Design and Calibration of Chambers for Measuring Ammonia Emissions from Tie-stall Dairy Barns

J. M. Powell, P. R. Cusick, T. H. Misselbrook, B. J. Holmes

Abstract. *Dairy barns are thought to emit large amounts of ammonia, which can have detrimental effects on human health and natural ecosystems. In the U.S., relatively little is known about the processes that affect the rate and magnitude of ammonia emissions from dairy barns. The end of a conventional tie-stall dairy barn was remodeled into four chambers (four animals per chamber) to initially evaluate dairy diet and bedding impacts on ammonia production and loss. This article describes the technical aspects of the chamber design, operation, and calibration. The chamber walls consisted of drop-down curtains of polyvinyl material, with Velcro seals at the edges and weighted at the bottom to minimize air loss other than through the exhaust ducts. The curtains were attached to automatic roll-up, roll-down mechanisms fixed to the ceiling. Intake air, which was drawn from outside the barn, provided information on background ammonia levels. Two types of chamber calibrations were performed: (1) release and capture of known amounts of ammonia gas, and (2) total nitrogen (N) balances for growing heifers, or the percentage difference between N outputs (manure, ammonia, and livestock weight gain) and N inputs (feed and bedding). On average, 102% (range 88% to 131%) of released ammonia was captured using the ammonia release-capture calibration method, and 99% (range 94% to 104%) of input N was accounted for by output N. Calibration results indicate that chambers should provide precise data on ammonia emitted from tie-stall dairy barns under the prevailing management and environmental conditions.*

Keywords. *Ammonia emissions, Dairy cattle, Environmental chamber, Tie-stall barns.*

In the U.S., the trend towards fewer and larger livestock farms has heightened public concern over the detrimental effects of livestock production on the environment. Over the past several years, environmental policy related to animal agriculture has focused on land application of manure, especially how to stop or reverse soil phosphorus build up, runoff, and the subsequent pollution of lakes, streams, and other surface water bodies. Policy is now being developed to reduce the emission of greenhouse and other hazardous gasses into the atmosphere. A recent report 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.

Only 20% to 30% of the N (crude protein) fed to dairy cows is converted into milk. Feed N not transformed into milk is excreted about equally in urine and feces. About three-fourths of the N in urine is in the form of urea, and urease enzymes in feces and soil rapidly convert this urea to ammonium. Ammonium can be transformed quickly into ammonia gas and lost to the atmosphere. After release, ammonia can combine with other chemicals in the atmosphere to form particulates that can adversely affect human health. Ammonia redeposited in dust, as acid rain and nitrates, can have detrimental impacts on natural ecosystems. Ammonia emitted 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).

Ammonia losses from dairy operations begin to occur immediately after manure (feces and urine) excretion, and continue through manure handling, storage, and land application. Ammonia emissions from dairy barns range from 20% to 55% of total manure N excretions (MWPS, 2001). The main factors affecting ammonia losses from dairy barns are housing, bedding type, ventilation, air velocity, and temperature. While relatively much is known about ammonia emissions from the mostly grazing-based dairy operations in Europe (e.g., Webb and Misselbrook, 2004; Jarvis and Ledgard, 2002; Monteny and Erisman, 1998), relatively little information is available on ammonia emissions from confinement dairy operations in the U.S.

Tie-stall barns are the most common housing types on dairy farms in the Midwest and Northeast regions of the U.S. (USDA, 2004). On these farms, cows are confined to stalls, and manure is collected in a gutter behind the cows. Moderate to large amounts of straw, wood shavings, etc., are used for bedding. The manure mixed with bedding is typically removed with a gutter cleaner once daily, and field applied daily or stored for later field application.

Management can have a large impact on reducing ammonia emissions from dairy farms (Rotz and Oenema, 2006). It is possible to reduce the excretion of urinary N (the principal

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source of ammonia) by dairy cows by 20% to 30% by manipulating dietary crude protein (CP) types and levels (Castillo et al., 2000; Broderick, 2003). In laboratory studies, dietary CP type and level (Misselbrook et al., 2005) and bedding materials (Misselbrook and Powell, 2005) had significant impacts on ammonia emissions. The N:P ratio of dairy manure was used to indirectly assess the impacts of floor-scraping frequency on ammonia loss from free-stall barns (Moreira and Satter, 2006). However, to guide the development of emission standards, and to evaluate management practices that reduce ammonia loss from dairy barns, more direct measurements of ammonia emissions at operational scales are needed.

In the U.S., an environmental chamber was built (Lefcourt et al., 2001) and calibrated (Lefcourt, 2001) to directly measure ammonia emission from dairy cows in tie-stalls. In the U.K., large polytunnels were modified to enable gaseous emission measurements from housed cattle (Gilhespy et al., 2007). The objective of this article is to describe the design, operational characteristics, and calibration of four environmental chambers used for direct measurement and statistical analyses of management (e.g., diets, bedding) impacts on ammonia emissions from tie-stall dairy barns.

Materials and Methods

Chamber Specifications

Tie-Stall and Manure Gutter Arrangement

Four chambers (fig. 1) to house four dairy cows each were constructed at the end of an existing tie-stall barn equipped with a standard manure gutter cleaning system at the research facilities of the USDA-ARS Dairy Forage Research Center in Prairie du Sac, Wisconsin. 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. The construction was such that the chamber walls could be raised and lowered. When the chamber walls were down, a 0.91 m alley separated sets of two chambers. Each tie stall (1.8 × 1.2 m) contained cow comfort mats (Kraiburg, Waldkraiburg, Germany). To collect manure, pans were constructed (Palmer Manufacturing, Merrimac, Wisc.) 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 the back of the manure gutter) and placed in a bracket to keep the pans high enough so that the manure scraper could function normally to clean the non-chamber part of the barn. The pan holders also contained manure gutter grates that could rotate up to 90° so that the pans could be removed during manure collection. To facilitate urine collection, 6.4 mm thick PolyMax urine deflectors (FarmTek, Dyersville, Iowa) were constructed 0.833 m long, with approximately 0.660 m angled from the back of the manure pan upwards to the top of the bottom chamber wall at an angle of about 45°. A 3 mm deep × 25.4 mm wide groove was routed into the PolyMax board every 25.4 mm to direct urine into the manure pans.

Drop-Down Chamber Walls

The chamber walls and four cows in a chamber are shown in figure 2. The long wall shown in figure 2 conceals two chambers that are separated by drop-down curtains attached to 0.457 m tall × 0.254 m wide wooden wall on the bottom and 0.305 m tall × 0.254 m wide wooden wall on the top. The bottom and top walls were covered by 9.5 mm thick strand board protected with fiberglass-reinforced plastic. The curtain material was Dura-Skrim, a reinforced, 4 mm thick clear polyvinyl sheeting (Raven Industries, Sioux Falls, S.D.). The walls were guided with 0.025 m rollers that ran in a Unistrut track (41.3 mm^2, 2.78 mm thick; Itasca, Ill.).

The walls were raised and lowered using a motor (Dodge Tigear 175, Relialube, Greenville, S.C.) mounted on the top

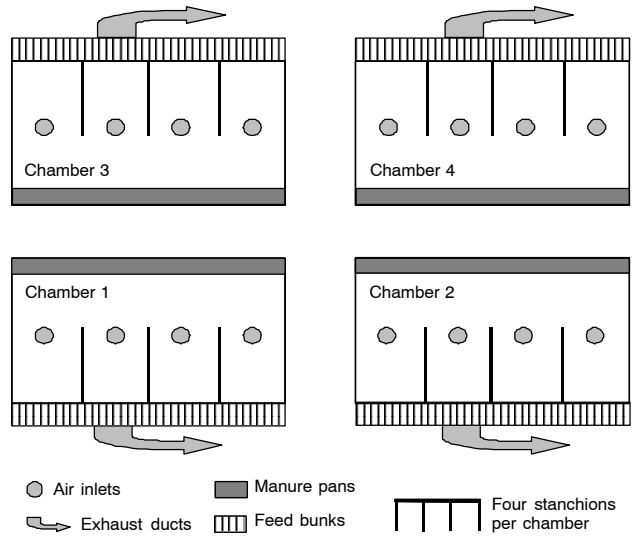

Figure 1. Schematic of four tie-stall air emission chambers.

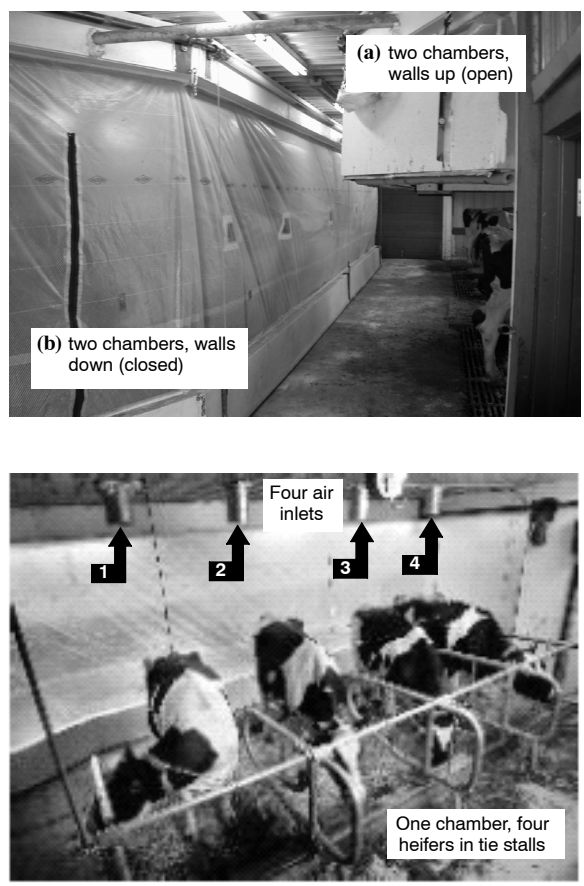

Figure 2. Upper photograph: four air emission chambers from center alley showing curtain walls (a) open and (b) closed. Lower photograph: interior of one chamber showing four dairy heifers, curtain walls, and four ceiling air inlets.

wooden wall. The motor was equipped with a 12-tooth gear that drove a 30-tooth gear on a 0.025 m shaft. The shaft was 0.508 m in length and turned a 0.064 m diameter pipe inset with a 0.025 m diameter bushing to accept the shaft. A 6.35 mm diameter cable attached to the top and bottom walls and wrapped around the pipe was used to raise the bottom wall to a height of 2.13 m so that a 1.59 m feed cart could pass underneath.

Each chamber had two 0.851 × 0.584 m side-by-side windows. One window was sealed closed. The other window was converted into an exhaust port. Polycarbonate sheets (6.4 mm thick) were used to construct a port protruding outward from the barn at an angle of 48° for 0.890 m, after which it proceeded upward at a 90° angle in reference to the ground for 0.546 m and then made another 90° angle to be parallel to the ground. Exhaust ducts (3.05 m in length and 0.559 m in diameter) parallel to the length of the barn were attached and sealed to the exhaust ports. To reduce impact of wind gusting, baffles made of plywood were placed 0.152 m past and perpendicular to the end of the exhaust ducts and were 0.305 m larger than the diameter of the exhaust ducts.

Chamber Ventilation

Airflow through each chamber was controlled by an intake fan and kept within the range of 5 to 15 air exchanges per hour, depending on ambient conditions and the need to maintain cow comfort. A forward-curve blower (0.670 m inlet diameter, 0.667 × 0.489 m output dimensions, Dayton Manufacturing, Niles, Ill.) was used to move air through the chambers. The fan was powered by a 5 hp, 1800 rpm, 3-phase, 230 V motor (model 184TTFS6026, Marathon, Wausau, Wisc.). The variable-speed motor was controlled using a 3-phase in, 3-phase out, 5 hp AC micro-drive (model GS2-25P0, Automation Direct, Cumming, Ga.).

Air was drawn from a 0.670 m diameter spiral-wound duct protruding above the barn roof, through the forward-curve blower, transitioned to a 0.559 m diameter duct, and then into four 0.406 m diameter ducts directed into each chamber. The source ducts transitioned from the 0.406 m diameter to 0.356 m at the first dropdown duct, subsequently to 0.305 m, and finally to 0.203 m diameter ducts that were evenly spaced to provide airflow over the top of the rear half of each animal in the chamber (fig. 2).

Air Movement Observations

An insect fogger was used to vaporize mineral oil, forming a smoke within each chamber. The motion of the smoke was observed to help visualize air movement within the chambers. Air movement within the chambers and through the exhaust duct appeared to be in a non-turbulent laminar flow pattern. No smoke was observed leaking from the chambers through joints in the materials of the chamber.

Airflow, Temperature, and Relative Humidity Measurements and Recordings

Air velocity was measured using stainless steel Pitot tubes (model 160, 0.305 m, Dwyer Instruments, Michigan City, Ind.) and very low pressure differential sensors (model 264, 0.249 mb, Setra, Boxburough, Mass.). Pitot tubes were placed in the center of the ductwork, facing the airflow, 0.76 m from the end of the exhaust ducts (fig. 3). The low-pressure differential sensor readings (0 to 5 VDC output, 0 to 25.4 mm water column) measured the difference between total pressure and static pressure, yielding the velocity pressure. Velocity pressures were recorded using a data logger (model 21X, Campbell Scientific, Logan, Utah). The data logger converted DC readings into cm of water to determine airflow using equation 1:

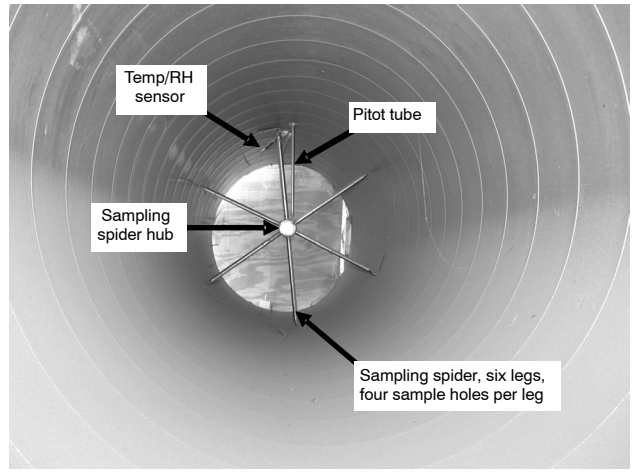

Figure 3. Location of spider air sampler, Pitot tubes, and temperature/RH sensor in exhaust duct.

$$\text{Air velocity (m min}^{-1}) = 265.2 \times (P_v/D)^{1/2} \qquad (1)$$

where P_v is the velocity pressure (cm of water), and D is the air density (kg m^{-3}).

Airflow (m^3 min^{-1}) rates were determined by multiplying air velocity by the cross-sectional area (0.0745 m^2) of the exhaust duct. Airflow rates for each chamber were averaged over 2 min intervals, which corresponded to the measurement interval of ammonia concentrations in the 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, Utah). Measurements were made at the center of the exhaust duct, 4.572 m from the end of the duct. The data logger was programmed using Loggernet software (Campbell Scientific, 2003). In operation, the data logger opened a solenoid valve (part 8214K21, McMaster-Carr, Chicago, Ill.) through a solid-state relay (120 VAC, 10 A, DC control solid-state relay; Opto 22, Temecula, Cal.) to allow air to flush the sampling line. The data logger then averaged the temperature, relative humidity, differential pressure (air velocity for inlet and exhaust), and ammonia concentration over a 1 min interval.

Air Sampling

Stainless steel cross-sectional (spider) samplers were constructed to sample air from the chamber inlets and exhaust ducts (fig. 3). Each spider sampler consisted of six round, hollow stainless steel legs (15.9 mm i.d.) fixed at 60° angles to a hollow 38.1 mm i.d. × 25.4 mm wide central hub to cover the entire circumference of the duct. Each spider leg had four 1.30 mm holes at 183, 228, 247, and 274 cm from the spider hub, representing four equal concentric volumes. Air samples were drawn through Teflon tubing (6.4 mm o.d., 4.8 mm i.d., Nalgene, Rochester, N.Y.) through a 63.5 mm hole in the rear of the spider sampler hub. All tubing was covered with standard polyethylene pipe insulation (12.7 mm i.d.) and heated with self-regulated heat tape (120 V, 500 W;

Easy Heat, New Carlisle, Ind.) to prevent condensation from forming inside the sample lines.

Ammonia Analyzer

Ammonia concentrations in the air samples were analyzed using an Air Sentry IonPro mobility spectrometer (Molecular Analytics, Boulder, Colo.) calibrated for 0 to 20 ppm ammonia, with an on-board calibration of 2 ppm ammonia (±0.1% detection limit). The IonPro requires clean, dry air for operation (−40°C dew point). Clean dry air was produced using a refrigerated air dryer (model HPR15, Hankinson International, Ocala, Fla.) powered by a 5 hp, 240 V, 3-phase compressor (model 1WD55, Speedaire, Dayton Electric Mfg. Co., Niles, Ill.). The air dryer removed most air moisture (3.3°C dew point at 425 L min^{-1}), and the remaining moisture was removed using a DryAire membrane air drying system (model 6770, Sharpe Mfg. Co., Minneapolis, Minn.).

Chamber Calibrations

Chamber ammonia capture efficiencies were determined using two methods: (1) by releasing known amounts of ammonia gas into empty chambers (no cattle) and calculating the ammonia capture efficiencies, and (2) by determining total N balances (percentage difference between ammonia N, manure N, and animal body N outputs, and feed N and bedding N inputs) while four growing heifers were housed in each chamber. Chambers were pressure-washed and allowed to dry between each calibration method.

Ammonia Capture-Release Calibration Method

A calibration using the ammonia N release-capture method took approximately 2 h per chamber. All four chambers were calibrated during a single day, and a second round of calibrations was done on the day following the first set of calibrations. A calibration proceeded as follows:

1. A chamber was sealed, sample lines were heated, airflow was set to 30 Hz fan speed, or approximately eight air exchanges per hour (the exchange rate deemed necessary for the February conditions of the calibration).
2. Background ammonia levels were established during a 30 min period just prior to ammonia release.
3. Ammonia cylinders (Linde Gas, Madison, Wisc.) were placed on balances outside the chambers. Stainless steel tubing was attached to the cylinders and fed into the chamber. The tubing outlet was branched four times, with each branch placed over the manure collection pan directly behind the four tie-stalls in each chamber. Ammonia flow regulators and cylinder weights before and after emissions were used to determine the exact amount of ammonia emitted into each chamber (Lefcourt, 2001).
4. Target ammonia release rates within the range of 10 to 20 g h^{-1} were selected to encompass the general average range of 10 to 24 g h^{-1} for four dairy cows, as reported by Lefcourt (2001).
5. The ammonia cylinder mass was recorded, ammonia was emitted for 30 min., and the ammonia cylinder mass was again recorded. Stagnant ammonia was purged from the sample lines.
6. The concentration of ammonia was allowed to return to approximately baseline levels. Once a chamber returned to approximately baseline ammonia levels, the calibration sequence was initiated on the next chamber, in the order of chamber 1, 2, 3 and 4 (fig. 1).

Ammonia flux from the cylinder (AF_{cl}, g h^{-1}) was calculated using equation 2:

$$AF_{cl} = (W_e - W_s) \div t \quad (2)$$

where W is the weight of the cylinder (g) at the end (e) and start (s) of the measurement period, and t is the duration of the measurement period (h).

Ammonia flux from the chamber (AF_{ch}, g h^{-1}) was calculated using equation 3:

$$AF_{ch} = [(V \times C_o) - (V \times C_i)] \div t \quad (3)$$

where V (m^3) is the volume of air passing through the chamber during time t (h), and C is the ammonia concentration of the air (g m^{-3}) at the chamber inlet (i) and exhaust (o).

Ammonia recovery (AR, %) was calculated as the percentage difference between captured and released ammonia as follows:

$$AR = \frac{\text{ammonia captured (g)}}{\text{ammonia released (g)}} \times 100 \quad (4)$$

Total N Balance Calibration Method

Initial chamber studies were designed to evaluate the effects of bedding materials (wheat straw, shredded newspaper, pine shavings, and composted manure solids) on ammonia emissions. A 4 × 4 Latin square statistical design was used to allocate the four bedding types to each chamber for a four-day ammonia monitoring period, followed by reallocation of beddings to different chambers, until each bedding type was observed once in each chamber. These trials included total N balance calculations based on percentage differences in N outputs (manure, ammonia, and heifer live-weight gains) and N inputs (feed and bedding). For the purpose of the present study, total N balances from the first four-week bedding trial are presented. This bedding trial was initiated the week that followed the ammonia release-capture chamber calibrations described previously, and covered the four-week period from 31 October to 22 November 2005. Chamber temperatures, relative humidity, and airflow during this month-long period are provided in table 1.

Daily total N recoveries (TNR, %) were calculated as follows:

$$TNR = \frac{(\text{manure N} + \text{ammonia N} + \text{heifer N gain})}{(\text{feed N} + \text{bedding N})} \times 100 \quad (5)$$

where "feed N" is the difference between feed N offered and feed N refused, "bedding N" is bedding dry matter (DM) mass (kg) multiplied by bedding N concentration (g kg^{-1}), "manure N" is manure DM (kg) multiplied by manure N concentration (g kg^{-1}), "heifer N gain" is heifer mass (kg) before and after two-week weighing periods multiplied by body N concentration of 24.7 g kg^{-1} for growing heifers (Marini and

Table 1. Chamber conditions during the initial bedding (total N balance) trial.

Parameter[a]	Statistic		
	Mean	SD	Min. - Max.
Temperature (°C)	7.3	5.49	0.1 - 27.9
RH (%)	72.9	10.83	38.8 - 95.7
Airflow (m^3 h^{-1})	1108	167	241 - 2420
Air exchanges ($chamber^{-1}$ h^{-1})	6.7	1.0	1.5 - 14.7

[a] Recorded during the period 31 October to 22 November 2005.

Van Amburgh, 2003), and "ammonia N" is the hourly ammonia flux from the chamber (eq. 3) multiplied by 24 h.

Each day, from approximately 0700 to 0900 h, the 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 the rate of 8 to 12 kg DM per heifer, or approximately 10% in excess of previous consumption. All soiled bedding was removed, and manure pans were emptied, weighed, and sampled. At approximately 0900 h, the chamber curtains were lowered, seams were sealed, and from 1000 to 1500 h emission recordings were made. For the first two weeks of this initial bedding study, the curtains remained up from 1500 to 0700 h the following morning. During the last two weeks, the curtains were lowered at approximately 1700 h for nighttime emission measurements. Ammonia flux calculations (eq. 3) for each chamber were scaled to hourly and daily fluxes. The daily cycle of heifer feeding, chamber cleaning, and ammonia emission recordings was carried out during four consecutive days (Tuesday through Friday). The 4 × 4 Latin square design was used to reassign beddings to new chambers, and a new cycle of heifer feeding, chamber cleaning, and ammonia emission was initiated.

After manure collection and weighing, approximately 10 kg of the total manure per chamber was blended in a cutter mixer (model R60, Robot Coupe, Ridgeland, Miss.), and a subsample was placed in 120 mL specimen cups and frozen until analysis could be performed. Manure analyses were usually done during the week following sample collection. 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 Corp., St. Joseph, Mich.). Manure samples were thawed, and subsamples were analyzed for total N using a micro-Kjeldahl assay (Peters et al., 2003) and oven-dried (100°C, 24 h) for DM determination. Chamber differences in ammonia recoveries (eq. 4) and total N balances (eq. 5) were delineated using analysis of variance procedures (SAS, 2000).

Results and Discussion

Patterns of ammonia capture using the ammonia release-capture calibration method were generally similar among the four chambers (fig. 4). Average baseline ammonia concentrations ranged from 0.3 to 0.5 mg kg^{-1}. Most of the 5 to 8 g of released ammonia gas was captured during the 60 min following the 30 min ammonia release period. Ammonia capture efficiencies ranged from 88% to 131%. An overall average ammonia capture efficiency of 102% was obtained for the four chambers, which was very similar to the average 105% ammonia recovery obtained by Lefcourt (2001) over 86 calibrations of a larger environmental chamber. Due to large chamber viabilities (fig. 4), no significant (P = 0.46) differences were determined between average ammonia capture efficiencies of 95%, 104%, 94%, and 115% for chambers 1, 2, 3, and 4, respectively.

During the four 4-day ammonia monitoring periods, feed comprised 90% to 95% of the N inputs into the chambers, and manure accounted for 80% to 85% of the N outputs from the chambers (fig. 5). Approximately 15% of N outputs were retained in growing heifer bodyweight, and 3% to 4% were trapped as ammonia gas. In this initial bedding experiment, ammonia N emissions equaled 4% to 5% of manure N excretion. An overall average total N balance of 99% was attained for the four chambers. No significant (P = 0.37) differences were determined between average total N balances of 97%, 94%, 99%, and 103% for chambers 1, 2, 3, and 4, respectively.

Large amounts of feed and manure mass were handled and sampled during the month-long bedding trial. Each morning, 40 to 85 kg of wet feed mass was delivered to each chamber,

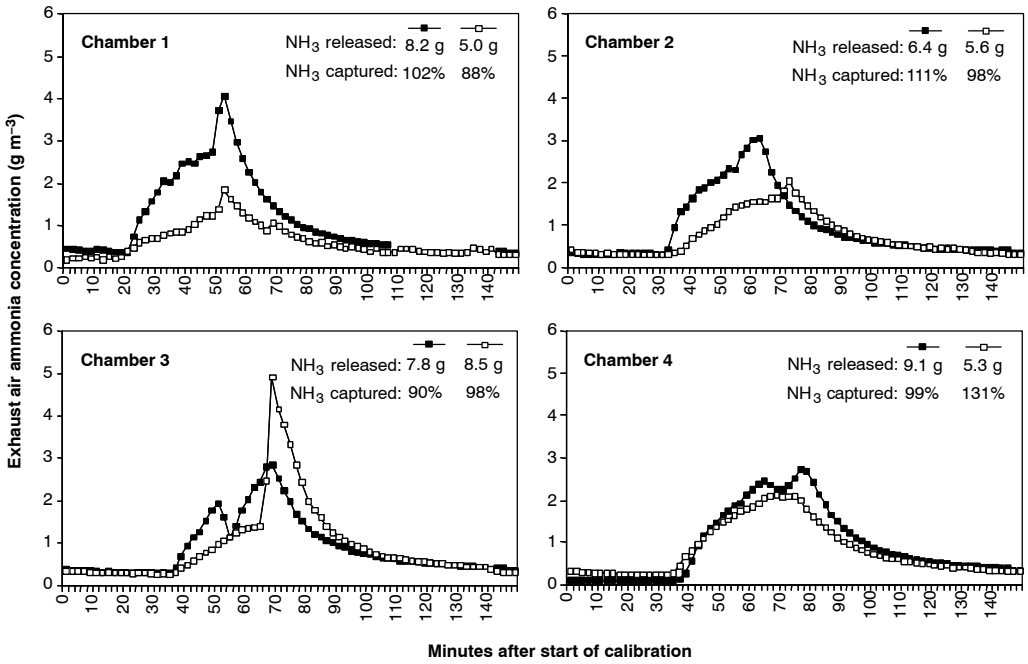

Figure 4. Exhaust air ammonia concentrations after release of ammonia for 30 min.

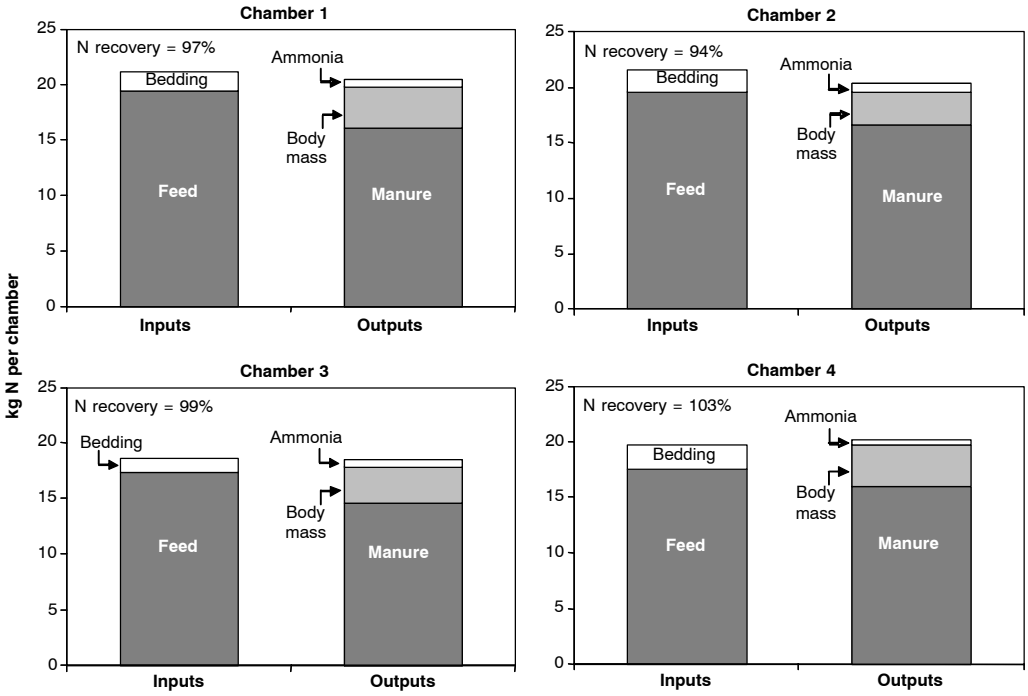

Figure 5. Quantity and source of nitrogen added to and removed from each chamber during a bedding study.

and 0 to 16 kg of wet refused feed was removed from each chamber. 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, total wet manure mass was first mixed manually, sampled, blended, subsampled, frozen, thawed, and analyzed for total N. Manure handling was done over a 2 h period for all four chambers to minimize N losses. The high total N balances (fig. 5) indicated that the methods used to estimate feed N intake and manure N excretions provided accurate results.

Summary and Conclusions

Part of a conventional tie-stall dairy barn was successfully converted into four chambers for air emissions research. Initial chamber calibrations performed well. Almost all measured amounts of released ammonia were captured in exhaust ducts, and most feed and bedding N inputs into the chambers were accounted for in manure, body mass, and ammonia N outputs. These calibrations indicate that studies using these chambers should provide precise, quantitative estimates of management (e.g., bedding type, dietary crude protein level) impacts on ammonia loss from tie-stall dairy barns under the prevailing environmental (temperature, relative humidity) conditions.

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