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Seasonal Diet Affects Ammonia Emissions from Tie-Stall Dairy Barns

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ABSTRACT

Federal and state regulations are being promulgated under the Clean Air Act to reduce hazardous air emissions from livestock operations. Although much is known about air emissions from livestock operations in Europe, few data are available on emissions from livestock facilities in the United States and the management practices that may minimize these emissions. The objective of this study was to measure seasonal and diet effects on ammonia emissions from experimental tie-stall dairy barns located in central Wisconsin. Four experimental chambers each housed 4 lactating Holstein dairy cows for three 28-d trial periods corresponding to spring, early fall, and winter. A 4 × 4 Latin square statistical design was used to evaluate 4 diets [corn silage (CS)- or alfalfa silage (AS)-based diets at low or high crude protein] in each chamber for a 4-d ammonia monitoring period. Partially due to higher crude protein levels, average ammonia-N emissions during spring (18.8 g/cow per d) were approximately twice the emissions recorded during early fall (8.4 g/cow per d) and 3 times greater than emissions during winter (6.7 g/cow per d). Ammonia-N emissions accounted for approximately 1 to 3% of consumed feed N, 2 to 5% of excreted manure N, and 4 to 11% of manure ammonical N. Nighttime ammonia emissions were on average 30% lower than daytime emissions. Forage type did not affect ammonia emissions during winter or early fall. Only during early spring were ammonia emissions lower from chambers containing cows fed low-CP diets than from cows fed high-CP diets. Of the total chamber N inputs (feed and bedding), 93, 91, and 95% were recovered in N outputs (milk, manure, body weight change, and ammonia N) during spring, early fall, and winter trials, respectively. Confidence in the accuracy of ammonia emission results was gained by the relatively high chamber N balances and favorable comparisons of study data with published relationships among the variables of feed N intake, milk urea N, manure N, and urine N excretion, and ammonia emissions.
Key words: diet, ammonia emission, manure, tie-stall

INTRODUCTION

Research, extension, the feed industry, and veterinarians have long advocated dairy cow diets that maximize milk production while assuring good animal health and reproduction. Under practical conditions, only 20 to 30% of the nitrogen (CP) fed to a dairy cow is converted into milk protein (Jonker et al., 2002; 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 al., 2000; Broderick, 2003). As much as three-fourths 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 ammonia, which is in equilibrium with ammonium. Depending on pH, ammonium is transformed into ammonia gas and lost to the atmosphere. Loss of N as ammonia is thought to range from 20 to 55% of manure N excretions (MWPS, 2001). The main factors that affect ammonia N loss are housing and manure-handling strategies, diets, bedding type, barn ventilation, and temperature.

After release, ammonia combines with other chemicals in the atmosphere to form fine particulates that can adversely affect human health. Ammonia is redeposited as ammonium containing dust particles, and as acid rain and nitrates, which can be detrimental to natural ecosystems. Excessive nutrients in lakes and streams accelerate eutrophication and impair water quality. The ammonia produced by dairy farms in the Midwest may be a main contributor to the N loading of the Mississippi river and the hypoxia zone in the Gulf of Mexico (Burkhart and James, 1999).

Over the past 15 yr, environmental concerns related to animal agriculture have focused on improvements in manure management to mitigate runoff and pollution of lakes, streams, and other surface waters (Moody and Burns, 2006). Air quality legislation targeted at animal agriculture is now being promulgated by the US Environmental Protection Agency. The Comprehensive En-

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vironmental Response, Compensation and Liability Act (**CERCLA**) enacted in 1980 aims to control the release of hazardous substances that might endanger public health. The Clean Air Act amendments of 1990 required the Environmental Protection Agency to establish National Ambient Air Quality Standards for pollutants considered harmful to human health. Of principal concern are fine particles in the atmosphere, referred to as PM 2.5, or particles less than 2.5 μm in diameter. Ammonia is a major precursor for fine particulates (NRC, 2003). The CERCLA requires the reporting of the release of a hazardous substance in excess of threshold levels (e.g., 45.5 kg of ammonia over a 24-h period). Although CERCLA is focused on emissions of hazardous wastes from industrial plants, the increased size and geographic consolidation of animal feeding operations make their ammonia emissions subject to the notification provisions (Aillery et al., 2006a,b).

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 United States and how management practices can be altered to minimize these emissions. A report by the National Academy of Sciences (NRC, 2003) made an urgent call for processed-based research that could assist producers and regulatory agencies in developing strategies to abate harmful air emissions from livestock farms.

Tie-stall barns are the most common housing type on dairy farms with small to medium herds, mostly in the Midwest and Northeast regions of the United States (USDA, 2004). On these farms, cows are confined to stalls, and manure is collected in a gutter behind the cows. The objective of this study was to measure seasonal differences in ammonia emissions from a tie-stall dairy barn containing lactating dairy cows fed different forage types and CP levels. These CP levels displayed a range of ammonia emission rates in a preliminary laboratory study (Misselbrook et al., 2005). An additional objective was to validate these results through mass N balances and by comparing data collected on manure N and urine N excretions, MUN concentrations, and ammonia emission with published values of these parameters.

MATERIALS AND METHODS

Tie-Stall Air Emission Chambers

Four chambers (Figure 1) to house 4 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 US Dairy Forage Research Center (Prairie du Sac, Wisconsin; 43°19′ N, 89°44′ W). Technical aspects of chamber design, operation, and calibration have been described by Powell et al. (2007), and the chambers have been used to evaluate seasonal bedding effects on ammonia emissions (Powell et al., accepted). In brief, a 36.6 m × 18.3 m area was divided to accommodate the 4 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 maintained within a range of approximately 1.5 to 33 air exchanges/h (Table 1), depending on ambient conditions and associated needs to maintain cow comfort. Airflow rates, temperature, and relative humidity for each chamber were averaged over 2-min intervals, which corresponded to the measurement interval of ammonia concentrations in exhaust air, as described below. Temperature and relative humidity were measured using a CS500-T Platinum Resistance Temperature detector and a Vaisala INTERCAP capacitive relative humidity sensor (Campbell Scientific, Logan, UT). Measurements were made approximately at the center, 4.6 m from the end of each exhaust duct. Temperatures were greatest during early fall, followed by spring and winter (Table 1). The relative humidity in chambers was greatest during winter, followed by fall and spring.

Stainless steel cross-sectional (spider) samplers were constructed to sample air from chamber inlets and exhaust ducts. Air samples were drawn through the spider hub using Teflon tubing. All tubing was covered with standard polyethylene pipe insulation and heated with self-regulated heat tape to prevent condensation from forming inside the sample lines. Ammonia concentrations in air samples were analyzed by ion mobility spectroscopy using an Air Sentry IonPro Mobility Spectrometer (Molecular Analytics, Boulder, CO) calibrated for 0 to 20 ppm of ammonia, with an onboard calibration of 2 ppm ammonia (±0.1% detection limit). Ion mobility spectroscopy has been used widely to measure ammonia from livestock buildings, manure, and anhydrous ammonia applications to crop lands, flux measurements, and other agricultural situations (Pfeiffer, 2002).

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

General Chamber Management

Three dietary trials were conducted: a spring trial from April 11 to May 27, 2005; an early fall trial from

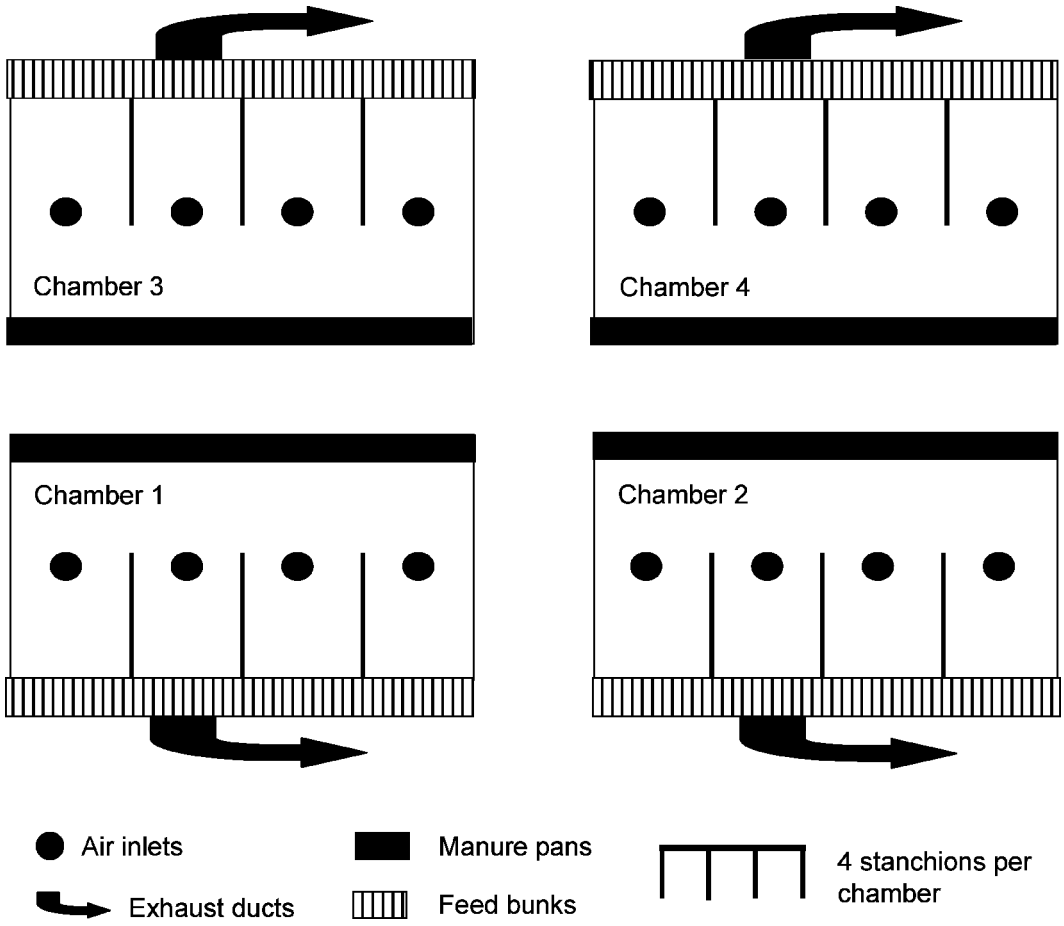

Figure 1. Configuration of tie-stall ammonia emission chambers (Powell et al., 2007).

August 29 to October 14, 2005; and a winter trial from January 2 to February 17, 2006. During each trial day, cows were milked, fed, and chambers were cleaned from approximately 0600 to 0900 h. Unconsumed feed per cow was collected, weighed, and sampled, and cows were offered fresh feed as a TMR at a per-cow rate of between 25 to 30 kg of DM, at approximately 10% in excess of the previous day's consumption. Cows were bedded on rubber mats with pine shavings used as bedding (approximately 2.5 kg of dry weight/cow per d). At approximately 0900 h, chamber curtains were lowered and curtain wall seams were sealed; emission re-

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

	Trial season[1]		
Parameter	Spring	Early fall	Winter
Temperature (°C)			
Mean (SD)	17.5 (4.8)	21.4 (4.9)	8.7 (2.4)
Minimum and maximum	7.2 and 27.9	10.9 and 35.5	–5.1 and 17.2
Relative humidity (%)			
Mean (SD)	59.7 (12.7)	66.8 (12.3)	80.2 (7.6)
Minimum and maximum	27.6 and 91.7	23.4 and 92.6	51.2 and 100.0
Airflow (m^3/h)			
Mean (SD)	3,240 (1,260)	1,423 (276)	1,168 (122)
Minimum and maximum	249 and 5,390	320 and 2,388	885 and 1,785

[1]Spring: April 11 to May 27, 2005; early fall: Aug. 29 to Oct. 14, 2005; winter: Jan. 2 to Feb. 17, 2006.

Table 2. Composition of diets fed to lactating cows during ammonia emission trials

	Spring				Early fall and winter			
	Alfalfa silage				Alfalfa silage		Corn silage	
Diet ingredient	CP1	CP2	CP3	CP4	Low CP	High CP	Low CP	High CP
	% of total DM offered							
Alfalfa silage	37.3	37.3	37.3	37.3	37.3	37.3	18.7	18.7
Corn silage	18.7	18.7	18.7	18.7	18.7	18.7	37.3	37.3
Rolled high-moisture corn	33.8	29.0	26.8	21.9	35.4	31.0	28.6	24.3
Solvent-extracted soybean meal	5.0	9.8	12.0	16.0	3.4	7.8	10.1	14.4
Premix[1]	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
	Total diet							
DM (%)	49.6	50.0	50.2	50.4	52.2	52.6	51.6	51.6
CP (%)	17.0	18.6	19.1	21.2	16.1	17.3	15.7	17.2

[1]Premix contained (% of DM) roasted soybeans (77.2), sodium bicarbonate (9.7), salt (5.8), dicalcium phosphate (3.9), and vitamin-trace mineral mix (3.5).

cordings were made from 1000 to 1500 h. Cows were milked from 1500 to 1700 h, curtains were lowered again at approximately 1800 h, and nighttime emission measurements were made from approximately 1900 until 0500 h the next morning. The daily cycle of cow feeding, chamber cleaning, and ammonia emission recordings was repeated during 4 consecutive days, Tuesday through Friday, this being the measurement period of a replication for each experimental unit.

Diet Treatments and Management

A 4 × 4 Latin square statistical design was used to allocate 4 diets to each of the 4 chambers for the 4-d ammonia monitoring period described above. The intended diets consisted of a 2 × 2 factorial arrangement of 2 forage mixtures: a 66%:34% alfalfa silage:corn silage DM ratio (**AS**) or a 66%:34% corn silage:alfalfa silage DM ratio (**CS**), and 2 CP levels: 16.5% (**LP**) or 18.5% (**HP**; Table 2). After each 4-d ammonia monitoring period, diets were reallocated to chambers and cows were allowed to adapt to the new diets for 10 d before the next ammonia monitoring period began.

The DM and N concentrations in diet components and TMR are given in Table 2. The intent at the study's onset was to observe the same 2 forages (AS and CS) fed at either CP level (LP or HP) during each seasonal trial. During the first part of the spring trial, however, a feed formulation error was made and only AS was fed. It was decided to maintain AS as the sole forage treatment throughout the spring trial, which created a dietary CP concentration range of 17.0 to 21.2% (Table 2). Actual dietary CP levels were between 15.7 and 17.3% during the early fall and winter trials when either AS or CS was fed.

Dairy Cow Selection and Milking

Cows were selected based on lactation number and DIM, with the goal of having 4 cows per chamber (i.e., 16 cows per trial) that resembled the profile of a lactating cow herd on a typical dairy farm. In general, each chamber contained 1 cow in first, 1 cow in second, and 2 cows in third lactation; at the onset of each seasonal trial the cows were from 70 to 365 DIM (Table 3). Cows were weighed at the beginning, middle, and end of each trial to estimate the amount of N in BW gain as a component of the chamber N balance calculations described later.

Cows were milked each a.m. and p.m. between approximately 0600 and 0800 h and between 1500 and 1700 h. On each Thursday, a.m. and p.m. milk samples were collected from each cow, preserved with bronopol (2-bromo-2-nitropropane-1,3-diol, D&F Control Systems, Dublin, CA), and analyzed for MUN (AgSource, Verona, WI) by infrared methods using a MilkoScan FT6000 (Foss North America, Eden Prairie, MN) using AOAC (1990) method 972.16, and for total N on a VarioMax elemental analyzer (Hanau, Germany). To evaluate possible relationships between Thursday's ammonia emissions from each chamber and MUN (van Duinkerken et al., 2005), chamber-weighted MUN values were calculated as the sum of the cows' fractional MUN outputs, which was computed by multiplying each cow's fractional chamber milk production by its associated MUN value.

Manure Management and Sampling

To collect manure, pans were constructed of stainless steel (1.23 m long × 0.38 m wide × 0.076 m deep, with a 0.025-m lip that was flush with back of manure gutter) and placed into a bracket to keep pans high enough so

Table 3. Body weight, lactation number, and DIM of dairy cattle at the beginning of each seasonal ammonia emission trial

	Trial season[1]		
Cow parameter	Spring	Early fall	Winter
Mean BW (kg)			
Mean	651	631	667
Minimum and maximum	511 and 796	553 and 759	516 and 780
Lactation number			
Mean	2.40	2.50	2.35
Minimum and maximum	1 and 4.5	1 and 5	1 and 4.5
Day is milk			
Mean	165	170	158
Minimum and maximum	70 and 310	72 and 319	71 and 365

[1]Spring: April 11 to May 27, 2005; early fall: Aug. 29 to Oct. 14, 2005; winter: Jan. 2 to Feb. 17, 2006.

that the manure scraper could function normally to clean the nonchamber part of the barn. To facilitate urine collection, plastic urine deflectors were constructed to direct urine into manure pans. Pans were scraped clean and manure was weighed during each milking period. After each manure collection, approximately 10 kg of the total manure mass 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 stored frozen (–20°C) until analyzed.

Feed, Bedding, and Manure 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 content by combustion assay (FP-2000 nitrogen analyzer, Leco, St. Joseph, MI). Manure samples were thawed and subsamples were analyzed immediately for total N using a micro-Kjeldahl assay, ammonium N by distillation (Peters et al., 2003), and oven-dried (100°C, 24 h) for DM determination.

Data Validation

The reliability of chamber ammonia emission data was assessed by determining chamber N balances (the difference between N inputs and N outputs for each chamber) daily, and by comparing data collected on 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 N Balances. Chamber N balances (**CNB**, %) were the percentage differences between N inputs (feed and bedding) and outputs (milk, manure, ammonia N emission, and cow BW gain) calculated as follows:

$$\text{CNB} = [(\text{milk N} + \text{manure N} + \text{ammonia-N emission} + \text{cow N gain}) \div (\text{feed N} + \text{bedding N})] \times 100. \quad [1]$$

In this equation, milk N was milk volume multiplied by its N concentration; manure N was manure DM (kg) multiplied by its N concentration; ammonia-N emissions were derived by multiplying by 24 the average hourly daytime and nighttime ammonia flux from each chamber assuming 12-h lengths for each period; cow N gain was the difference between cow mass (kg) before and after each trial multiplied by body N concentration of 24.7 g/kg (Marini and Van Amburgh, 2003); feed N was the difference between feed N offered and refused; and bedding N was bedding DM mass (kg) multiplied by its N concentration.

Excreted N. Excreted N (**ExN**, g/chamber per d) in feces and urine was calculated by subtracting bedding N input from the sum of manure N and emitted ammonia N as follows:

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

Total Ammonium N. Total ammonium N (**TAN**, g/chamber per d) in manure was determined by multiplying manure DM (kg) by its ammonium N concentration as removed from each chamber.

Emitted Ammonia N. Emitted ammonia N (g/chamber per d) was calculated as percentage of nitrogen intake (**NI**), ExN, and TAN as follows:

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

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

$$\%\text{TAN} = [\text{emitted ammonia N}/(\text{emitted ammonia N} + \text{TAN})] \times 100. \quad [5]$$

Urinary N Excretion. Urinary N (**UN**, g/chamber per d) was calculated as the sum of TAN and emitted ammonia N. This calculation assumed that fecal N was not volatilized during this short period (Haynes and Williams, 1993), which implied that all TAN and emitted ammonia N was derived from UN.

Statistical Analysis

Statistical analyses of the 4 × 4 Latin square were performed using the SAS statistical package (SAS Institute, 1990). Seasonal (early fall and winter) and diet differences in response variables were analyzed by generalized least-squares ANOVA, assuming chamber and time periods to be random effects, and seasons, diets, and season × diet interactions to be fixed effects. Where relevant, the protected least significant difference (LSD) test was used to determine significant differences among treatments at $P < 0.05$.

RESULTS

Seasonal Diet Effects on Milk Production, ExN, and UN

Very few treatment interactions were observed, and those that occurred accounted for only a small proportion of total sums of squares in the least-squares ANOVA (data not shown). Results are therefore presented as seasonal forage type and CP level effects on ammonia emissions and other response variables.

Seasonal differences in feed DMI, NI, milk production, feed N use efficiencies (**FNUE**), ExN, UN, and ammonia N emissions are given in Table 4. Average NI values were greatest and FNUE lowest during the spring trial, when only AS, and therefore the greatest levels of dietary CP, was fed (Table 2). During both early fall and winter, FNUE by cows fed the LP (32.9%) diets were greater ($P < 0.05$) than those of cows fed the HP (29.9%) diets. There were no significant differences in FNUE by cows fed diets based on AS or CS during either the early fall or winter trials.

In-depth results and discussion of impacts of AS:CS ratios and dietary CP level differences on milk production, composition, and so on can be gleaned from previous nutrition trials conducted in Wisconsin (Dhiman and Satter, 1997; Moreira et al., 1999; Wattiaux and Karg, 2004; Brito and Broderick, 2006). Some general conclusions can be drawn, however, about the effect of the present study's diets on milk production. During the early fall and winter trials, there were no significant differences in milk production by cows fed a low CP (38.4 kg/cow per d) or high CP (37.4 kg/cow per d) diet, or by cows fed the AS (37.6 kg/cow per d) or CS (38.1 kg/cow per d) diets. During the spring trial, average milk production (39.4 kg/cow per d) by cows fed the greatest CP level was greater ($P < 0.05$) than milk production (37.5 kg/cow per d) by cows fed lower CP levels.

As reported by Nennich et al. (2005), ExN in the present study was closely related to NI (Table 2). Manure N excretions (ExN) were greatest during spring (420 g/cow per d) when only AS (and therefore the highest levels of dietary CP) was fed. During both early fall and winter, there was significantly less ExN (318 g/cow per d) by cows fed LP diets than by cows fed HP diets (354 g/cow per d). Also during early fall and winter, ExN was the same from cows fed AS or CS (336 g/cow per d).

Seasonal Diet and Diurnal Effects on Ammonia Emissions

Greatest ammonia emissions were recorded during spring (18.8 g/cow per d). As mentioned previously, only AS was fed during the spring trial. Forage-type effects on ammonia emissions could be evaluated, therefore, only during early fall and winter. During both seasons, forage type did not significantly impact ammonia emissions, and only during the early fall trial did dietary CP level affect ammonia emissions. During the early fall, ammonia emissions from chambers containing cows fed the LP diet (8.0 g/cow per d) were significantly ($P < 0.05$) less than from cows fed the HP diet (8.8 g/cow per d). Frank and Swensson (2002) also found that ammonia emissions from cows fed a low CP (13.1 to 13.5%) diet were significantly less than emissions from cows fed a high CP (17%) diet.

Ammonia-N emissions accounted for approximately 1 to 3% of NI, with the greatest percentages occurring during spring (Table 4). On average, ammonia-N emissions accounted for 2 to 5% of ExN, and 4 to 11% of either UN or TAN.

During each of the 3 seasons, temperatures were lower and relative humidity greater during night than day (Table 5). Cooler nighttime temperatures resulted in lower nighttime ammonia emissions during each of the 3 study seasons. Ammonia emissions during the night were approximately 10 to 20% less than during the day.

DISCUSSION

The following discussion focuses on answering the question "how good are the present study's measurements of ammonia emissions from tie-stall barns?" To answer this question, we evaluated how well we were able to account for chamber N inputs and chamber N outputs, how well ExN, UN, ammonia emissions, and concentrations of MUN corresponded to published val-

Table 4. Alfalfa silage (AS), corn silage (CS), and dietary CP level effects on DMI, N intake (NI), milk production, feed N use efficiency (FNUE), manure N excretion (ExN), urine N (UN) excretion, and ammonia loss from lactating dairy cows in tie-stall chambers

	Trial season[1]														
	Spring					Early fall					Winter				
Diet ingredient[2]	Mean				SE	Mean				SE	Mean				SE
AS, % of DM	37.3	37.3	37.3	37.3		37.3	37.3	18.7	18.7		37.3	37.3	18.7	18.7	
CS, % of DM	18.7	18.7	18.7	18.7		18.7	18.7	37.3	37.3		18.7	18.7	37.3	37.3	
CP, %	17.0	18.6	19.1	21.5		16.1	17.3	15.7	17.2		16.1	17.3	15.7	17.2	
Intake															
DMI, kg/cow per d	23.8	23.8	22.9	24.1	0.40	22.2	22.7	22.1	22.3	0.53	21.0	20.4	24.5	23.7	0.68
NI, g/cow per d	651	712	704	825	21.9	575	619	574	620	25.3	553	564	634	648	25.8
Milk secretion															
Milk, kg/cow per d	38.2	38.3	36.0	39.4	0.56	38.6	38.3	38.6	37.5	0.56	37.3	36.4	39.0	37.5	0.86
FNUE, %	30.2	25.9	25.9	23.8	1.21	32.2	30.7	32.0	29.2	1.10	33.8	31.8	33.6	27.8	2.01
Excretion															
ExN, g/cow per d	381	427	412	458	18.8	288	341	298	324	11.1	344	372	344	377	8.0
UN, g/cow per d	165	198	209	248	2.4	95	121	110	138	4.1	112	153	115	158	2.9
Ammonia emission															
g/cow per d	18.2	16.8	20.5	19.8	2.10	7.8	8.7	8.2	8.9	0.36	5.6	7.2	7.4	6.6	0.79
mg/g of NI	30	24	29	24	3.1	14	12	11	14	0.6	11	11	8	10	1.0
mg/kg of milk	485	445	585	514	22.6	203	231	212	239	7.8	145	195	196	177	6.2
mg/g of Ex-N	46	39	50	42	5.6	28	26	28	28	1.1	16	19	22	17	2.2
mg/g of urine-N	110	87	102	80	11.8	80	72	78	66	4.1	48	47	64	40	7.4
mg/g of TAN	114	85	99	80	11.8	81	71	74	64	4.0	50	47	64	42	7.4

[1]Spring: April 11 to May 27, 2005; early fall: Aug. 29 to Oct. 14, 2005; winter: Jan. 2 to Feb. 17, 2006.

[2]Refer to Table 3 for diet compositions.

ues, and where and to what magnitude study errors occurred.

CNB

Chamber N balances (Table 6) provided a method to account for N inputs and outputs and therefore an indirect way to evaluate the relative accuracy of the ammonia emission data (NRC, 2003). Feed accounted for 99% of chamber N inputs and manure accounted for approximately 62 to 86% of N outputs. The CNB (% of N inputs recovered in N outputs) were greatest during winter (95%) followed by spring (93%) and early fall (91%).

Chamber N balances of less than 100% were likely due to 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, approximately 200 kg of (wet) feed was delivered to, and 0 to 21 kg of (wet) feed refusals was removed from, each chamber. Our experience in weighing feed offered and refused and in determination of DM and N contained in feed offered and refused indicated that estimates of feed DMI and NI were more precise than estimates of ExN.

Our inability to capture all ExN was likely linked to 2 possible explanations: 1) incomplete urine collection, and, to a lesser extent, 2) error in measuring ammonia N loss during manure handling, sampling, and analyses. Each morning and evening approximately 100 to 150 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,

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

	Trial season[1]								
	Spring			Early fall			Winter		
Item	Day[2]	Night[2]	SE	Day	Night	SE	Day	Night	SE
Temperature (°C)	19.6	16.4	0.06	24.1	19.9	0.06	9.9	8.3	0.03
Relative humidity (%)	55.6	61.9	0.16	60.5	70.2	0.15	77.5	81.7	0.09
Ammonia-N emission (g/chamber per h)	3.41[a]	3.02[b]	0.02	1.60[a]	1.26[b]	0.01	1.27[a]	1.06[b]	0.01

[a,b]Within a season, row means followed by different superscript letters differ significantly ($P < 0.05$).

[1]Spring: April 11 to May 27, 2005; early fall: Aug. 29 to Oct. 14, 2005; winter: Jan. 2 to Feb. 17, 2006.

[2]Day measurements from approximately 1000 to 1500 h, night from 1900 to 0500 h.

Table 6. Seasonal chamber N inputs, outputs, and balances during 3 seasonal ammonia emission trials

Variable	Trial season[1]		
	Spring	Early fall	Winter
Inputs	g of N/chamber per d		
Feed consumed	2,964 (350)[2]	2,433 (405)	2,416 (414)
Bedding	103 (8)	110 (14)	94 (17)
Outputs			
Milk	775 (72)	736 (55)	731 (90)
Manure removed	1,933 (296)	1,331 (179)	1,495 (130)
Live weight gain	41 (175)	188 (206)	71 (46)
Ammonia loss	83 (37)	34 (6)	27 (13)
	%		
Balance	93 (9)	91 (17)	95 (17)

[1]Spring: April 11 to May 27, 2005; early fall: Aug. 29 to Oct. 14, 2005; winter: Jan. 2 to Feb. 17, 2006.

[2]Mean (standard deviation in parentheses).

thawed, and analyzed. Ammonia-N losses during this process may have occurred, but were likely slight. Manure removal, blending, and sampling was accomplished over an approximately 90-min period and N analyses were done immediately after thawing samples, which were stored at –20°C in tightly sealed plastic urine specimen cups.

Urine losses were possible, although visual observations during twice-daily manure collections indicated that these were likely low. The maximum amount of UN that could have been lost through drainage beneath manure pans can be calculated from the amount of N (g/chamber per d) required to achieve 100% chamber N balance (Table 6), assuming all unaccounted-for N was due to uncollected urine. Concentrations of N in dairy cow urine vary considerably (1 to 20 g/L; Bussink and Oenema, 1998). Assuming an average urine N concentration of 10 g of N/L for the present study, the 235, 254, and 186 g of N required to achieve chamber N balances of 100% during spring, early fall, and winter, respectively (Table 6) would translate into possible daily urine losses of approximately 18 to 25 L/chamber or 4 to 6 L/cow per d. This could comprise approximately 20 to 30% of excreted urine volume, assuming an average daily excretion of 20.5 L of urine/cow per d, although urine excretion volumes also vary greatly (Nennich et al., 2006). Even if all unaccounted-for N in the chamber N balances (Table 6) was attributed to uncollected urine, these losses would not necessarily have affected the measured seasonal and dietary effects on ammonia emissions, the principal study objectives.

Seasonal Diet Effects and Diurnal Differences in Ammonia Emissions

Seasonal and diurnal differences in ammonia emissions (Tables 4 and 5) can be attributed to the relationship between temperature, urease enzymatic activity, and subsequent ammonia production and loss. Urease is produced by microorganisms abundantly present in feces and, therefore, 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 indicate any discernible lags in ammonia emissions, either during the initial part of the 6-h daytime measurement period, or the initial part of the 12-h nighttime measurement period. After chamber walls were lowered, we provided a 40- to 60-min stabilization period for the ammonia analyzer. After this period, all ammonia emission recordings were used to determine, for example, seasonal and diet effects (Table 4) and diurnal differences (Table 5) in ammonia emissions.

In the present study, seasonal diet effects on ammonia emissions could be determined by comparing 1) winter and early fall (daytime temperatures of between –5 and 35°C; Table 1) when similar diets were fed, and 2) AS treatments having CP levels of 17% (spring) and 17.2% (early fall and winter). For the first comparison, average ammonia emissions (across all 4 diets, Table 4) during winter (6.7 g/cow per d) were 20% less than during early fall (8.4 g/cow per d). For the second comparison of AS-based diets at approximately 17% CP, average ammonia emissions during winter (7.2 g/cow per d) were 17% less than during early fall (8.7 g/cow per d) and 62% less than during spring (18.2 g/cow per d).

Urease activity is low between 5 and 10°C and increases exponentially above 10°C (Braam et al., 1997). Smits et al. (1995) determined that 46% less ammonia was emitted from free-stall dairy barns in the United Kingdom 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 9 free-stall dairy barns in Denmark within the temperature range of approximately 2 to 22°C.

In the present study across AS treatments, the much greater ammonia emissions during cooler (17.5°C) spring compared with warmer (21.4°C) early fall was likely due to much greater NI during spring than early fall (Table 4). 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). Estimated UN during spring was approximately twice as high as that during the other 2 trial seasons (Table 4).

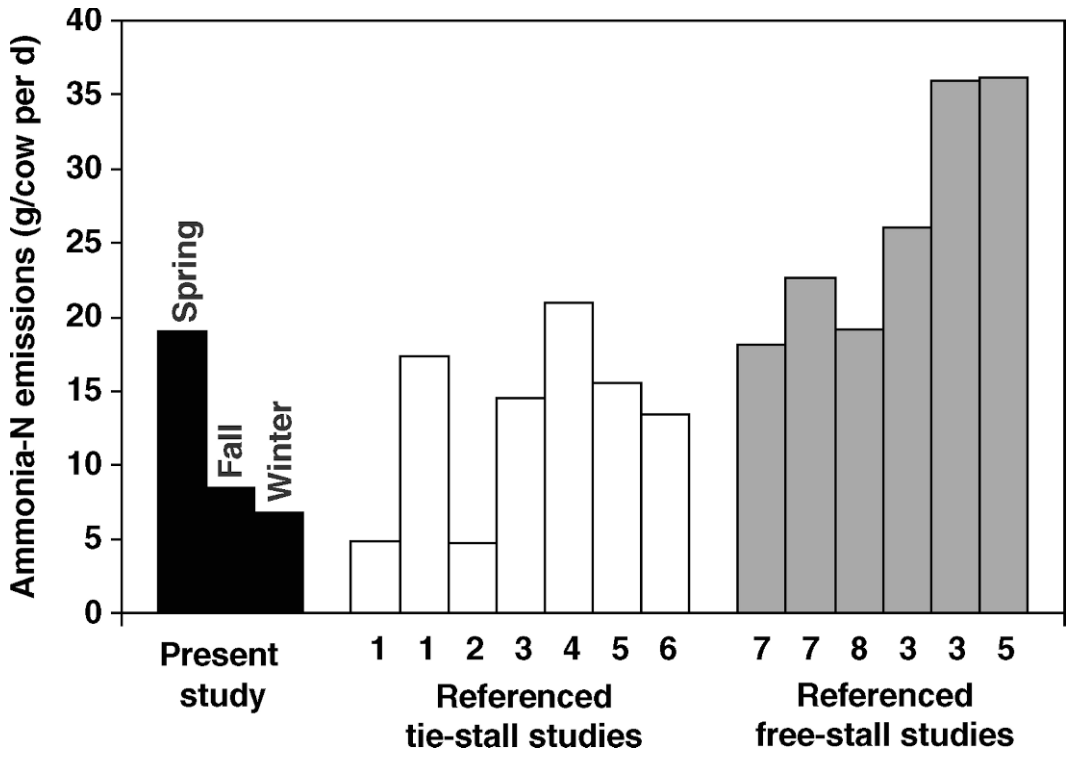

Figure 2. Ammonia emission rates: Present study compared with published studies. Numbers on the x-axis indicate 1) compiled from literature review of Monteny and Erisman (1998), dairy cow type not provided; 2) measured from cement barn floor and reported for 450-kg dairy cow by Amon et al. (2001); 3) manure, which included 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 per yr; 5) simulations by Rotz and Oenema (2006) and revised to include only lactating cows by C. A. Rotz, USDA-ARS; personal communication; 6) hourly emissions reported by Pedersen (2006) scaled to daily emissions; 7) simulations by Pinder et al. (2004); and 8) monthly emissions reported by Hutchings et al. (2001) scaled to daily emissions.

The ammonia emissions measured during the present study were somewhat lower than has been measured in other tie-stall studies (Figure 2). This may have been due, in part, to the pine shavings used for bedding. In a preliminary laboratory study (Misselbrook and Powell, 2005) and a study with the same chambers used in the present study (Powell et al., accepted), ammonia emissions from pine shavings were 20 to 25% lower than emissions from other tie-stall bedding materials tested (wheat straw, chopped newspaper, composted manure solids). A calculated average ammonia emission rate based on the chamber floor surface area from the present study (5.3 g/m^2 per d) was similar, however, to the average (5.8 g/m^2 per d) of 2 studies in the United Kingdom (Misselbrook et al., 1998, 2001), in which emissions were measured from outdoor concrete yards used by dairy cattle.

Ammonia emissions from tie-stall dairy barns are usually lower than those from free-stall barns (Figure 2) for several reasons. Whereas relatively narrow gutter scrapers remove manure from tie-stall barns once daily, wide alley scrapers constantly mix urine and feces and remove manure from free-stall barns. This results in large differences in the emitting surface area of tie-stall and free-stall barn floors. In the Netherlands, Monteny and Erisman (1998) concluded that 35% less ammonia was emitted from cows in tie-stalls than in free-stalls 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 that (10%) for free stalls (Pedersen, 2006).

Average ammonia N emissions (11.3 g/cow per d) by lactating cows in the present study accounted for only 1.6 to 5.0% of ExN (Table 4). These emission rates were lower than a general ammonia N loss value from tie-stall barns of 8% of ExN summarized in a literature review (Rotz, 2004), and less than simulated ammonia N 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 United Kingdom, 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 adult cattle, respec-

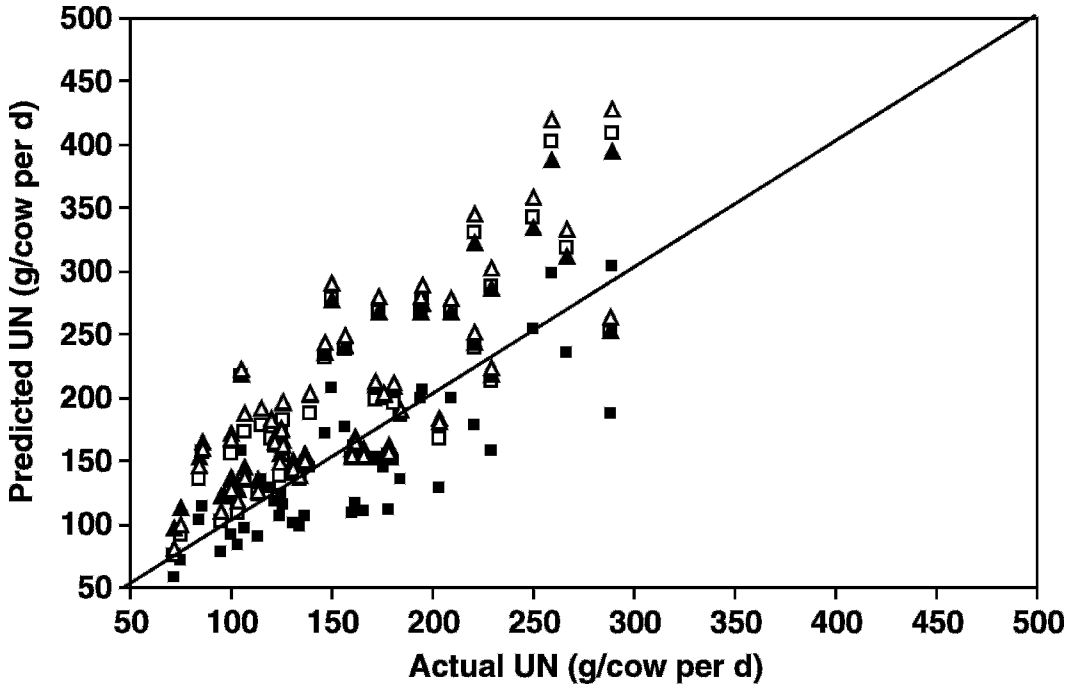

Figure 3. Actual vs. predicted urine N (UN) excretion (predictions using equations from the following sources: □ UN = 0.0259 × MUN × BW, Kauffman and St-Pierre (2001); ■ UN = 12.54 × MUN, Jonker et al. (1998); △ UN = 17.64 × MUN, Kauffman and St-Pierre (2001); ▲UN = 15.1 × MUN + 27.8, Kohn et al. (2002).

tively. In the present study, ammonia N emissions accounted for 4.2 to 11.4% of excreted TAN (Table 4). This range was lower than the modeled 6 and 21% of TAN emitted by calves and adult dairy cattle in tie-stall barns in the United Kingdom (Webb and Misselbrook, 2004).

Relationship Among UN, MUN, and Ammonia Emissions

Estimates of UN excretions were calculated by adding manure ammonium N to emitted ammonia N. Average daily UN excretions ranged from 33 to 54% of ExN (Table 4), somewhat lower percentages than would have been expected for lactating Holstein cows consuming similar diets and producing similar amounts of milk (Broderick, 2003; Wattiaux and Karg, 2004). In other studies, UN excretions have been estimated from a combination of NI and milk N (Jonker et al., 1999), a combination of MUN and BW (Kauffman and St-Pierre, 2001), and MUN only (Jonker et al., 1998; Kauffman and St-Pierre, 2001; Kohn et al., 2002). A comparison of actual vs. predicted UN using various algorithms in the literature (Figure 3) indicates that the present study's estimates of UN (TAN plus emitted ammonia N) are somewhat lower than expected. This perhaps supports the previous hypothesis that unaccounted N in the chamber N balances (Table 6) may have been because of our inability to collect all urine.

Concentrations of MUN have been used to monitor dietary N intake and to adjust dietary CP content to help minimize feed N wastage (Broderick and Clayton, 1997). The use of MUN has also been extended to estimate UN excretion (Jonker et al., 1998; Kauffman and St-Pierre, 2001; Kohn et al., 2002) and ammonia emissions (van Duinkerken et al., 2005). In the present study, there were significant positive relationships between MUN, ExN, and UN (Figure 4), and between MUN and emitted ammonia N (Figure 5). A possible reason why MUN was not a better predictor of emitted ammonia N was likely related to the use of different cows for each trial and seasonal differences in temperature and relative humidity, which would affect transient, static, and reactive ammonia emissions. Transient emissions are the result of animal behavior, such as manure excretion patterns and animal activity; static emissions are dependent on liquid-gaseous equilibrium; and reactive emissions are due to chemical reactions (Starmans, 2007).

CONCLUSIONS

There were distinct seasonal and dietary effects on ammonia emissions from lactating dairy cattle housed

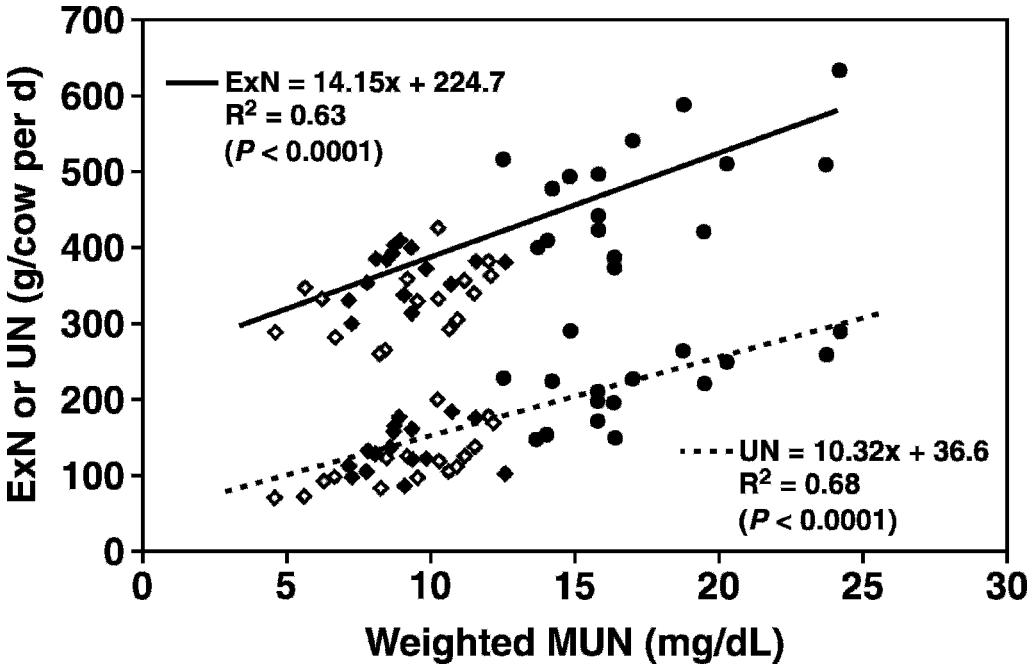

Figure 4. Relationship between chamber-weighted MUN, total excreted N (ExN), and urinary N (UN). Chamber-weighted MUN was calculated as the sum of each cow's fractional MUN outputs, which was computed by multiplying each cow's fractional chamber milk production by its associated MUN value. ExN and UN were calculated by dividing daily ExN and UN per chamber by 4 cows per chamber. ● = spring, ◇ = early fall, ◆ = winter.

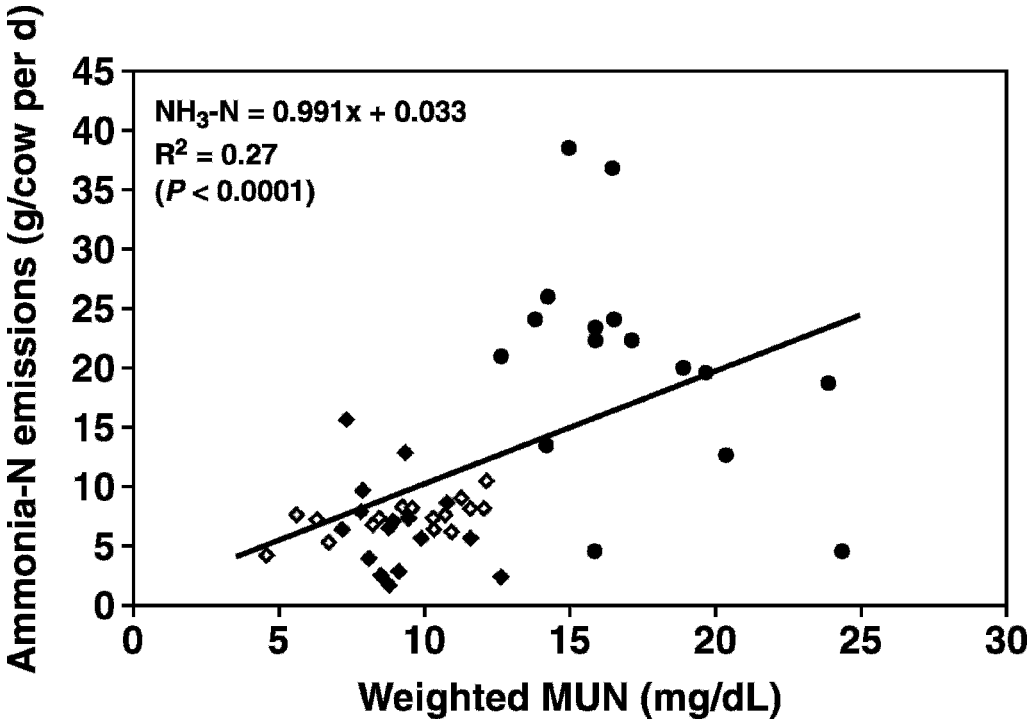

Figure 5. Relationship between chamber-weighted MUN and ammonia-N emissions. Chamber-weighted MUN was calculated as the sum of each cow's fractional MUN outputs, which was computed by multiplying each cow's fractional chamber milk production by its associated MUN value. Ammonia-N emissions were calculated by dividing daily chamber emissions by 4 cows per chamber. ● = spring, ◇ = early fall, ◆ = winter.

in tie-stall chambers. The greatest emissions (6.9 kg of NH_3-N/cow per yr) were recorded during spring when NI and ExN were greatest from AS-based diets. Comparing only data from cows fed diets with similar CP levels also indicated that the greatest ammonia emissions occurred during spring. Ammonia emissions during early fall (3.1 kg of NH_3-N/cow per yr) were greater than during winter (2.4 kg of NH_3-N/cow per yr) when similar AS- and CS-based diets were fed. Results from these large-scale chamber studies appeared to provide accurate information on seasonal differences and diet effects on ammonia emissions from tie-stall barns. Confidence in study results was derived from 1) 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; 2) the generally favorable comparisons between study results and published values of ammonia emissions; and 3) between-study estimates and published values of excreted N and urine N.

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