Season and Bedding Impacts on Ammonia Emissions from Tie-stall Dairy Barns

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Federal and state regulations are being promulgated under the Clean Air Act to reduce hazardous air emissions from livestock operations. Few data are available on emissions from livestock facilities in the USA and the management practices that may minimize emissions. The objective of this study was to measure seasonal and bedding impacts on ammonia emissions from tie-stall dairy barns located in central Wisconsin. Four chambers each housed four Holstein dairy heifers (~17 mo of age; body weights, 427–522 kg) for three 28-d trial periods corresponding to winter, summer, and fall. A 4×4 Latin Square statistical design was used to evaluate four bedding types (manure solids, chopped newspaper, pine shavings, and chopped wheat straw) in each chamber for a 4-d ammonia monitoring period. Average ammonia-N emissions (g heifer^{-1} d^{-1}) during summer (20.4) and fall (21.0) were similar and twice the emissions recorded during winter (10.1). Ammonia-N emissions accounted for approximately 4 to 7% of consumed feed N, 4 to 10% of excreted N, and 9 to 20% of manure ammonical N. Cooler nighttime temperatures did not result in lower ammonia emissions than daytime temperatures. Ammonia emissions (g heifer^{-1} d^{-1}) from chambers that contained manure solids (20.0), newspaper (18.9), and straw (18.9) were similar and significantly greater than emissions using pine shavings (15.2). Chamber N balances, or percent difference between the inputs feed N and bedding N, and the outputs manure N, body weight N, and ammonia N were 105, 90, and 89% for the winter, summer, and fall trials, respectively. Relatively high chamber N balances and favorable comparisons of study data with published values of ammonia emissions, feed N intake, and manure N excretion provided confidence in the accuracy of the study results.

In the USA, the trend toward fewer and larger livestock farms has heightened public concern about pollution. Over the past decade or so, environmental policy under the Clean Water Act has been focused on abating manure runoff from agricultural land and the effects of this runoff on the pollution of lakes, streams, and other surface water bodies. Recently, regulations have been promulgated under the Clean Air Act to reduce hazardous air emissions from livestock operations.

Relatively much is known about air emissions from livestock operations in Europe (e.g., Hutchings et al., 2001; Webb and Misselbrook, 2004; Pedersen, 2006), and air emission standards are in place. Little information is available, however, on emissions from livestock facilities in the USA and management practices to minimize emissions. The recent report "Air Emissions from Animal Agriculture" by the National Academy of Sciences (NRC, 2003) made an urgent call for processed-based research that can assist producers and regulatory agencies in developing strategies that abate harmful air emissions from livestock farms. The objective of this study was to determine seasonal differences and the impact of bedding on ammonia emissions from tie-stall dairy barns.

Stanchion or tie-stall barns are the most common housing types on dairy farms in the Midwest and Northeast regions of the USA (USDA, 2004), where approximately 50% of the USA dairy herd reside. On farms that operate tie-stall barns, cows are confined to stalls, and manure is collected in a gutter behind the cows. Moderate to large amounts of bedding (e.g., straw or wood shavings) are used. The manure mixture of feces-urine-bedding is typically removed from the barn with a gutter cleaner once daily and is field-applied daily or stored for later field application.

Ammonia losses from dairy operations begin immediately after manure N excretion and continue through manure handling, storage, and land application. Ammonia emissions from dairy barns are thought to range from 20 to 55% of manure N excretions (MWPS, 2001). The main factors that affect this value are diets, housing, bedding type, barn ventilation, and temperature.

Under producer conditions in Wisconsin, only 20 to 30% of the N (crude protein) fed to dairy cows is converted into milk (Powell et al., 2006). The remaining feed N is excreted about equally in urine and feces, although this can be highly influenced by diet (Castillo et

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Abbreviations: CNB, chamber N balance; DM, dry matter; ExN, excreted N; TAN, total ammonical N in manure; TN, total N contained in feed, bedding, or manure; UN, urinary N.

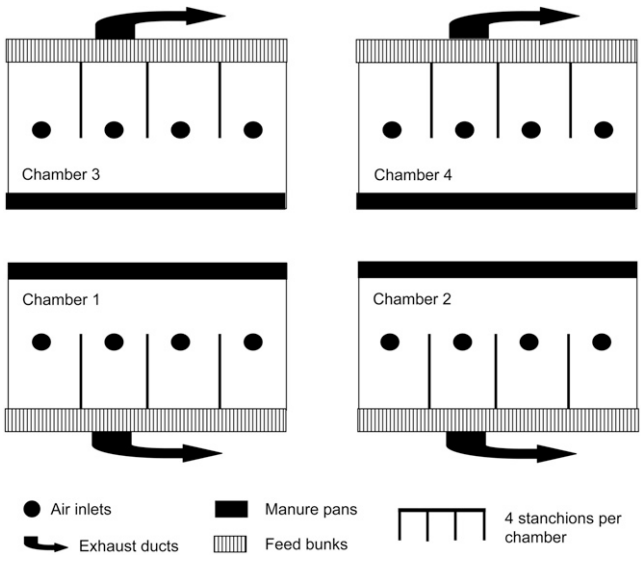

Fig. 1. Configuration of tie-stall ammonia emission chambers (Powell et al., 2007)

al., 2000; Broderick, 2003). About 75% of the N in urine is in the form of urea (Bristow et al., 1992). Urease enzymes, which are present in feces and soil, rapidly convert urea to ammonium. Ammonium can be transformed quickly into ammonia gas and lost to the atmosphere. After release, ammonia is redeposited as acid rain and nitrates, which are detrimental to natural ecosystems and combine with other chemicals in the atmosphere to form particulates that adversely affect human health. The ammonia produced by dairy farms in the Midwest is thought to be a major contributor to the N loading of the Mississippi river and the hypoxia zone in the Gulf of Mexico (Burkart and James, 1999).

It may be possible to reduce ammonia emissions from dairy barns by 20 to 30% by manipulating dietary protein and energy levels in cattle diets, selection of bedding, and other measures. The objective of this study was to measure seasonal differences in ammonia emissions from a tie-stall dairy barn using bedding types that displayed a range of urine absorbance and ammonia emission rates in a precursor, small-scale laboratory study (Misselbrook and Powell, 2005). An additional objective was to validate study results through mass N balances and comparison of collected data on feed intake, manure N excretion, and ammonia emission with published values of these parameters.

Table 1. Seasonal temperatures, relative humidity, and air flow in tie-stall chambers during ammonia measurement periods.

	Trial season†		
Parameter	**Winter**	**Summer**	**Fall**
Temperature (°C)			
Mean (SD)	5.3 (5.5)	26.1 (3.7)	10.1 (4.9)
Min. and max.	0.1 and 27.9	16.8 and 35.2	−5.0 and 20.8
Relative humidity (%)			
Mean (SD)	72.9 (10.8)	71.1 (14.0)	76.2 (12.9)
Min. and max.	38.8 and 95.8	31.0 and 98.2	36.2 and 100.0
Air flow (m^3 h^{-1})			
Mean (SD)	1108 (167)	1400 (286)	1285 (273)
Min. and max.	241 and 2420	722 and 3006	807 and 2430

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

Materials and Methods

Tie-Stall Air Emission Chambers

Four chambers (Fig. 1) to house four dairy cows each were constructed at the end of an existing stanchion barn equipped with a standard manure gutter cleaning system at the research facilities of USDA-Agricultural Research Service's U.S. Dairy Forage Research Center, Prairie du Sac, central Wisconsin (43°19′ N, 89°44′ W). Technical aspects of chamber design, operation, and calibration have been described by Powell et al. (2007). In brief, a 36.6 × 18.3 m area was divided to accommodate four chambers, each approximately 6.0 m wide × 9.1 m long × 2.9 m high and containing 165 m^3 of air space. Airflow through each chamber was controlled by an intake fan and kept within the range of approximately 2 to 18 air exchanges h^{-1} (Table 1), depending on ambient conditions and requirements to maintain cow comfort. Air velocity was measured using stainless steel Pitot tubes (Model 160, 0.305 m; Dwyer Instruments, Michigan City, IN) and a very low pressure differential sensor (Model 264, 0.249 mb; Setra, Boxburough, MA). Air flow rates (m^3 min^{-1}) were determined by multiplying air velocity by the surface area (0.0745 m^2) of the exhaust duct's opening. Air flow rates for each chamber were averaged over 2-min intervals, which corresponded to the measurement interval of ammonia concentrations in exhaust air, as described below.

As part of initial chamber calibrations (Powell et al., 2007), air movement tests using mineral oil foggers showed no visual air escape from any of the four chambers. Known amounts of ammonia were then released from cylinders into empty chambers (no cattle). Ammonia recovery (i.e., the percentage difference between captured and released ammonia) averaged 102% (range, 85–131%) with all four chambers having statistically similar rates of ammonia recovery.

Temperature and relative humidity were measured using a CS500-T Platinum Resistance Temperature detector and a Vaisala INTERCAP capacitive relative humidity sensor from Campbell Scientific (Logan, UT). Measurements were made at the center, approximately 4.6 m from the end of each exhaust duct.

Stainless steel cross-sectional (spider) samplers were constructed to sample air from chamber inlets and exhaust ducts. Air samples were drawn first through a dust filter then through the spider hub using Teflon tubing. All tubing was covered with standard polyethylene pipe insulation and heated with a self-regulated heat tape to prevent condensation from forming inside the sample lines. Ammonia concentrations in air samples were analyzed using an Air Sentry IonPro Mobility Spectrometer (Molecular Analytics, Boulder, CO), calibrated for 0 to 20 ppm ammonia, with an on-board calibration of 2 ppm ammonia (±0.1% detection limit).

A data logger was programmed using Loggernet software (Campbell Scientific, 2003). The data logger opened a solenoid valve thru a solid state relay for 1 min to allow air to flush the sampling line. Over each minute, the datalogger averaged temperature, relative humidity, differential pressure (air velocity for inlet and exhaust), and ammonia concentration.

Ambient chamber conditions during the three seasonal periods of the study are given in Table 1. Temperatures were highest during summer, followed by fall and winter. The relative

humidity in chambers was highest during fall, followed by winter and summer, which had similar relative humidity. Air flow provided 1.5 (lowest, winter trial) to 18.2 (highest, summer trial) air exchanges chamber^{-1} h^{-1}, with adjustments based on seasonal requirements to maintain cow comfort.

General Chamber Management

Three bedding trials were conducted during 2005: a winter trial from 25 February to 18 March 18, a summer trial from 21 July to 12 August, and a fall trial from 31 October to 22 November. Each day during each trial, from approximately 7:00 to 9:00 AM, chambers were cleaned, and heifers were fed. Unconsumed feed per heifer was collected, weighed, and sampled, and heifers were offered fresh feed as a total mixed ration (TMR) at a per-heifer rate of between 8 and 12 kg dry matter (DM), or approximately 10% in excess of previous consumption. All soiled bedding was removed, and manure was weighed and sampled as described below. At approximately 9:00 AM, chamber curtains were lowered, and curtain wall seams were sealed. From 10:00 AM to 3:00 PM, emission recordings were made. For the first 2 wk of the initial bedding study (winter), the curtains remained up from 3:00 PM to 7:00 AM the following morning. During the last 2 wk of the winter trial and during all weeks of the summer and fall trials, curtains were lowered at approximately 5:00 PM for nighttime emission measurements. The daily cycle of heifer feeding, chamber cleaning, and ammonia emission recordings was performed during four consecutive days, Tuesday through Friday, which was the measurement period for a replication for each experimental unit.

Bedding Treatments and Management

A 4×4 Latin Square statistical design was used to allocate four bedding types (manure solids, chopped newspaper, pine shavings, and chopped wheat straw) to each of the four chambers for the 4-d ammonia monitoring period (Tuesday through Friday) described previously, followed by reallocation of beddings to different chambers after 7 d until each bedding type was observed once in each chamber during the 28-d winter, summer, and fall trial periods. The amount of bedding used was based on visual estimates of the bedding mass required to achieve a surface area cover that mimicked conventional bedding practices on dairy farms having tie-stalls. Fresh bedding samples were taken daily, bulked by week, and subsampled to provide one sample per week (experimental replication).

Manure solids, and to a lesser extent chopped newspaper, had a great range in DM concentrations, which affected the wet mass used to achieve the desired floor cover (Table 2). Additional physical and chemical characteristics of the beddings are provided in Misselbrook and Powell (2005). The masses of pine shavings and chopped straw were fairly constant during the three trials. Concentrations of N were fairly uniform in manure solids. Concentrations of N in the other bedding types, especially newspaper, varied considerably. Bedding N variations had little impact on major study results. Bedding N comprised only a very small input in the calculations of chamber N-input and N-output balances.

Table 2. Characteristics of bedding used during the three seasonal ammonia emission trials.†

Bedding type	Bedding characteristic	Trial season‡ Winter	Summer	Fall
Manure solids	Wet mass (kg chamber^{-1} d^{-1})	44.1	38.0	21.9
	DM (g kg^{-1})§	249¶ (201–297)	577 (455–699)	727 (664–791)
	N (g kg^{-1})	25.4 (22.8–27.9)	28.8 (25.7–32.0)	26.6 (25.9–27.3)
Newspaper	Wet mass (kg chamber^{-1} d^{-1})	7.6	4.7	7.6
	DM (g kg^{-1})	932 (913–952)	956 (924–989)	900 (856–945)
	N (g kg^{-1})	0.65 (0.60–0.70)	3.34 (1.65–5.03)	2.10 (1.63–2.56)
Pine shavings	Wet mass (kg chamber^{-1} d^{-1})	10.7	10.5	10.5
	DM (g kg^{-1})	921 (916–927)	935 (928–942)	905 (857–945)
	N (g kg^{-1})	1.12 (1.02–1.23)	2.42 (1.79–3.05)	1.66 (1.16–2.16)
Chopped straw	Wet mass (kg chamber^{-1} d^{-1})	5.0	4.8	4.8
	DM (g kg^{-1})	904 (888–921)	895 (847–944)	885 (869–901)
	N (g kg^{-1})	8.1 (7.2–9.0)	10.4 (8.0–12.8)	4.2 (3.5–4.9)

† See Misselbrook and Powell (2005) for information on physical and other chemical properties of these beddings.
‡ All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.
§ DM, dry matter.
¶ Mean, 95% confidence interval in parentheses.

Heifer and Feed Characteristics

Dairy heifers approximately 17 mo of age having body weights between 370 and 620 kg heifer^{-1} were used during the three trials (Table 3). During the 28-d period of each trial, daily body weight gains of 0.5 to 2.8 kg heifer^{-1} were recorded. Concentrations of DM and N in the TMR offered to heifers were fairly uniform during the three trials. Average feed N intake (NI) by heifers ranged from 0.55 to 0.82 g kg^{-1} body weight, which is expected for growing Holstein heifers (Marini and Van Amburgh, 2003).

Manure Management and Sampling

To collect manure, pans were constructed of stainless steel and placed into a bracket that kept pans at a height that did not impede normal gutter function to clean the non-chamber part of the tie-stall barn. To facilitate urine collection, plastic urine deflectors were constructed to direct urine into manure pans. After each twice-daily manure collection and weighing, approximately 10 kg of the total manure per chamber was blended in a cutter mixer (Model R60; Robot Coupe, Ridgeland, MS), and a subsample was placed in 120-mL specimen cups and frozen until analysis.

Sample Analyses

Samples of feed offered, feed refused, and bedding were oven-dried (60°C, 72 h) and ground to pass a 2-mm screen. Ground feed and bedding subsamples were oven-dried (100°C, 24 h) for DM determination and analyzed for total N (TN) content by combustion assay (FP-2000 nitrogen analyzer; Leco, St. Josephs, IN). Manure samples were thawed, and subsamples were analyzed immediately for TN using a micro-Kjeldahl assay. Ammonium N was determined by distillation

Table 3. Heifer age, body weight (BW), average daily body weight gain (ADG), feed dry matter intake (DMI), feed N concentrations, and feed N intake (NI) during the three seasonal ammonia emission trials.

	Trial season†		
Parameters	Winter	Summer	Fall
Animal (n = 16 heifers season^{-1})			
Age (mo)	17.4‡ (16.9–17.9)	17.2 (17.0–17.5)	17.3 (16.3–18.2)
BW (kg heifer^{-1})	495 (469–522)	445 (428–463)	442 (427–457)
ADG (kg heifer^{-1} d^{-1})	1.2 (1.0–1.3)	1.8 (1.6–1.9)	1.6 (1.3–1.9)
Feed (n = 256 heifer days season^{-1})			
DM of feed offered (g kg^{-1})	471 (468–475)	496 (494–499)	528 (525–531)
N in feed offered (g kg^{-1} DM)	25.0 (24.6–25.3)	27.4 (27.1–27.8)	25.9 (25.7–26.1)
DMI (kg heifer^{-1} d^{-1})§	10.8 (10.6–11.0)	11.4 (11.2–11.6)	14.0 (13.7–14.3)
NI (g heifer^{-1} d^{-1})	270 (263–276)	313 (306–321)	364 (355–373)

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

‡ Mean, 95% confidence interval in parentheses.

§ DMI was calculated as the difference between feed DM offered and refused.

(Peters et al., 2003), and subsamples were oven-dried (100°C, 24 h) for DM determination. Manure pH was measured in a mixture containing 50 g wet manure mass and 50 g deionized water only on samples taken during the fall trial.

Data Validation

The reliability of chamber ammonia emission data was assessed by determining chamber N balances, or the difference between N inputs and N outputs for each chamber on a daily basis, and by comparing collected data on feed consumption, excreted N (feces plus urine), manure ammonium concentrations, overall ammonia emissions, and ammonia emissions as percentages of N inputs and output with published values.

Chamber nitrogen balances (CNB, %) were calculated as a percent difference between N inputs (feed and bedding) and outputs (manure, heifer live-weight gains, and ammonia) according to Eq. [1]:

$$\text{CNB} = [(\text{manure N} + \text{ammonia N} + \text{heifer N gain})/(\text{feed N} + \text{bedding N})] \times 100 \quad [1]$$

where manure N is manure DM (kg) multiplied by its respective manure N concentration, ammonia N is average hourly ammonia flux from the chamber multiplied by 24 h, heifer N gain is heifer mass (kg) before and after 2-wk weighing periods multiplied by body N concentration of 24.7 g kg^{-1} for growing Holstein dairy heifers consuming feed containing 25 g N kg^{-1} (Marini and Van Amburgh, 2003), feed N is the difference between feed N offered and refused, and bedding N is bedding DM mass (kg) multiplied by bedding N concentration (Table 2);

Excreted N (ExN, g chamber^{-1} d^{-1}) in feces and urine was calculated by subtracting bedding N input from the sum of manure N and emitted ammonia N according to Eq. [2]:

$$\text{ExN} = (\text{manure N scrapped from chamber} + \text{emitted ammonia N}) - \text{bedding N} \quad [2]$$

Total ammonical N (TAN, g chamber^{-1} d^{-1}) in manure was determined by multiplying manure DM by its ammonium N concentration.

Emitted ammonia N (g chamber^{-1} d^{-1}) was calculated as percent of NI, ExN, and TAN using Eq. [3], [4], and [5]:

$$\%\text{NI} = \frac{\text{emitted ammonia N}}{\text{NI}} \times 100 \quad [3]$$

$$\%\text{ExN} = \frac{\text{emitted ammonia N}}{\text{ExN}} \times 100 \quad [4]$$

$$\%\text{TAN} = \frac{\text{emitted ammonia N}}{\text{emitted ammonia N} + \text{TAN}} \times 100 \quad [5]$$

Urinary N excretion (UN) was calculated as a percent of ExN according to Eq. [6]:

$$\text{UN} = \frac{(\text{TAN} + \text{emitted ammonia N})}{\text{ExN}} \times 100 \quad [6]$$

This calculation assumed that most fecal N is nonvolatile (Haynes and Williams, 1993). This assumption meant that all manure ammonium N and emitted ammonia N was derived from UN.

Statistics

Statistical analyses were performed using the SAS statistical package (SAS Institute., 1990). Seasonal and bedding differences in response variables were analyzed by generalized least squares ANOVA assuming chamber and time periods to be a random effects and seasons, beddings, and season × bedding interactions to be fixed effects. Where relevant, the protected LSD test was used to determine significant differences among treatments at $P < 0.05$.

Results

Seasonal and Diurnal Ammonia Emissions

Few treatment interactions were observed, and those that occurred accounted for a small proportion of total sums of squares in the least squares ANOVA. Results are therefore presented as seasonal and bedding impacts on ammonia emissions and other response variables.

Ammonia N emissions (g heifer^{-1} d^{-1}) during summer and fall were similar and approximately twice the level of emissions recorded during winter (Table 4). Ammonia N emissions accounted for approximately 4 to 7% of consumed feed N, with the highest percentages calculated for summer, followed by fall and winter. On average, ammonia N emissions accounted for 4 to 10% of ExN and 9 to 20% of TAN. The pattern of these ammonia emission percentages followed the same seasonal pattern as calculated for NI.

During each of the three seasons, temperatures were cooler and relative humidity greater during night than day (Table 5). Cooler nighttime temperatures did not result in lower ammonia emissions. During summer and fall, ammonia emission rates were higher during night than day. The opposite was true during winter. Ammonia emissions during winter nights were less than during winter days.

Table 4. Seasonal ammonia emissions as percentage of feed N intake (NI), excreted manure N (ExN), and total ammonical N in manure (TAN).

	Trial season†		
Ammonia-N emission variable	Winter	Summer	Fall
g heifer^{-1} d^{-1}	10.1b‡	20.4a	21.0a
% NI	3.7c	6.5a	5.8b
% ExN	4.3c	9.4a	7.8b
% TAN	9.2c	19.4a	14.4b

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

‡ Within an ammonia-N emission variable, means followed by different letters differ significantly ($P < 0.05$).

Bedding Impacts on Ammonia Emissions

Ammonia emissions from chambers that contained manure solids, newspaper, or straw were similar and significantly ($P < 0.0001$) greater than emissions from chambers that contained pine shavings (Table 6). This same pattern of bedding impacts on ammonia emissions was observed for relative NI, ExN, and TAN losses as ammonia N. Chambers that contained manure solids, newspaper, and straw for bedding lost similar percentages of NI, ExN, and TAN as ammonia, which were greater than percent losses from chambers that contained pine shavings.

There were distinct seasonal and bedding impacts on manure chemical characteristics (Table 7). During winter, manure from chambers that used manure solids and straw as bedding had greater TN concentrations than manure from chambers that contained newspaper. Also during winter, manure from chambers that contained pine shavings had lower TN concentrations than manures containing the other three bedding types, and TAN concentrations were highest in manure that contained manure solids, newspaper, and straw. These patterns of manure TN concentrations observed during the winter trial were also observed during the summer and fall trials. During summer, manure TN from chambers that contained newspaper and straw were similar and greater than manure TN from chambers that contained pine shavings. During fall, manure from chambers that contained manure solids, newspaper, and straw had similar TN concentrations, which were greater than manure TN from chambers that contained pine shavings. Manure TAN concentrations during summer were highest in manures that contained straw and newspaper, and manure that contained manure solids generally had lower TAN than the three other bedding types.

After urea N has been transformed to ammonium by the urease enzyme, the disassociation of ammonium into the hydrogen ion and ammonia and the partitioning of ammonia into aqueous and gas phases are dependent on temperature and pH (e.g., Pinder et al., 2004; Rotz and Oenema, 2006). In the present study, ammonia emissions were affected by temperature (Table 5) but very little by pH. For all bedding types during fall, there was no significant ($P < 0.05$) relationship between the pH of manure scrapped from chambers and ammonia emissions (Fig. 2). There were significant relationships between the pH of manure scraped from chambers that used manure solids and straw as bedding types and ammonia emissions from chambers that contained these two bedding types. The reason for these different bedding impacts on manure pH and ammonia emissions is unclear. In a laboratory study that used the same bedding types as the present study, Misselbrook and Powell (2005) found no relationship between initial bedding pH and ammonia emissions after urine application to these beddings.

Table 5. Diurnal differences in temperature, relative humidity, and ammonia emissions from study chambers.

	Trial season†					
	Winter		Summer		Fall	
Variable	Day‡	Night	Day	Night	Day	Night
Temperature (°C)	6.3a§	4.9b	28.7a	24.6b	12.1a	8.9b
Relative humidity (%)	67b	76a	62b	77a	70b	80a
Ammonia-N (g chamber^{-1} h^{-1})	2.09a	1.56b	2.99b	3.81a	3.22b	3.50a

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

‡ Daytime measurements from approximately 10:00 am to 3:00 pm; nighttime measurements from approximately 5:00 pm to 6:00 am.

§ Within a trial season, means followed by different letters differ significantly ($P < 0.05$).

Discussion

The following discussion focuses on answering the question, "How good are this study's measurements of ammonia emissions from tie-stall barns?" To answer this, we evaluated how well we were able to account for chamber N inputs and chamber N outputs, how the ammonia emission data correspond to published values, and where and to what magnitude possible study errors occurred.

Chamber Nitrogen Balances

Chamber N balances (Table 8) provided a method to validate ammonia emission data. Feed accounted for 95 to 98% of chamber N inputs, and manure accounted for approximately 78 to 84% of N outputs. Approximately 14% of N outputs was retained in growing heifer bodyweight, and 4 to 6% was trapped as ammonia gas. During winter, all (105%) N inputs were accounted for in N outputs. Summer (90%) and fall (89%) chamber N balances were significantly lower than winter N balances.

Chamber N balances greater than 100% (winter trial, Table 8) indicate underestimates of feed N intake (NI) or overestimates of manure N excretion (ExN). Chamber N balances of less than 100% indicate overestimates of NI or underestimates of ExN. Large amounts of feed and manure mass were handled and sampled daily during each season's 28-d trial. Every morning, 40 to 85 kg of (wet) feed was delivered to each chamber,

Table 6. Bedding impacts on ammonia-N emissions as percentage of feed N intake (NI), excreted manure N (ExN), and total ammonical N in manure (TAN).

	Bedding type			
Ammonia-N emission variable	Manure solids	Newspaper	Pine shavings	Chopped straw
g heifer^{-1} d^{-1}	20.0a†	18.9a	15.2b	18.9a
% NI	6.4a	5.8a	4.7b	5.9a
% ExN	7.8a	8.5a	6.6b	8.7a
% TAN	16.0a	16.3a	13.0b	16.4a

† Within an ammonia-N emission variable, bedding row means followed by different letters differ significantly ($P < 0.05$).

Table 7. Impacts of bedding type on manure chemical characteristics during the three seasonal ammonia emission trials.

Manure characteristic	Bedding type	Trial season†		
		Winter	Summer	Fall
DM (g kg^{-1})	manure solids	173‡c§ (168–179)	191a (176–207)	187a (176–197)
	newspaper	190b (182–199)	173ab (154–193)	154b (146–163)
	pine shavings	212a (201–223)	185a (174–197)	187a (177–197)
	chopped straw	182bc (174–189)	164b (152–177)	167b (159–174)
Total-N (g kg^{-1})	manure solids	41.4a (39.4–43.4)	35.2bc (33.8–36.6)	44.3a (42.3–46.3)
	newspaper	35.9b (33.9–37.9)	37.6a (36.0–39.2)	44.7a (42.2–47.3)
	pine shavings	31.5c (29.4–33.6)	34.1c (32.1–36.0)	37.3b (35.3–39.3)
	chopped straw	39.5a (37.1–41.9)	36.8ab (35.1–38.6)	45.4a (41.6–49.2)
Ammonical-N (g kg^{-1})	manure solids	17.0ab (15.4–18.6)	13.0c (11.6–14.5)	18.0b (16.5–19.6)
	newspaper	18.0a (16.3–19.6)	15.3ab (13.6–17.0)	22.4a (20.6–24.3)
	pine shavings	15.2b (13.9–16.5)	14.1bc (13.1–15.1)	17.6b (16.2–19.0)
	chopped straw	18.4a (16.7–20.0)	16.1a (15.2–17.1)	21.6a (19.6–23.6)

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

‡ Mean, 95% confidence interval in parentheses.

§ Within a manure characteristic and trial season, bedding column means followed by different letters differ significantly ($P < 0.05$).

and 0 to 16 kg of (wet) feed refusals was removed from each chamber. The precise weighing of feed DM offered and refused and determination of N contained in feed offered and refused likely led to fairly precise estimates of feed DM intake and NI.

During summer and fall, inabilities to capture all excreted N were likely linked to two possible reasons: (i) ammonia N losses during manure handling, sampling, and analyses and (ii) incomplete urine collection. Each morning and evening, 40 to 90 kg of wet manure mass was removed from each chamber. To obtain a representative sample for DM and N analyses, the total wet manure mass was mixed manually, sampled, blended, subsampled, frozen, thawed, and analyzed. Ammonia-N losses during this process perhaps occurred but were likely slight. Manure removal, blending, and sampling were accomplished over approximately 90 min, and N analyses were done immediately after thawing samples, which were stored in tightly sealed plastic urine specimen cups.

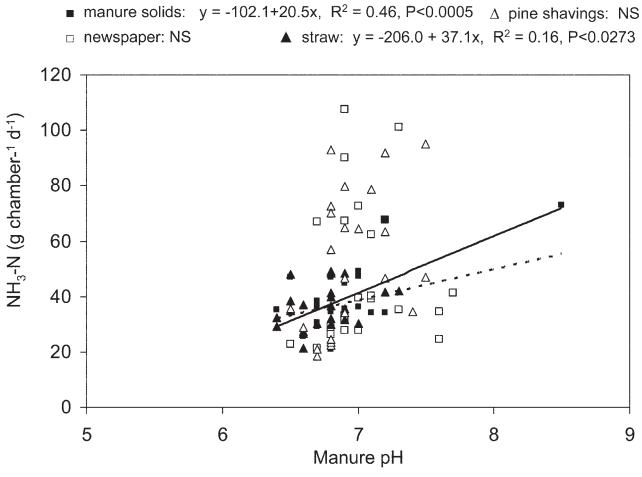

Fig. 2. Relationship between manure pH and ammonia emission from tie-stall chambers during the fall trial. Solid line indicates manure solids; dashed line indicates straw.

Urine losses were possible, and this may have been affected by bedding type. Average N balance in chambers that contained manure solids (104%) was significantly ($P < 0.05$) greater than N balances in chambers that used newspaper (90%), pine shavings (92%), and straw (90%) as bedding (data not shown). Misselbrook and Powell (2005) determined that the ability of beddings to separate feces and urine was the most important factor in ammonia emission rates from simulated tie-stall barn floors. In their study, manure solids absorbed 60% more urine than pine shavings, 48% more than straw, and 10% more than newspaper. It is perhaps for this reason that chambers bedded with manure solids had very close to perfect (100%) chamber N balances compared with the other bedding types. Also, manure from chambers that used manure solids for bedding was visibly much less bulky than manure from chambers that used newspaper, pine shavings, or straw. Oversampling the bulky, relatively low-N (Table 2) bedding component of manure would underestimate manure N and therefore reduce chamber N balances. It was perhaps for this reason that manure samples from chambers that contained the less bulky, relatively high TN manure solids (Table 2) as bedding provided more precise estimates of manure N and therefore had higher ($P < 0.05$) chamber N balances than chambers that used the other bulkier bedding types.

The amount of UN that theoretically could have been lost through drainage beneath manure pans can be calculated based on the amount of N (g chamber^{-1} d^{-1}) required to achieve 100% chamber N balance (Table 8). Concentrations of N in urine of Holstein dairy cows vary considerably (1–20 g L^{-1}; Bussink and Oenema, 1998). Assuming a UN concentration of 10 g N L^{-1} for the present study, the 129 and 163 g of N required to achieve

Table 8. Seasonal chamber N inputs, outputs, and balances during three seasonal ammonia emission trials.

Variable	Trial season†		
	Winter	Summer	Fall
	g chamber^{-1} d^{-1}		
Inputs			
Feed consumed	1043	1254	1455
Bedding	30	34	29
Outputs			
Manure removed	965	899	1082
Heifer live weight gain	118	178	158
Ammonia loss	40	82	81
	%		
Balance	105a‡	90b	89b

† All seasons during 2005. Winter: 25 Feb. to 18 Mar.; summer: 21 July to 12 Aug.; fall: 31 Oct. to 22 Nov.

‡ Balance row means followed by different letters differ significantly ($P < 0.05$).

chamber N balances of 100% during summer and fall (Table 8) would translate into UN losses of approximately 13 to 16 L chamber^{-1} or 3 to 4 L heifer^{-1} d^{-1}. This would comprise approximately one third of excreted urine, assuming that approximately one half of total excreted N was in the form of urine, as described below. Despite the apparent inability to collect all urine-affected chamber N balances, it would not have necessarily affected measured ammonia emissions.

Seasonal Ammonia Emissions

Urease is produced by microorganisms that are abundantly present in feces and therefore on barn floors (Ketelaars and Rap, 1994). Muck and Steenhuis (1981) observed occasional 0.5- to 1.0-h lags in urease activity and ammonia emissions from urine deposited on dairy barn floors. In the present study, the data did not display any discernable lags in ammonia emissions during the initial part of 6-h daytime measurement period or during the initial part of the 12-h nighttime measurement period. After chamber walls were lowered, we provided a 15- to 20-min stabilization period for the ammonia analyzer. After this period, all ammonia emission recordings were used to determine seasonal (Table 4), diurnal (Table 5), and bedding (Table 6) impacts on ammonia emissions.

Urease activity is low between 5 and 10°C and increases exponentially above 10°C (Braam et al., 1997). In the present study, ammonia emissions during cold (5°C) winter were approximately 50% of the emissions recorded during warm (26°C) summer (Tables 4 and 5). Smits et al. (1995) determined that 46% less ammonia was emitted from free-stall dairy barns in the UK during winter (10°C) than summer (24°C). In The Netherlands, Kroodsma et al. (1993) determined that ammonia emissions from a free-stall barn during winter (11.8°C) were only 18% less than during summer (18.2°C). Pedersen (2006) determined exponential increases in ammonia emissions from nine free-stall dairy barns in Denmark within the temperature range of approximately 2 to 22°C.

A somewhat surprising result was the statistically similar ammonia emissions during summer and fall, even though chamber temperatures during summer were on average twice as high as during fall. Seasonal differences in relative humidity and NI were likely the main reasons for this result. The higher ($P < 0.05$) relative humidity in chambers during fall than summer (Tables 1 and 5) perhaps created a greater sink for aqueous ammonia, which created higher ammonia emissions at lower temperatures during fall when compared with summer emissions.

Another reason for the unexpected relatively high ammonia emissions during fall may have been associated with the relatively high levels of NI during this trial. Although heifers were approximately the same size during summer and fall, NI was much greater during fall than summer, and this seems to have affected ammonia emission. A significant positive relationship between NI and ammonia emissions was determined for the fall trial (Fig. 3) but not for the winter or summer trials. Feed N consumption in excess of animal requirements is excreted in urine (Castillo et al., 2000; Broderick, 2003; Wattiaux and Karg 2004), which increases ammonia emissions from dairy barn floors (Misselbrook et al., 2005).

The positive relationship between IN and ammonia emissions during fall (Fig. 3) implies that NI is perhaps three times more

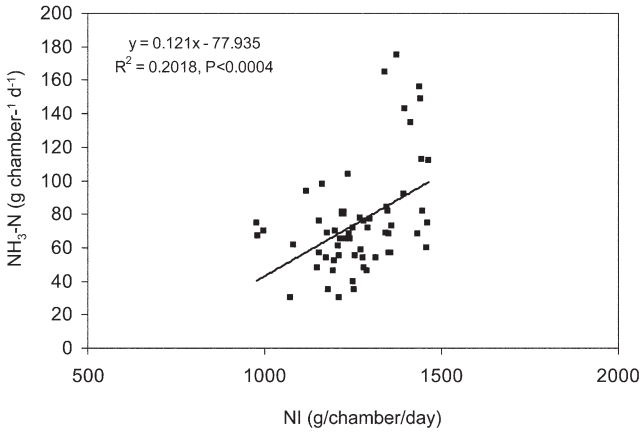

Fig. 3. Relationship between feed-N intake and ammonia emissions during the fall ammonia emission trial.

important than bedding in regulating ammonia emissions from tie-stall dairy barns. Whereas the maximum difference in ammonia emission rates (g heifer^{-1} d^{-1}) due to bedding (Table 6) was approximately 5, the maximum difference in ammonia emissions due to NI was 15 (i.e., range of approximately 60 g chamber^{-1} d delineated by regression line in Fig. 3 divided by four heifers chamber^{-1}). The cluster of high ammonia emissions at high NI (i.e., data points well above the regression line in Fig. 3) further indicate that NI in excess of animal requirement is excreted in urine, which elevates ammonia emissions (Misselbrook et al., 2005).

The ammonia emissions measured during the present study corresponded well to other tie-stall studies (Fig. 4). Ammonia emissions from tie-stall dairy barns are usually much lower than those from free-stall barns due to several reasons. The beddings typically used in tie stalls separate urine and feces, which reduces ammonia production and loss (Misselbrook and Powell, 2005).

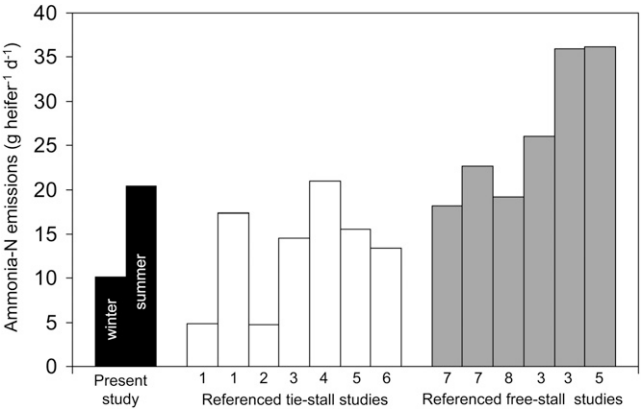

Fig. 4. Ammonia emission rates (g heifer^{-1} d^{-1}). Present study compared with published studies. Footnoted references: (1) Compiled from literature review of Monteny and Erisman (1998), dairy cow type not provided. (2) Measured from cement barn floor and reported for 450 kg dairy cow by Amon et al. (2001). (3) Manure (including straw) and reported for 500 kg dairy cow by Demmers et al., 1998. (4) Compiled from literature review by Anderson et al.(2003) and reported as kg cow^{-1} yr^{-1}. (5) Simulations by Rotz and Oenema, 2006 and revised by Rotz (personnal communication, 22 Jan. 2007). (6) Hourly emissions reported by Pedersen (2006) scaled to daily emissions. (7) Simulations by Pinder et al. (2004). (8) Monthly emissions reported Hutchings et al. (2001) scaled to daily emissions.

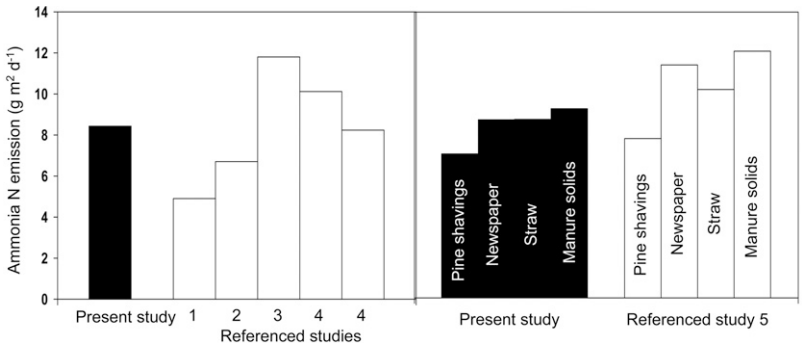

Fig. 5. Ammonia emission rates from barn floors (g m^2 d^{-1}): present study compared with published studies. Footnoted references: (1) Measured from concrete barnyards by Misselbrook et al. (1998). (2) Measured from concrete outside feed areas by Misselbrook et al. (2001). (3) Hourly measurements reported by Kroodsma et al. (1993) scaled to daily emissions. (4) Simulated hourly measurements by Swensson (2003) scaled to daily emissions. (5) Laboratory measurements of simulated barn floors by Misselbrook and Powell (2005).

Also, whereas relatively narrow gutter scrapers remove manure from tie-stall barns usually once daily, wide alley scrappers constantly mix urine and feces and remove manure from free-stall barns. This results in large differences in emitting surface area of tie-stall and free-stall barn floors. In The Netherlands, Monteny and Erisman (1998) concluded that 35% less ammonia emitted from cows in tie-stalls than in free-stalls was due to a reduction in barn floor area covered by feces and urine. In Denmark, the emission factor (5% of excreted N) for tie-stalls is one half the emission factor (10%) for free stalls (Pedersen, 2006).

The average ammonia emission rate (8.45 g m^2 d^{-1}) from the present study (Fig. 5) based on the chamber floor surface area corresponded well with the average (8.35 g d^{-1}) of two studies in the UK (Misselbrook et al., 1998 and 2001) measuring emissions from outdoor concrete yards used by livestock and single studies in The Netherlands (Kroodsma et al., 1993) and Sweden (Swensson, 2003). In a laboratory study that used the same bedding types as the present study, Misselbrook and Powell (2005) determined a similar pattern of bedding impacts on ammonia emission rates (Fig. 5). Higher ammonia emissions determined by the former study (Misselbrook and Powell, 2005) were likely due to the 48-h measurement period, although most emissions were recorded during the first 24 h, the period used to calculate ammonia emission rates from barn floors in the present chamber study. Differences in temperature and air flow rates would also contribute to overall differences in ammonia emissions estimated by the laboratory and present study.

In the present study, ammonia N emissions accounted for 4.3 to 9.4% of ExN (Tables 4 and 6). These emission rates corresponded well to a general ammonia N loss from tie-stall of 8% of ExN based on a literature review (Rotz, 2004) and measured ammonia losses of 5.6 and 7.5% of ExN in The Netherlands and Pennsylvania, respectively (Rotz and Oenema, 2006). In Denmark, Pedersen (2006) reported that 5% of ExN was lost from tie-stall barn floors. In the UK, Webb and Misselbrook (2004) used a mass flow model to estimate ammonia N emissions of 3.5 and 12.5% of ExN for dairy calves and gown cattle, respectively. In the present study, ammonia N emissions accounted for between 9 and 19% of TAN (Tables 4 and 6). This range corresponded well to 6 and 21% of TAN emitted by calves and grown dairy cattle determined by Webb and Misselbrook (2004) in the UK.

Manure Nitrogen Excretion

Estimates of ExN were made by subtracting bedding N inputs from the sum of manure N and emitted ammonia-N outputs (Table 8). Average ExN (238 g heifer^{-1} d^{-1}) for heifers in the present study (Fig. 6) was considerably higher than average ExN estimates of 187 g heifer^{-1} d^{-1} from literature based on heifer body weights (Rotz, 2004; Wilkerson et al., 1997) or DM intake and NI (Nennich et al., 2005). In the present study, the relatively high chamber N balances (Table 8) indicated fairly accurate information on NI and ExN for dairy heifers of approximately 17 mo of age weighing 427 to 522 kg (Table 3).

In the present study, seasonal estimates of UN excretions (g heifer^{-1} d^{-1}) were calculated by adding manure ammonium-N with emitted ammonia N, and percent UN was determined (Eq. [3]). Average estimates (53%) of percent UN of ExN determined by the present study were the same as average estimates (53%) from the literature (Fig. 6), even though UN excretion by dairy cattle is known to vary widely (Nennich et al., 2006).

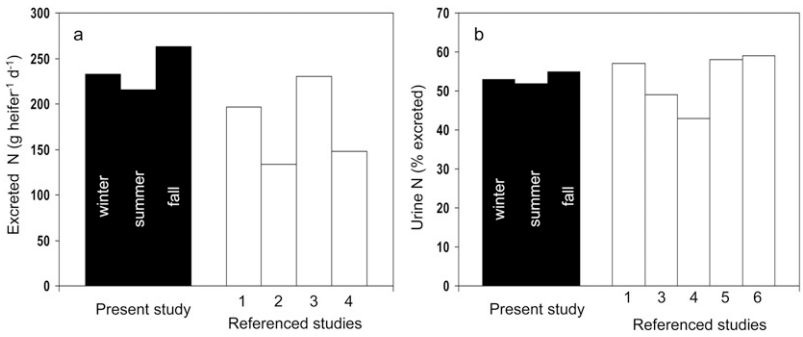

Fig. 6. Comparisons of excreted N (a) and percent urine N (b) from the present study with calculated values for dairy heifers from referenced studies (1) Wilkerson et al. (1997), (2) Rotz (2004), (3) Nennich et al. (2005), (4) Kebreab et al. (2002), (5) Marini and Van Amburgh (2003), and (6) James et al. (1999).

Conclusions

Season and bedding affected ammonia emissions from the chamber tie-stalls. Emission rates during summer and fall were statistically similar and about twice the emission rates measured during winter. Spring measurements are needed to evaluate other possible seasonal impacts on ammonia emission from tie-stall dairy barns. Ammonia emissions from manure solids, newspaper, and wheat straw were similar and consistently greater than emissions from pine shavings. As observed in the laboratory study (Misselbrook and Powell, 2005) that preceded the present study, bedding

types that physically separate feces and urine (e.g., sand, pine shavings) have lower ammonia emissions than bedding that fail to do so. The correspondence between the laboratory and chamber studies results (Fig. 4) indicates that the small-scale laboratory methods may provide a good tool for screening treatments before testing on a larger scale in emission chambers.

Results from these large-scale chamber studies seem to provide accurate information on seasonal differences and bedding impacts on ammonia emissions from tie-stall barns. Confidence in study results were derived from (i) the relatively high chamber N balances or the ability to account for most all feed and bedding N inputs in manure N, ammonia N, and animal N outputs; (ii) the generally favorable comparisons between study results and published values of ammonia emissions; and (iii) between-study estimates and published values of excreted N and UN.

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