Daily, Monthly, Seasonal and Annual Ammonia Emissions from Southern High Plains Cattle Feedyards

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Ammonia emitted from beef cattle feedyards adds excess reactive N to the environment, contributes to degraded air quality as a precursor to secondary particulate matter, and represents a significant loss of N from beef cattle feedyards. We used open path laser spectroscopy and an inverse dispersion model to quantify daily, monthly, seasonal, and annual NH_3 emissions during 2 yr from two commercial cattle feedyards in the Panhandle High Plains of Texas. Annual patterns of NH_3 fluxes correlated with air temperature, with the greatest fluxes (>100 kg ha^{-1} d^{-1}) during the summer and the lowest fluxes (<15 kg ha^{-1} d^{-1}) during the winter. Mean monthly per capita emission rate (PCER) of NH_3–N at one feedyard ranged from 31 g NH_3–N head^{-1} d^{-1} (January) to 207 g NH_3–N head^{-1} d^{-1} (October), when increased dietary crude protein from wet distillers grains elevated emissions. Ammonia N emissions at the other feedyard ranged from 36 g NH_3–N head^{-1} d^{-1} (January) to 121 g NH_3–N head^{-1} d^{-1} (September). Monthly fractional NH_3–N loss ranged from a low of 19 to 24% to a high of 80 to 85% of fed N at the two feedyards. Seasonal PCER at the two feedyards averaged 60 to 71 g NH_3–N head^{-1} d^{-1} during winter and 103 to 158 g NH_3–N head^{-1} d^{-1} during summer. Annually, PCER was 115 and 80 g NH_3–N head^{-1} d^{-1} at the two feedyards, which represented 59 and 52% of N fed to the cattle. Detailed studies are needed to determine the effect of management and environmental variables such as diet, temperature, precipitation, and manure water content on NH_3 emissions.

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Ammonia emitted from beef cattle feedyards adds excess reactive N to the environment and contributes to degraded air quality as a precursor to secondary particulate matter. Accurate NH_3 emissions are required because, beginning in 2009, the USEPA required most feedyards to report their NH_3 emissions under the Emergency Planning and Community Right-to-Know Act.

Ammonia volatilized from beef cattle feedyards represents a significant loss of N from the feedyard system. Summertime NH_3 loss, estimated as the residual in feedyard N balances, ranged from 51 to 68% of fed N in studies in Nebraska (Bierman et al., 1999; Erickson and Klopfenstein, 2001; Erickson et al., 2000; Farran et al., 2006). In Alberta, Canada, McGinn et al. (2007), using open path laser spectroscopy and an inverse dispersion model, found that summertime NH_3 loss was 63% of fed N. Van Haarlem et al. (2008), working in an Alberta feedyard, reported that 73% of fed N was lost as NH_3 during 12 d in autumn; this high percentage was attributed to crude protein (CP) in rations that were as high as 23%, compared with the recommended CP of 12.5 to 13.5% (National Research Council, 2000). Cole et al. (2006) applied manure collected from a feeding trial in New Mexico to a laboratory system of small, closed chambers and found that from 51 to 65% of fed N was volatilized as NH_3. Flesch et al. (2007) and Todd et al. (2008) independently measured ambient NH_3 concentrations at the same Texas feedyard using open path laser spectroscopy and acid gas washing, respectively, and then both used an inverse dispersion model to estimate NH_3 emissions; NH_3–N losses were 63 and 68% of fed N during the summer. Baum and Ham (2009) used relaxed eddy accumulation to directly measure NH_3 flux at a Kansas feedyard; NH_3–N volatilization was 38% of fed N during 8 d in July and August. Studies that focus on wintertime NH_3 emissions are not as common. Bierman et al. (1999) estimated that winter NH_3–N losses were 35% of fed N. Winter NH_3–N losses ranged from 27 to 44% at a Texas feedyard (Todd et al., 2005, 2008).

Multiyear, continuously quantified NH_3 emissions from beef cattle feedyards are needed to understand the effect of changing

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Abbreviations: BLS, backward Lagrangian stochastic; FYA, Feedyard A; FYE, Feedyard E; PCER, per capita emission rate.

seasons and management decisions on the dynamics of emissions. Our objective was to use open path laser spectroscopy, coupled with an inverse dispersion model, to quantify daily, monthly, seasonal, and annual NH_3 emissions from two commercial cattle feedyards located in the Panhandle High Plains of Texas.

Materials and Methods

Feedyards

Two commercial feedyards were chosen that were located in the heart of the cattle-feeding industry of the Texas Panhandle. Feedyard A (FYA) and Feedyard E (FYE) had total pen areas of 36.4 and 34.1 ha, respectively (Fig. 1). Feedyard A averaged 12,684 head of cattle, but the cattle population was highly variable, with a maximum of 15,430 and a minimum of 8927; the mean occupancy was 56 ± 7% (mean ± SD). The head count at FYE averaged 19,620 (maximum = 22,437, minimum = 17,260) and the mean occupancy was 78 ± 6%. The commercial feedyards cooperatively provided monthly data, including head counts, mean cattle weight, total feed fed, average daily gain, days on feed, and diet composition, although the information provided differed for each feedyard. We collected feed samples at each feedyard either bimonthly or monthly by sampling rations from the feed bunks of five pens. The samples were dried to determine the dry matter content, wet digested, and then analyzed for total N using a QuikChem flow injection autoanalyzer (QuikChem Method 10-107-06-2-E, Lachet Instruments, Milwaukee, WI) and the CP content calculated.

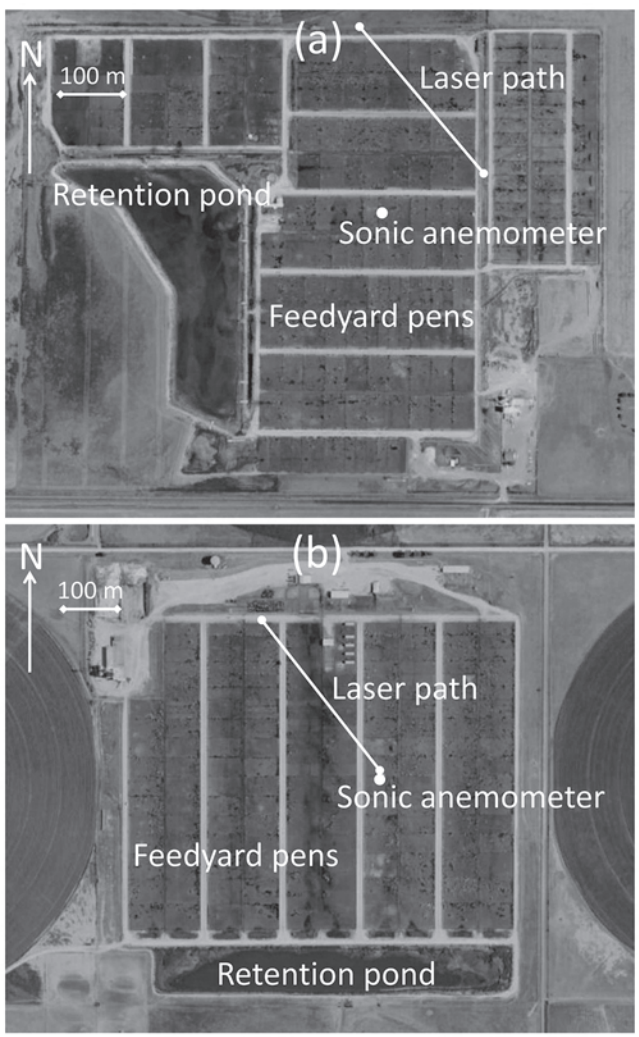

Fig. 1. Aerial views of feedyards used in the study, showing locations of instrumentation and key features, for (a) Feedyard A and (b) Feedyard E.

Ammonia Emissions

Ammonia emissions at the two feedyards was quantified using an atmospheric inverse dispersion model (Windtrax 2.0.7.9, Thunderbeach Scientific, Nanaimo, BC, Canada). Flesch and Wilson (2005) offered a comprehensive discussion of the methodology. The inverse dispersion model requires gas concentration downwind of an emission source area, upwind (background) concentration, wind information, and an accurate map of the source area. The inverse dispersion uses a description of turbulent transfer based on Monin–Obukhov similarity theory and a backward Lagrangian stochastic (BLS) model that calculates the upwind trajectories of large ensembles of gas particles from the concentration measurement location to the source area. The emission rate is quantified by calculating the emission rate necessary to cause the measured increase in concentration above the background. It assumes that the atmospheric surface layer is homogeneous, that flow is stationary, and that the source strength is spatially uniform. The BLS flux estimates from several studies have ranged from −14 to 9% of known tracer releases (Gao et al., 2009; Harper et al., 2009). The NH_3 source area of each feedyard (feedyard pens) was mapped using geographic coordinates taken from a georeferenced digital orthophoto quadrangle of each feedyard (MrSID Geoviewer 2.1, LizardTech Inc., Seattle, WA). All pens were included in the source area map; roads and feed alleys were excluded. Retention ponds used to hold runoff water were not included as source areas because (i) NH_3 flux from feedyard retention ponds is small relative to cattle pens (Flesch et al., 2007), and (ii) a sensitivity analysis performed using Windtrax showed that NH_3 emissions from retention ponds had negligible effect on NH_3 concentrations measured over the feedyard pens under a wide range of retention pond source strengths and atmospheric stabilities.

Optimally, the dispersion model uses as inputs wind speed, wind direction, friction velocity (u^*), turbulence statistics, and the Monin–Obukhov length (L) (Flesch and Wilson, 2005; Flesch et al., 2005). These input variables were provided using measurements from a three-dimensional sonic anemometer (Model 81000, R.M. Young, Traverse City, MI) that was deployed on a 7.2-m tower located near the center of each feedyard. Sonic anemometer data were collected at 10-Hz frequency by a datalogger (CR23X, Campbell Scientific, Logan, UT). Means, variances, and covariances were calculated every 15 min, coordinate rotations were used, and wind speed, wind direction, u^*, L, and the standard deviations of the wind velocity components were calculated (van Boxel et al., 2004).

The BLS model requires a measurement of the atmospheric NH_3 concentration. At each feedyard, an open path laser (Boreal Laser Inc., Spruce Grove, AB, Canada) specifically tuned to detect NH_3 was deployed. At FYA, the laser was mounted on a tower at 3.5 m and integrated the NH_3 concentration along a 335-m path over the feedyard pens. At FYE,

the laser was mounted at 4.2 m and operated along a 350-m path over the feedyard pens. The lasers measured the concentration every 50 s, and 15-min means were calculated. The lasers used during the study were not independently calibrated; we relied on the lasers' internal calibration reference cells and the laser operational diagnostics. Subsequent calibrations in our laboratory using standard gas concentrations passed through a 4-m-long, 0.05-m-diameter tube showed that the lasers were measuring the NH_3 concentration within ±4% of calibration concentrations. Dust or water droplets in the air can reduce the light level of the laser, but they do not affect the accuracy of the concentration measurement.

Background atmospheric NH_3 concentrations were assumed to be constant at 10 μg m^{-3}. Previous studies at cattle feedyards (Todd et al., 2006, 2008) showed that the background concentration varied little within a narrow range. Assuming a concentration of 10 μg m^{-3} would induce an error of about 3% in a typical concentration over the feedyard.

Data were collected from March 2007 through February 2009. Model runs were executed on input data sets with 15-min time steps using ensembles of 10,000 particles. Roughness length was set at 0.09 m (Todd et al., 2008). Input data were excluded when $u^* < 0.15$ m s^{-1} (low wind speed) or $|L| < 10$ (extreme atmospheric stability or instability). Days with 72 or more of the 96 15-min fluxes (75%) were considered complete days, and the mean daily flux was calculated as the mean of the 15-min fluxes. At FYA, 224 d out of 397 total d (56.5%) had <10 15-min observations missing, while at FYE 149 d out of 284 (52.5%) had <10 observations missing. Per capita NH_3–N emission rate (g NH_3–N $head^{-1}$ d^{-1}) was calculated by dividing the mean monthly emission rates by the monthly head counts provided by the feedyard.

At each feedyard, the wind speed and temperature were taken from sonic anemometer measurements and precipitation was measured using a tipping rain bucket. Temperature and wind speed are summarized by month in Fig. 2 and were similar at the two feedyards. Precipitation at FYE was not available for September 2008 through February 2009. For the 18 mo from February 2007 through August 2008, precipitation totaled 670 and 767 mm at FYA and FYE, respectively.

Results and Discussion

Daily Ammonia Flux Density

The time series of mean daily NH_3 flux density at FYA yielded 397 d during 2 yr of measurements (Fig. 3a). The annual pattern of fluxes correlated with the annual pattern of air temperature, with the greatest fluxes during the summer and the least fluxes during the winter. The lowest flux density at FYA included 4 d with fluxes <5 kg ha^{-1} d^{-1} during January and February 2008 when mean daily temperatures ranged from −8.4 to −2.0°C. The flux density exceeded 100 kg ha^{-1} d^{-1} on 8 d out of 397 in the 2-yr time series, with seven

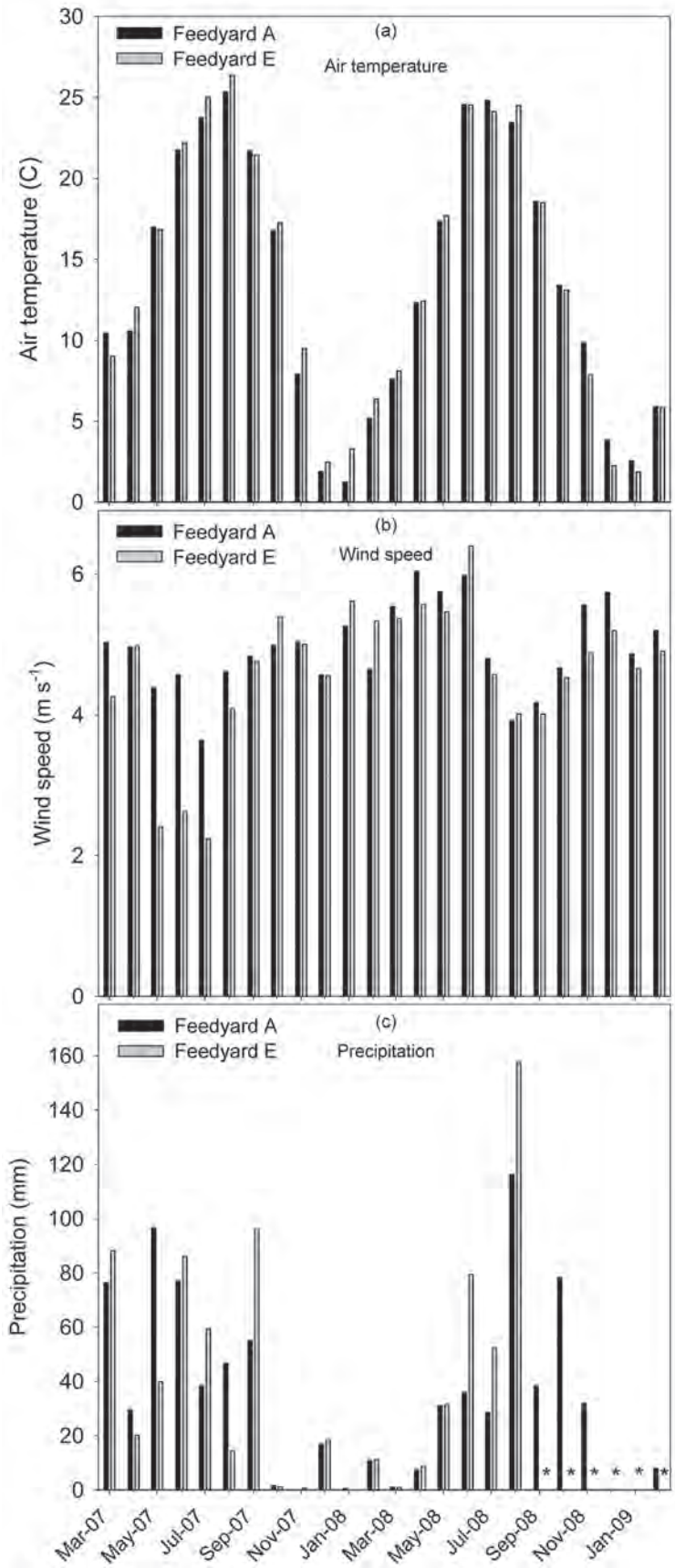

Fig. 2. Mean monthly (a) air temperature and (b) wind speed measured at a height of 7.2 m above the ground, and (c) precipitation from March 2007 to February 2009. Asterisks indicate that data were not available for Feedyard E.

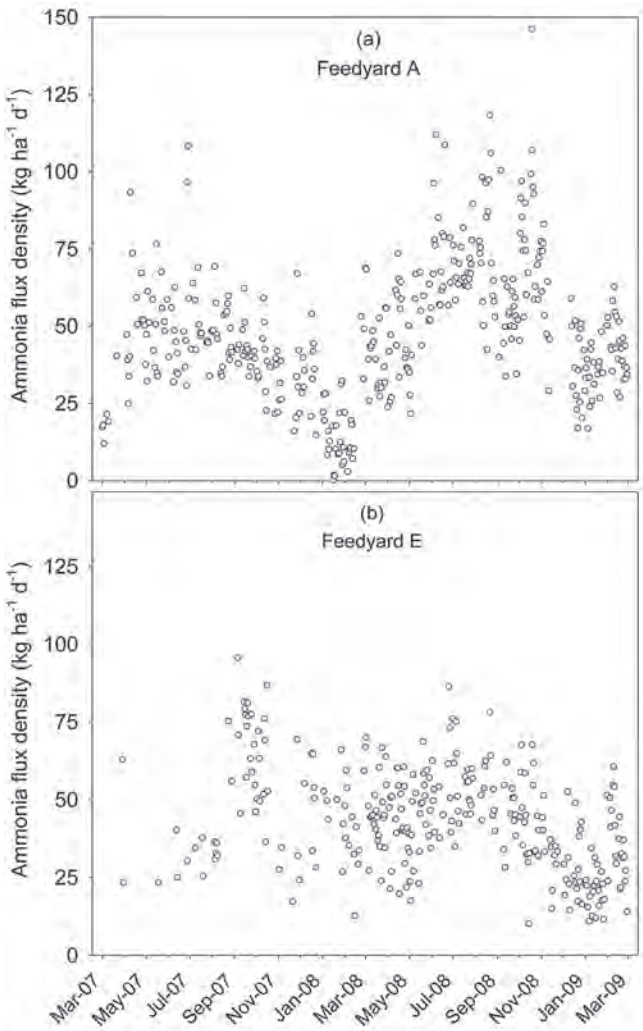

Fig. 3. Mean daily NH_3 flux density from March 2007 through March 2009 from (a) Feedyard A and (b) Feedyard E.

of those days during the summer of 2008. Fluxes during the second year beginning March 2008 were generally greater than those observed in the first year. Beginning in January 2008, wet distillers grains were substituted for some of the steam-flaked corn in the feed rations. The crude protein content of the rations subsequently increased from 12.9% at the beginning of February 2008 to a mean of 18.8% during August, September, and October 2008. The optimum crude protein content for beef cattle rations ranges from 12.5 to 13.5% (National Research Council, 2000). Excess N in the diet from crude protein is excreted, mostly as urea in urine, and this N is readily available for hydrolysis and subsequent volatilization as NH_3. It was this excess excreted N that probably contributed to the increased NH_3 flux observed during 2008.

The first 5 mo of data collection at FYE in 2007 yielded only 9 d with >72 15-min observations per day because of operational difficulties (Fig. 3b). These included power loss to the open path laser, failure of the sonic anemometer, and low friction velocity. Most of these missing data occurred during the nighttime. A total of 284 d populated the FYE database, with 219 d during the second year beginning with March 2008. For the year beginning with March 2008, NH_3 flux densities at FYE showed an annual pattern similar to that observed at FYA, with fluxes generally tracking air temperature. Minimum daily fluxes ranged from 10 to 15 kg ha^{-1} d^{-1}, observed on 7 d during February, October, and December 2008 and January 2009. Fluxes did not exceed 100 kg ha^{-1} d^{-1}; the maximum flux was 97 kg ha^{-1} d^{-1} on 3 Sept. 2007. Relatively high wintertime fluxes were observed during January and February 2008. A close look at temperature, wind speed, wind direction, and precipitation offered no clues as to why, although high-flux days were correlated (as expected) with high wind speeds (8–12 m s^{-1}).

Monthly Per Capita Ammonia Nitrogen Emission Rate

Daily NH_3 flux densities were averaged for each month and then converted to PCERs by normalizing with the mean monthly cattle population provided by the feedyards. March through July 2007 at FYE were not included because of the low number of days in each month.

At FYA (Fig. 4a), PCER ranged from 31 g NH_3–N head^{-1} d^{-1} during January 2008 to 207 g NH_3–N head^{-1} d^{-1} during October 2008. Emissions during the second year were probably greater than those during the first year because of increased fed N provided by wet distillers grains in the rations. The NH_3–N emissions at FYE ranged from 36 g NH_3–N head^{-1} d^{-1} during January 2009 to 121 g NH_3–N head^{-1} d^{-1} during September 2007 (Fig. 4b). The PCERs at FYE did not vary as much from month to month as at FYA. A number of management differences between the feedyards could have influenced this difference in monthly amplitude, including differences in crude protein fed, summertime sprinkling for dust control at FYE, and number of common days (204 out of 578 d from August 2007–February 2009).

Monthly Ammonia Nitrogen Emission Rate as Fraction of Fed Nitrogen

Feed data provided by the feedyards were combined with laboratory analyses for N content of regularly collected feed samples to calculate the total and per-head N fed during each month; the NH_3–N loss as a fraction of fed N was then calculated by dividing the monthly PCER by the monthly fed N per head.

Monthly NH_3–N loss at FYA ranged from 19 to 85% of fed N (Fig. 5a). Values were lowest during the winter months and greatest during the summer months. Fractional NH_3–N loss also tended to be greater during the second year. The fed N averaged 184 ± 17 g N head^{-1} d^{-1} during the first year and increased to 201 ± 40 g N head^{-1} d^{-1} during the second year, with greater fed N and greater variability because of increased N in the rations during the second year. Feedyard E showed a similar range of fractional NH_3–N loss, from 24 to 80% of fed N, although the fractional loss at FYE tended to be greater during the winter months and less during the summer months compared with FYA (Fig. 5b).

Seasonal and Annual Ammonia Emissions

The seasonal NH_3–N PCER at FYA averaged 71 g NH_3–N head^{-1} d^{-1} during the winter and 158 g NH_3–N head^{-1} d^{-1} during the summer, with PCER during the spring and autumn intermediate between the summer and winter values (Table 1). Fractional loss of NH_3–N was least during the winter and

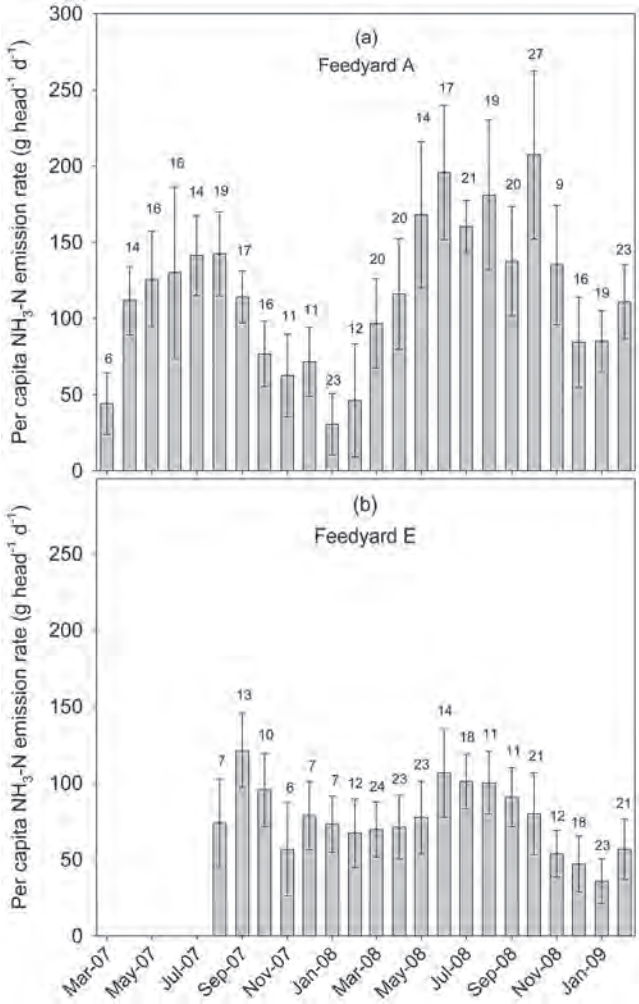

Fig. 4. Mean monthly per capita NH_3–N emission rate from March 2007 to February 2009 for (a) Feedyard A and (b) Feedyard E. The error bars represent ±1 standard deviation of the mean for the month. The number indicates the number of days that contributed to the monthly mean.

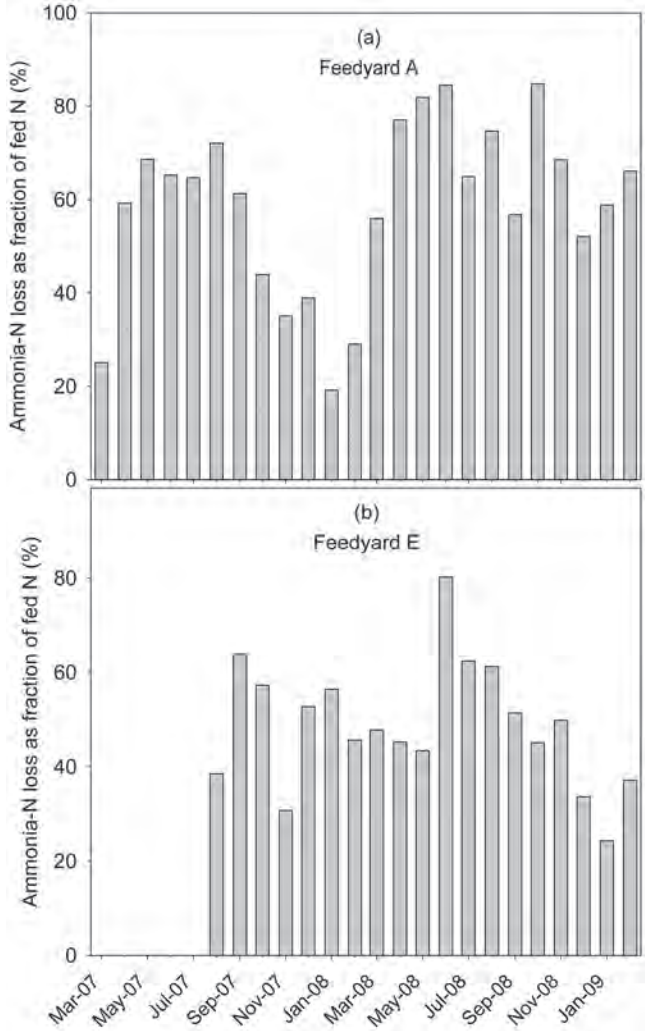

Fig. 5. Mean monthly NH_3–N loss as a fraction of fed N from March 2007 to February 2009 for (a) Feedyard A and (b) Feedyard E.

greatest during the summer (44 and 71%, respectively), with spring and autumn fractional losses similar to each other. Feedyard E showed a similar pattern of seasonal NH_3 emissions, with a mean summer PCER of 103 g NH_3–N head^{-1} d^{-1} and winter PCER of 60 g NH_3–N head^{-1} d^{-1}. Greater values of fed N, PCER, and fractional loss at FYA, compared with FYE, reflect the greater crude protein provided by distillers grains in the rations fed during January through November of the second year. On an annual basis, the NH_3–N PCER and fractional NH_3–N loss averaged 115 g NH_3–N head^{-1} d^{-1} and 59%, respectively, at FYA and 80 g NH_3–N head^{-1} d^{-1} and 52%, respectively, at FYE.

These seasonal emission metrics fall within the range of values for cattle feedyards reported in the literature. Per capita emission rates averaged 124 g NH_3–N head^{-1} d^{-1} during April and July at a Texas feedyard (Flesch et al., 2007). At the same feedyard, but spanning different times, Todd et al. (2008) found that PCERs averaged 128 and 64 g NH_3–N head^{-1} d^{-1} during the summer and winter, respectively. McGinn et al. (2007) quantified PCER during June through October at an Alberta feedyard and found that PCER averaged 115 g NH_3–N head^{-1} d^{-1}. At another feedyard in Alberta, van Haarlem et al. (2008) reported a mean October PCER of 262 g NH_3–N head^{-1} d^{-1}.

Summertime loss of NH_3–N as a fraction of fed N ranged from 38% (Baum and Ham, 2009) to 68% (Todd et al., 2008),

Table 1. Mean seasonal fed N, per capita emission rate (PCER) of NH_3–N, and fractional loss of fed N as NH_3–N. Means for each season are for 2 yr, except for spring and summer at Feedyard E, which are for 1 yr.

Season (months)	Feedyard A			Feedyard E		
	Fed N	PCER	Loss of fed N	Fed N	PCER	Loss of fed N
	g head^{-1} d^{-1}		%	g head^{-1} d^{-1}		%
Spring (Mar.–May)	179	110	61	160	73	46
Summer (June–Aug.)	223	158	71	153	103	68
Autumn (Sept.–Nov.)	204	122	58	167	83	50
Winter (Dec.–Feb.)	163	71	44	144	60	42

with others falling between 51 and 65% (Bierman et al., 1999; Cole et al., 2006; Erickson and Klopfenstein, 2001; Erickson et al., 2000; Flesch et al., 2007; McGinn et al., 2007). Fractional loss during the winter ranged from 27 to 44% (Bierman et al., 1999; Todd et al., 2005, 2008). Exceptional was the fractional loss of 73% reported by van Haarlem et al. (2008) during the autumn in Alberta, attributed to a high crude protein diet (∼23%). Similarly, we found that 70% of fed N was lost as NH_3–N during the autumn of 2008, when crude protein reached 19% due to the inclusion of wet distillers grains in the rations.

Ammonia emissions are sensitive to crude protein in rations and increased as crude protein provided by wet distillers grains increased above the level needed to meet the physiological needs of the cattle. This poses a feed management problem for cattle producers who seek to reduce NH_3 emissions yet face a feed supply environment increasingly dominated by the growing demand for corn-based ethanol. The feeding of distillers grains thus complicates efforts to reduce NH_3 emissions from cattle feedyards. There was considerable variability both within and between the two feedyards studied here, and more detailed studies are needed to determine the effect of management and environmental variables such as diet, temperature, precipitation, and manure water content on NH_3 emissions. Additional analysis of the interplay of source area and occupancy is needed to assess its effect on the performance of the inverse dispersion model.

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