of NH_3 emission, dietary CP and N intake were important factors to consider. In the analysis, 9.3% of N intake (SD = 6.6) was lost via NH_3 emission, ranging from 1.6 to 30%. The CP content of the diet was variable across the studies, ranging from 14.1 to 20.7%. Ammonia emissions were, in part, influenced by dietary CP content (Fig. 3; $r = 0.51$) and N intake ($r = 0.55$).

Milk production in the database ranged from 19.9 to 41.0 kg cow^{-1} d^{-1} (Table 4), with days in milk ranging from 73 to 223 d. The NH_3 emission per kilogram of milk produced varied from 0.3 to 6.3 g kg^{-1}, with an average of 1.9 g kg^{-1} (SD = 1.5). However, milk yield was not significantly associated with NH_3 emission ($r = -0.13$). The mean BW varied, ranging from 500 to 648 kg, and NH_3 emission had a tendency to increase in heavier animals ($r = 0.26$).

Random-Effect Models and Ammonia Emission

As stated by Hedges and Vevea (1998), when using random effect models in a meta-analysis, one can assume that the studies are a random sample of the entire population of studies, and

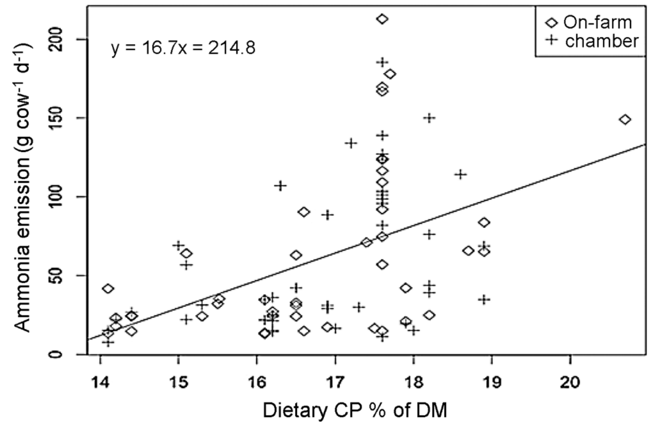

Fig. 3. The relationship between NH_3 emission and dietary crude protein (CP) content of the diet as a percentage of the dry matter intake ($r^2 = 0.31$; $NH_3 = -214.8 + 16.7 \times$ diet CP) for both on-farm studies and chamber experiments.

as a consequence, any inference can be generalized beyond the studies included. Thus, in the current study, inferences could be extended and generalized to any dairy barns using the same housing systems with similar climates.

Random-effect model analysis revealed that the effect of NH_3 emission was associated with significant ($P < 0.001$) heterogeneity for dairy cows. The I^2 statistics showed that the total variance of the NH_3 emission was all due to heterogeneity (Table 7). Funnel plots constructed using random-effect models were used to assess publication bias. The funnel plots in Fig. 4 show the mean NH_3 emission vs. the corresponding standard error (SE) measures. A vertical line is drawn at zero on Fig. 4B, with a confidence interval region given by ±1.96 SE (Viechtbauer, 2010). It assumes that studies with larger sample sizes will be found near the average, while studies with smaller sample sizes will be spread on both sides of the mean. Thus, in the absence of publication bias, the majority of the points would be expected to fall inside the confidence region of the funnel plot as seen in Fig. 4B. Besides visual assessment, Egger's regression test was used to assess funnel-plot asymmetry. Asymmetrical funnel plots indicate the presence of publication bias.

Egger's regression test showed that the funnel plots were not significantly asymmetrical ($P > 0.01$; data not shown), suggesting the presence of substantial publication bias in the random-effect models. Visual assessment of Fig. 4A also strongly indicates the presence of publication bias. Heterogeneity also alters funnel-plot shape significantly (Rothstein et al., 2005). Given the

Table 7. Number of studies used for the analysis (n), heterogeneity (τ^2), τ^2 as a percentage of the total variability (I^2) from random-effect models, and effect size and τ^2 of mixed-effect models.

Parameter	n	Mean ± SE	P value	τ^2	I^2	P value
					%	
			Random-effect models			
NH_3 emission, g cow^{-1} d^{-1}	87	60.1 ± 5.3		2424 ± 371	100	
			Mixed-effect models			
		Effect size			Heterogeneity	
Intercept		60.0 ± 3.9	<0.0001			
Dietary crude protein, %		10.2† ± 3.41	0.0010	1322 ± 207		<0.0001
Milk yield, kg d^{-1}		−4.9† ± 1.4	0.0004			
Dry matter intake, kg d^{-1}		16.3† ± 2.7	<0.0001			

† Regression using the actual value minus the mean in the data set.

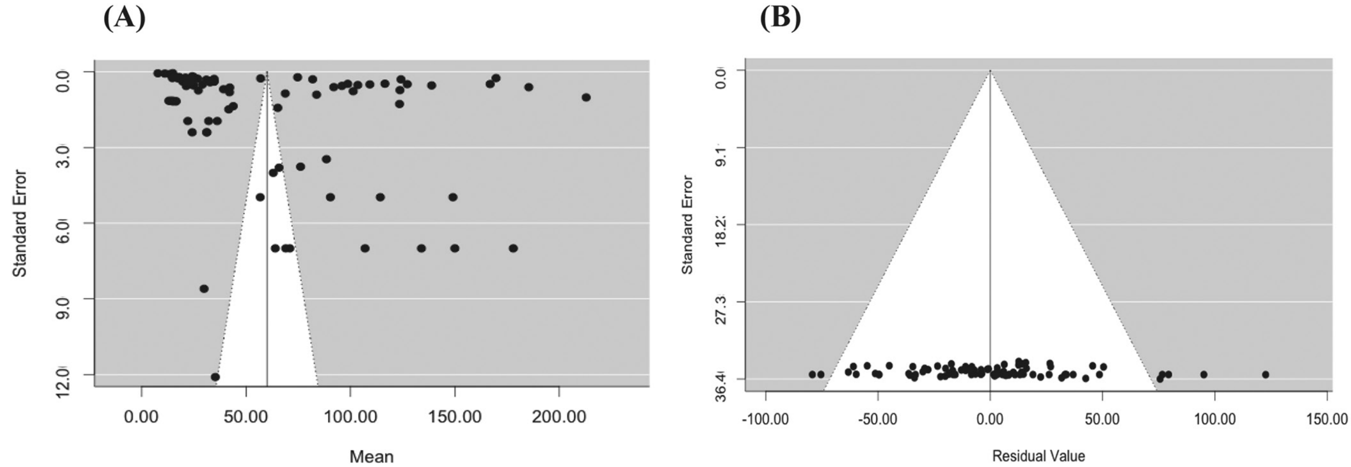

Fig. 4. Funnel plots for NH_3 emission from (A) random-effect models and (B) mixed-effect models.

significant heterogeneity estimates mentioned above, mixed-effect models were constructed to explain the heterogeneity. A substantial part of the heterogeneity has been explained thanks to the mixed-effect models, as the majority of the points fall inside the confidence region of the funnel plot in Fig. 4B.

Explanatory Variables and Ammonia Emission

The explanatory variables having significant effects ($P < 0.2$) when fitted individually and subsequently selected for the full mixed-effect model were DMI, days in milk, milk yield, dietary CP, and BW. After stepwise elimination of variables, the final mixed-effect model included dietary CP, milk yield, and DMI, indicating significant independent effects on NH_3 emission (Table 7).

The selected variables explained 45.5% ($\tau^2 = 1322$ vs. 2424) of the NH_3 emission from dairy cows used in the experiments that contributed to the meta-analysis. Assuming all other variables are constant, increasing a unit of CP in the diet increased NH_3 emission by 10.2 g cow^{-1} d^{-1}. A linear increase in manure NH_3 losses when dietary CP concentration increased has been previously described by Paul et al. (1998). Thus, dietary CP and NH_3 emissions from either manure or housing are closely related. Ammonia release can be two- to threefold greater when dietary CP increases from approximately 13 to 19% (Swensson, 2003). Smits et al. (1995) and Külling et al. (2001) have shown that there is a greater variation in NH_3 emission due to dietary CP than variation from manure handling. Furthermore, increasing dietary CP concentration has been shown to increase NH_3 emission from beef (Todd et al., 2006) and dairy cattle (Powell et al., 2011). The impact of dietary CP has been widely explored (Broderick, 2003; Wattiaux and Karg, 2004; Colmenero and Broderick, 2006; Aguerre et al., 2010), and the results showed that a reduction in CP from 18 to 16.5% does not impact the milk yield but influences the N excretion in manure (9% reduction) and urinary urea-N excretion (16% reduction). Because NH_3 is mainly produced from urinary urea-N and then volatilized from the barn floor (Muck and Richards, 1983), reducing excess dietary N through lower dietary CP content is an effective strategy for NH_3 abatement. Thus, excess dietary CP results in an economic loss that also negatively impacts environmental quality.

Dry matter intake was positively related with NH_3 emissions. Holding all other variables constant, a unit increase in DMI increased NH_3 emission by 16.3 g cow^{-1} d^{-1}. A cow consuming 25.0 kg dry matter d^{-1} would be expected to emit 106 g NH_3 d^{-1} in comparison with one consuming 22.2 kg dry matter d^{-1} that would release 60.0 g d^{-1}. Manure production increases with DMI (Weiss, 2004), with potential increases in daily NH_3 emission. Overall intake of N is related to DMI and affects the amount of N excreted in urine as urea-N. Increasing urea-N, which is correlated to N intake, has been shown to lead to higher NH_3 emissions (Weiss et al., 2009). Furthermore, as DMI increases, the passage rate increases, which typically decreases the overall digestibility of organic matter and, to some extent, the dietary CP (National Research Council, 2001; Knapp et al., 2014). The extra N excreted as urea-N when DMI increases can lead to a potentially greater NH_3 release.

Milk yield was negatively related to NH_3 emission, as a unit increase in milk yield led to an NH_3 emission reduction of 4.9 g cow^{-1} d^{-1}. Higher producing cows had less NH_3 emissions than cows with low milk production. Milk yield does not explain a large part of the heterogeneity (8%), thus not as much importance should be focused on this variable. However, as with milk yield, DMI and N intake are positively correlated, a high-producing cow may be fed a diet closer to the actual nutrient requirements, resulting in higher milk production and a lower NH_3 emission rate.

Milk protein yield is positively related to milk yield, thus more N would be secreted in milk as the milk yield increases. Milk yield, DMI, and dietary CP content were significantly associated with NH_3 emission and explained 45.5% of the heterogeneity in the final mixed-effect model. Other variables such as cow characteristics including breed and health status, amount of urine excreted, urine composition, urine and feces pH, and other dietary characteristics such as energy, rumen-degradable protein (RDP), and rumen-undegradable protein (RUP), could further explain the heterogeneity of NH_3 emissions. For example, Reynal and Broderick (2005) reported that providing an optimal balance of RDP and RUP, without impairing the performance, reduced N excretion. Thus, a potential NH_3 emission reduction could be observed when RDP is well balanced in the diet. Wattiaux and Karg (2004) reported that cows consuming alfalfa

(*Medicago sativa* L.)-based diets excreted more N in feces (49.0 g d^{-1}) than those fed corn (*Zea mays* L.) silage-based diets.

Most nutrition studies focus on production parameters and rarely measure NH_3 emissions. On the other hand, most studies that measure NH_3 emissions do not adequately describe dietary and animal characteristics, which limited the analysis in this study. For further research, it would be interesting and useful to measure the NH_3 emission rate along with more detailed dietary and animal-related variables. Also, emission rates described in this study do not represent whole-farm NH_3 losses, as some emissions occur during manure storage outside the barn, composting, or land application. Therefore, although there are differences in NH_3 emissions from the various housing systems, whole-farm NH_3 loss should be studied to determine the effects of the various systems on the total NH_3 emissions.

Conclusion

Examining the results from several studies confirmed previous conclusions showing that NH_3 emission is driven by several factors including flooring system, season, and diet. Open-lot systems had greater NH_3 emissions than slatted or solid floors in barns. Milk yield, DMI, and CP content significantly affected NH_3 emissions, explaining 45.5% of the heterogeneity in the final mixed-effect model. Dietary CP content and DMI positively affected the NH_3 emissions, whereas milk yield had a negative relationship with NH_3 emissions. The heterogeneity could have been further explained by considering other variables representing more detailed dietary and animal characteristics but could not be completed for this meta-analysis due to limited available data. Data from this study can be further used to develop prediction equations for NH_3 emissions from dairy cattle housing.

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