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Ammonia losses and nitrogen partitioning at a southern High Plains open lot dairy

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HIGHLIGHTS

- Quantified ammonia emissions at an open lot dairy during summer in New Mexico.
- Almost half of the nitrogen fed to cows was lost to the atmosphere as ammonia.
- Almost all ammonia emissions came from the open lot area where cows were housed.
- Manure handling and animal housing affect the source and magnitude of ammonia loss.

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ABSTRACT

Animal agriculture is a significant source of ammonia (NH_3). Cattle excrete most ingested nitrogen (N); most urinary N is converted to NH_3, volatilized and lost to the atmosphere. Open lot dairies on the southern High Plains are a growing industry and face environmental challenges as well as reporting requirements for NH_3 emissions. We quantified NH_3 emissions from the open lot and wastewater lagoons of a commercial New Mexico dairy during a nine-day summer campaign. The 3500-cow dairy consisted of open lot, manure-surfaced corrals (22.5 ha area). Lactating cows comprised 80% of the herd. A flush system using recycled wastewater intermittently removed manure from feeding alleys to three lagoons (1.8 ha area). Open path lasers measured atmospheric NH_3 concentration, sonic anemometers characterized turbulence, and inverse dispersion analysis was used to quantify emissions. Ammonia fluxes (15-min) averaged 56 and 37 μg m^{-2} s^{-1} at the open lot and lagoons, respectively. Ammonia emission rate averaged 1061 kg d^{-1} at the open lot and 59 kg d^{-1} at the lagoons; 95% of NH_3 was emitted from the open lot. The per capita emission rate of NH_3 was 304 g cow^{-1} d^{-1} from the open lot (41% of N intake) and 17 g cow^{-1} d^{-1} from lagoons (2% of N intake). Daily N input at the dairy was 2139 kg d^{-1}, with 43, 36, 19 and 2% of the N partitioned to NH_3 emission, manure/lagoons, milk, and cows, respectively.
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1. Introduction

Ammonia (NH_3) is a major trace gas emitted from concentrated cattle operations like dairies and beef feedyards (Hristov et al., 2011; Leytem et al., 2013; Todd et al., 2008, 2011). This fugitive NH_3 is a major pathway for reactive nitrogen (N) entering the atmosphere and subsequently being deposited to terrestrial and aquatic ecosystems. It is a precursor to $PM_{2.5}$ particulates that can negatively impact air quality (Hristov, 2010). It is also a precursor to the greenhouse gas nitrous oxide (N_2O) when deposited on land (IPCC, 2006). Dairies with more than 700 mature cows and that exceed the reportable quantity of emitted NH_3 (45.4 kg NH_3 d^{-1}) are required under the U.S. Emergency Planning and Community Right to Know Act (EPCRA) to report an estimate of NH_3 emissions.

Dairies are highly diversified in both animal housing design and management practices for handling manure. Housing for milk cows includes tie stall barns, freestall barns, bedded pack barns and covered or uncovered open lots (Hristov et al., 2011; USDA, 2010). Manure is generally handled intensively in dairies. Practices include daily scrape or flush manure removal systems, solids

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separations, covered or uncovered wastewater lagoons, recycling and reuse of wastewater, frequent manure removal and mechanical grooming of open lot surfaces. The physical scale of dairies varies greatly, from smaller, more traditional dairies in the eastern U.S., to very large dairies of the drier western U.S. that can exceed 10,000 cows (USDA, 2010).

When animals are concentrated in feeding operations like dairies, excreted nutrients are also concentrated. For example, a 680 kg cow in mid-lactation requires from 20 to 30 kg of dry matter intake (DMI) each day and from 0.45 to 0.80 kg N d^{-1}, depending on factors such as milk production, diet composition, feeding behavior and weather (NRC, 2001). About 20–25% of N intake is used for milk production and the physiological needs of the cow, but from 70 to 80% of N intake is excreted (Hristov et al., 2011). Urinary N, mostly in the form of urea, is readily hydrolyzed to NH_3. The temperature-dependent process requires the enzyme urease, ubiquitous in dairy manure, and can be considered a fast pool source of NH_3. Nitrogen in feces is mostly in more complex organic forms that are transformed through slower mineralization processes into reactive compounds.

Ammonia emissions from feedyards general do not vary much across the beef-producing region of the U.S. Great Plains (Hristov et al., 2011; Preece et al., 2011), indicating a more common set of management practices. For example, manure is typically cleaned from a feedyard pen only once, at the end of a 150–180 day feeding period. Because manure handling is standardized, the most critical drivers of feedyard NH_3 emissions are temperature and dietary crude protein (Cole et al., 2005; Todd et al., 2011, 2013). Dairy NH_3 emissions on the other hand are quite variable from region to region and from practice to practice (Hristov et al., 2011; Moore et al., 2014). This diversity in emissions probably reflects the diversity in housing and manure management systems.

The southern High Plains of the southwestern United States has been a growing and major dairy producing region for over three decades. Production has centered in New Mexico, with milk cow population of 142,000 cows in three eastern High Plains counties in 2013 (USDA, 2014). Recent growth has occurred in seven southern High Plains counties in West Texas where the milk cow population has increased from 16,800 cows in 2000 to 209,000 cows in 2013 (USDA, 2014).

Ammonia emissions from open lot dairy production systems have been studied in California (Cassel et al., 2005a,b; Moore et al., 2014), Idaho (Bjorneberg et al., 2009; Leytem et al., 2011) and east Texas (Mukhtar et al., 2008), but not in the southern High Plains region. Our objective was to quantify NH_3 emissions at a commercial southern High Plains dairy farm. We focused on the two major sources of NH_3 volatilization, the open lot and the wastewater lagoon system. We also sought to build a nitrogen balance for the dairy that partitioned feed intake N, N retention in cows, milk N, volatilized NH_3–N, urinary N and feces N.

2. Materials and methods

2.1. Description of dairy

Research was conducted at a commercial dairy farm located in Curry County, New Mexico (USA) from 7 August 2009 to 15 August 2009 (day of year, DOY 219–227). Production practices at the dairy were typical of regional practices. The production facilities consisted of twelve open lot, manure-surfaced corrals (from 82 to 96 m by 225 m) with total area of 22.5 ha, and a nearby system of three wastewater lagoons (1.8 ha surface area); a fourth lagoon was unfilled (Fig. 1). A sun shade (7 m by 192 m) was located along the center line of each corral. Manure was not removed from corrals during the study, but the corral surfaces were groomed with a tractor-drawn harrow. A concrete-surfaced feeding alley was located on one long side of each corral. Feed was deposited just outside corrals in the feed alley and cows accessed the feed through stanchions while standing in concrete-surfaced flush lanes. The flush lanes were scheduled to be flushed twice a day using water recycled from the wastewater lagoons. However, operationally the flushing schedule was irregular and depended on whether dairy personnel were available, so that some days the lanes were flushed less than twice. The flush water removed and carried accumulated manure from the flush lane through a 700 m long canal that flowed into the first of the three lagoons; lagoons 1 and 2 were directly connected, lagoon 3 received overflow water (Fig. 1). Sediment from the bottom and near the inlet of the first lagoon was continually pumped to an adjacent solids separator; separated solids were stored at the separator for the duration of the study in a 10-m by 10-m stockpile.

Potential sources of ammonia at the dairy were the open lot, the lagoons, the canal that carried flush water to the lagoons, and the separated solids pile. We treated the open lot and lagoons as the major sources. However, this meant that any emissions from the canal would be included with open lot emissions when winds were southerly or south-westerly. We expected canal emissions to be very small and to make a negligible contribution to the open lot and total dairy emissions. It was not possible to discriminate lagoon emissions from emissions from the separated solids pile just to the east of the first lagoon. When wind direction was south-easterly, emissions from the solids pile and lagoon were combined, while at other times, the solids pile emissions were not included with lagoon emissions. Leytem et al. (2011) reported that NH_3 fluxes from dairy compost were similar to those from wastewater lagoons. If we take fluxes from compost as an approximation of fluxes from the separated solids, then emissions from the 100-m^2 solids pile would contribute little to emissions from the 18,000-m^2 lagoons.

2.2. Cow population, diets and milk production

Dairy management provided us with detailed information on the types and numbers of cows resident at the dairy during the study. Information on the composition of rations fed to the different cow classes was not available, but a representative ration in the region would include 30% corn silage, 30% rolled corn, 20% alfalfa hay, 10% dry distillers grains, 4% soybean meal, and 6% minerals and supplements. Dairy management was able to provide us with total dry mater intake (DMI) and diet crude protein (CP) content for each cow class, and total milk production. Cows were milked three times a day, however we did not have the times when individual pens were vacant.

2.3. Dairy nitrogen balance

A nitrogen balance for the dairy was calculated that included measured N feed intake, milk N and NH_3–N loss, and estimated values of N retained in cows and excreted N. For the estimated values, we used the empirical equations of Castillo et al. (2000), based on a meta-analysis of a database of 581 cows fed 91 different diets. Milk N was calculated by assuming that 3.31% of milk was crude protein and that 16% of crude protein was N. No off-farm manure N losses were considered, nor did we attempt to partition N between open lot and lagoons.

2.4. Inverse dispersion analysis

Ammonia emissions were quantified using inverse dispersion analysis (IDA; Flesch and Wilson, 2005). Inverse dispersion analysis has become a commonly used micrometeorological method to

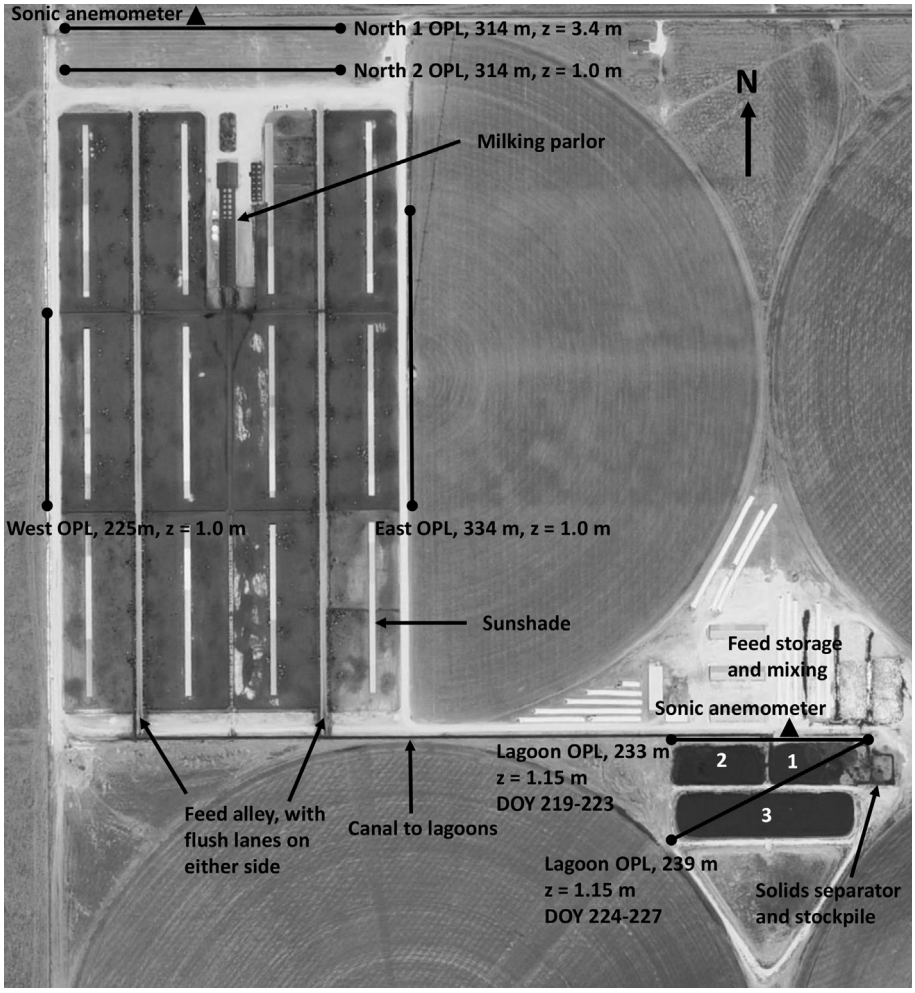

Fig. 1. Layout at the 3500-head New Mexico commercial dairy where sampling took place. The North 1 open path laser (OPL, solid lines with end circles) remained in place, but the North 2, West and East OPL were deployed depending on wind direction. The path of the lagoon OPL was changed on DOY 224 from along the north side of the lagoons to diagonally across the lagoons. Area of the open lot was 22.5 ha and area of the three lagoons was 1.8 ha.

quantify gaseous emissions (Bjorneberg et al., 2009; Flesch et al., 2009; Harper et al., 2009; Leytem et al., 2011). It relies on Monin–Obukhov similarity theory to describe wind flow characteristics. Four parameters are needed to specify the near-surface turbulence: the friction velocity (u^*), Monin–Obukhov length (L), the surface roughness parameter (z_0) and the wind direction (β). The IDA uses these parameters in a backward Lagrangian stochastic model to follow the backward upwind trajectories of a large ensemble of tracer gas particles, in this case parcels of ammonia gas, from concentration sensor to source. This establishes a simulated ratio of concentration to flux, $(C/Q)_{sim}$ (s m^{-1}), for a given set of turbulence parameters and touchdowns of particles in the defined source area, which is used in the equation

$$Q = \frac{(C_d - C_b)}{(C/Q)_{sim}}$$

where Q ($\mu g\ m^{-2}\ s^{-1}$) is the tracer gas flux density of the source, C_d ($\mu g\ m^{-3}$) is the tracer gas concentration downwind from the source and C_b ($\mu g\ m^{-3}$) is the tracer gas background, or upwind, concentration.

Inverse dispersion analysis for NH_3 emission from the open lot and lagoons of the dairy was handled using the software package WindTrax (version 2.0.8.8, Thunder Beach Scientific). The software requires accurate mapping of the locations of concentration and meteorological measurements, and NH_3 sources. The corrals and lagoons were considered to be area sources, with manure and NH_3 source strength distributed evenly. We mapped the source areas, individual corrals and lagoons, using coordinates extracted from georeferenced satellite imagery. The locations of concentration sensors and meteorological towers were located using measured distances from georeferenced landmarks. All Windtrax simulations used ensembles of 50,000 particles. The IDA for the open lot and lagoons were conducted separately, not in a multiple source mode.

Background NH_3 concentration, based on our experience and a seven-year database of regional NH_3 atmospheric concentration measurements taken at the Ammonia Monitoring Network site 150 km northeast of the dairy, was assumed constant at 5 $\mu g\ m^{-3}$ (NADP, 2014). Observations when the lagoons were upwind of open lot concentration measurements were not used in the IDA of open lot emissions. Similarly, observations when the open lot was upwind of lagoon concentration measurements were not used in the IDA of lagoon emissions. Other nearby sources of NH_3 were 14 similarly sized dairies within 10 km of the study dairy. Almost 94% of the observations used in the open lot IDA and over 98% of the observations used in the lagoon IDA had wind directions in the southerly arc between 135° and 270°. There were only four upwind dairies within this arc of accepted data, at distances of 5–10 km.

Typical effective turbulent transport experienced during the study was expected to keep C_b low. Stable nighttime conditions could contribute to greater C_b, but these were also the times when C_d was greatest. We considered variations in background concentration negligible because background NH_3 concentration was a very small fraction of downwind NH_3 concentration. For example, NH_3 concentration downwind from the open lot averaged 214 μg m^{-3} and ranged as high as 1113 μg m^{-3}. Concentrations were of similar magnitude over the lagoons.

2.5. Atmospheric turbulence and ammonia concentration measurements

Two three-axis sonic anemometers (Model 81,000, R.M. Young), one north of the open lot and one north of the lagoons, were used to provide turbulence inputs for the IDA. The sonic anemometers were deployed at a height (z) of 3.4 m. Sonic anemometers were sampled at 10 Hz frequency by a datalogger (CR23X, Campbell Scientific). Means, variances and covariances were calculated every 15-min and coordinate rotations were applied. Equations from van Boxel et al. (2004) were used to calculate u^*, L, z_0, β and the standard deviations of wind velocity components (σ_u, σ_v, σ_w). Other meteorological variables measured at the same location as sonic anemometers included relative humidity and air temperature (HMP45, Vaisala), and precipitation (tipping bucket). These sensors were sampled every 5 s and data recorded to the datalogger at 15-min time steps.

Ammonia concentration downwind from the open lot was measured from DOY 219 to 227 using two open path tuned diode lasers (OPL, Gasfinder 2.0, Boreal Laser Inc.). An OPL setup consisted of the laser transmitter/detector and a retroreflector populated with corner cube mirrors. The OPL integrated the NH_3 concentration along the length of the laser beam path. One OPL was located on a tower 90 m north of the open lot at $z = 3.4$ m. It scanned a path 314 m long. This OPL remained at this location throughout the study and measured ammonia concentration from the open lot whenever winds were from the prevailing southerly directions. The second OPL was opportunistically deployed ($z = 1.0$ m) depending on the wind direction. For southerly winds it was located 50 m north of the open lot and scanned a 314-m path; for easterly winds, it was located 20 m west of the open lot and scanned a 225-m path; for westerly winds, it was located 20 m east of the open lot and scanned a 334-m path. This flexible arrangement assured that we had one or two OPL measuring NH_3 concentrations for southerly wind directions, which occurred 79.0% of the time. Westerly and easterly wind directions occurred 6.5% and 10.7% of the time, respectively. Ammonia concentration at the three wastewater-filled lagoons was measured with an OPL that scanned a 233-m path along the north side of the lagoons at $z = 1.15$ m above the water surface from DOY 219 to 223. On DOY 224 we moved the retroreflector of the OPL so that the path (239 m) extended diagonally over the lagoons from northeast to southwest. This was intended to accommodate more variable wind directions that we anticipated.

All OPL sampled NH_3 concentration about every 35 s; data were transferred from each OPL to a laptop computer twice a day. The OPL software calculated a metric called R^2 that relates the signal from the sampled NH_3 to that of the laser's internal reference cell. During post-measurement processing, we rejected all concentration readings with $R^2 < 95\%$, which assured that we retained concentrations with accuracies of ±2%, according to the manufacturer. The three OPL were calibrated in the laboratory prior to the study using the procedure described in Todd et al. (2014) and calibration coefficients (0.91, 0.97 and 1.01) were applied to concentration measurements of respective OPL. The NH_3 concentration data were then averaged on 15-min time steps and combined with sonic anemometer data into WindTrax input files.

2.6. Data quality and gap filling

Assumptions of IDA are that the source area surface conditions are homogenous, emission is spatially uniform and flow is stationary. For somewhat complex source areas like the open lot, where there are obstacles like sun shades, wind breaks, corral fences, milking parlor and cows, the wind field can be disturbed and these assumptions challenged. Flesch et al. (2005) recommended that IDA error can be minimized if concentration is measured at a distance more than 10 times the height (z_h) of the obstacles. This criterion was met for NH_3 concentration measurements north of the open lot, but not for NH_3 concentration measurements east or west of the open lot, which were separated from the open lot by about 4 z_h. However, these measurements only accounted for 17% of observations.

Monin–Obukhov similarity theory fails under certain conditions. Following the recommendation of Flesch and Wilson (2005), data were not used for IDA analysis when mechanical turbulence was low ($u^* < 0.15$ m s^{-1}), during extreme thermal stability or instability ($|L| < 10$ m), or when z_0 exceeded 1.0 m. We also rejected concentration data that were less than two times the assumed constant background concentration. Gaps in flux data from WindTrax were filled using linear interpolation for gaps of 1 h or less. Data retention at the open lot was 78% of possible 15-min observations over eight days, and 9.3% of retained data were interpolated. At the lagoons, 68% of possible 15-min observations over eight days were retained; 5.6% of retained data were interpolated. Most missing data were because of unacceptable wind directions. Other gaps were distributed during early morning, midmorning, late morning or late afternoon and were mostly associated with low friction velocity. Diel ensembles of open lot or lagoon NH_3 fluxes were composited by calculating three-point running means of quarter-hour fluxes for each quarter-hour in the day. This gave the quarter-hour means from 71 to 100% of the 21 or 24 possible data points for a mean, which minimized the potential for bias due to data gaps. Mean NH_3 emissions for open lot and lagoons for the whole study were calculated by integrating emissions from these diel composites. Harper et al. (2009) presented results of eight gas release studies that showed a mean recovery of 100% using the IDA. Errors of those eight studies ranged from 13 to 29%. Our stochastic simulations of IDA yielded a mean error of 17%. Harper et al. (2009) recommended that an uncertainty of 20% is appropriate for IDA.

3. Results and discussion

3.1. Meteorological conditions during the study

The study period was characterized by warm weather, with daily mean temperatures ranging from 23.2 to 27.7 °C (Table 1). The maximum temperature recorded during the study was 34.4 °C. A thunder storm during the evening of DOY 222 produced 29.0 mm of rain and divided the study into four days of warmer, drier weather followed by four days of relatively cooler, moister weather. The wind was generally calm during the nighttime and especially during early morning hours. Maximum wind speeds were usually logged during the afternoon, and ranged from 4.6 to 7.8 m s^{-1}, with exceptions being the 16.1 m s^{-1} wind speed recorded during the thunder storm on DOY 222 and the 8.8 m s^{-1} wind speed during the small storm on DOY 224. Meteorological conditions at the lagoons (data not shown) were similar to those near the open lot, although humidity tended to be about four to six percentage points higher, and air temperatures tended to be warmer at night and cooler during the day, compared with temperatures near the open lot.

Table 1
Meteorological conditions during the study, measured at the sonic anemometer tower located 90 m north of the open lot. Sensors were at z = 3.4 m.

DOY	Relative humidity (%)			Air temperature (°C)			Wind speed (m s^{-1})			Precipitation (mm)
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Total
219[a]	22	37	68	24.9	30.3	33.8	1.9	4.7	6.4	0
220	13	31	50	20.6	27.7	34.4	1.5	3.7	6.4	0
221	17	41	56	20.6	25.9	32.9	0.5	4.2	7.8	0
222	28	56	86	16.8	23.6	32.3	0.6	3.6	16.1	29.0
223	32	62	88	17.9	24.2	30.8	0.6	2.8	6.5	0
224	30	60	89	16.9	24.0	31.1	0.4	2.8	8.8	2.3
225	28	58	88	17.4	24.3	31.3	1.3	3.5	5.6	0
226	61	74	87	18.0	23.2	30.2	1.4	3.0	4.6	0
227[b]	84	93	95	18.1	19.6	21.2	0.4	1.5	3.6	0

[a] 1100 h–2400 h.
[b] 2400 h–0745 h.

The 29 mm of rain and subsequent runoff from the open lot overwhelmed the lagoon system. The first two lagoons filled and overflowed the berm into the third lagoon, which subsequently filled to near capacity. The pumping system that brought solids from the bottom of the first lagoon to the solids separator and that pumped water to the open lot for flushing the feeding alleys was damaged, so that there was no solids separation or alley flushing until late on DOY 223, and then intermittently after that.

3.2. Cow population, diets and milk production

The cow population at the dairy was composed of the production herd, both milking and dry cows. This is typical of southern High Plains dairies, where heifer calves are often housed at a different facility. The total cow population during the study was 3492 cows; 73% were in full lactation (mean 150 days in milk), 7% were fresh (mean 20 days in milk) and 20% were dry (Table 2). Although typical of the region, this size cow population is among the larger of U.S. dairies.

The CP content of diets ranged from 0.136 kg CP kg^{-1} DMI (dry, far cows) to 0.174 kg CP kg^{-1} DMI (milking cows); the weighted (by cow class population) mean CP for the herd was 0.167 kg CP kg^{-1} DMI. Milking cows consumed on average 701 g N cow^{-1} d^{-1}, which was 83.3% of the N fed at the dairy. The weighted (by cow class population) mean N intake for the entire dairy herd was 612 g N cow^{-1} d^{-1}. Total daily milk production (milking and fresh cows) was 81,770 kg d^{-1}, equivalent to 29.2 kg cow^{-1} d^{-1}. Daily milk N production was 406 kg d^{-1} (0.145 kg cow^{-1} d^{-1}). Milk N utilization efficiency was 21%.

3.3. Ammonia concentrations measured at open lot and lagoons

Median NH_3 concentration measured by the OPL that was 90 m north of the open lot at z = 3.4 m was 116 μg m^{-3}, and the values at the 10th and 90th percentile for the 665 measurements were 31 and 239 μg m^{-3}, respectively (Fig. 2). Concentration measured by the OPL that was 50 m north of the open lot at z = 1.0 m was greater, with a median concentration of 164 μg m^{-3} and 10th and 90th percentile values of 43 and 264 μg m^{-3}, respectively. The West OPL, located only 20 m from the west side of the open lot, measured the greatest concentrations, primarily because about two-thirds of the readings occurred at night between 2000 and 0800, when stable conditions contributed to greater concentrations.

The median concentration measured at the lagoon decreased by more than half, from 203 to 94 μg m^{-3}, when the lagoon OPL was relocated from a path along the north side of the lagoons to a path that crossed diagonally across the lagoons following the large rain.

Atmospheric NH_3 concentrations can vary greatly because of sensor height, distance from source, meteorological conditions and emission rate; the concentrations we observed were within ranges found at other open lot dairies (Bjorneberg et al., 2009; Leytem et al., 2009; Moore et al., 2014).

Table 2
Cow population, feed dry matter intake (DMI) and crude protein (CP), and the fraction of N fed for each cow class.

Cow class	Population	DMI (kg cow^{-1} d^{-1})	CP (kg CP kg^{-1} DMI)	Fraction of total N intake (%)
Milking	2541	25.1	0.174	83.3
Fresh	261	21.5	0.163	7.0
Dry (close)	168	13.4	0.152	2.5
Dry (far)	522	13.5	0.136	7.2
Total	3492	–	–	100
Weighted mean[a]	–	22.5	0.167	–

[a] Weighted by population of each cow class.

3.4. Ammonia emissions from open lot and lagoons

Ammonia flux densities from the open lot on 15-min time steps ranged from 6 to 192 μg m^{-2} s^{-1} and averaged 55 μg m^{-2} s^{-1} (Fig. 3a). The 15-min NH_3 emission rates ranged from 386 to 1745 kg d^{-1} (Fig. 4a). Emission rate minima occurred during early morning and bimodal daily maxima tended to peak during

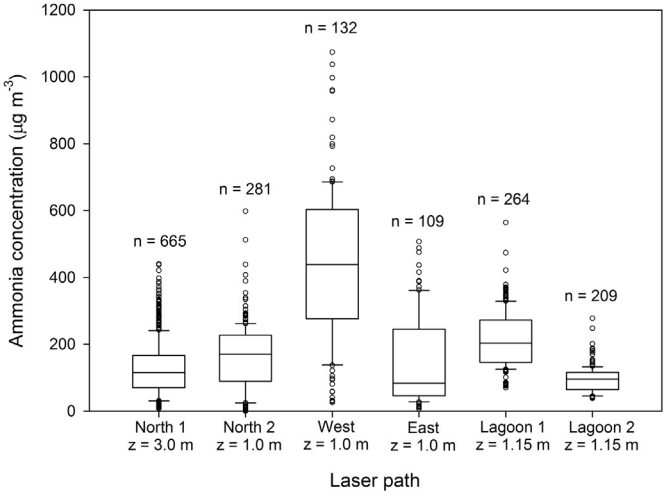

Fig. 2. Ammonia concentration measured by open path lasers (OPL) at the open lot and lagoons. The box represents the first, second (median) and third quartiles. The error bars are values for the 10th and 90th percentiles. Outliers are shown as open circles.

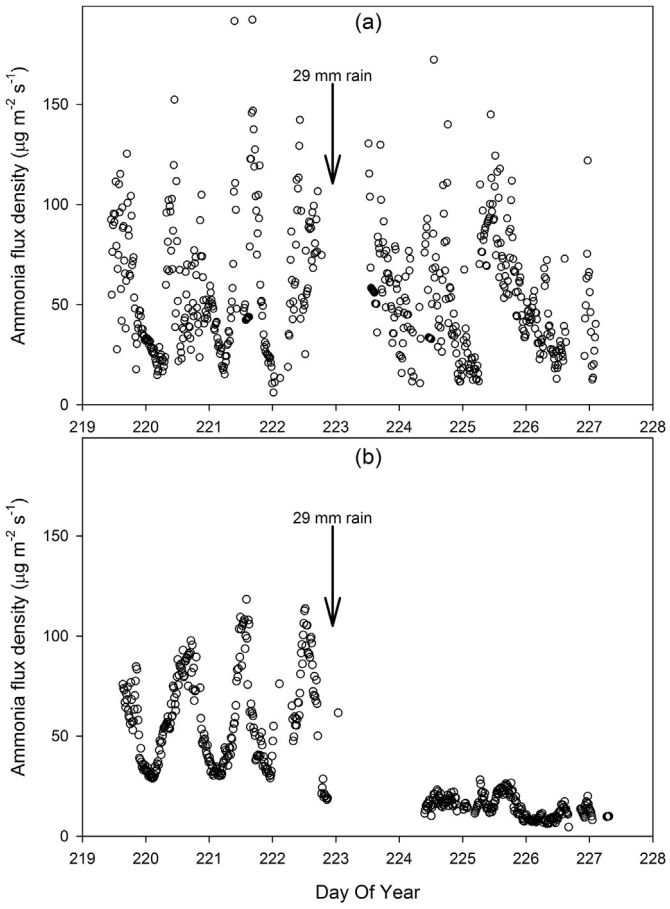

Fig. 3. Ammonia flux density, 15-min time steps, at the open lot (a) and at the lagoons (b).

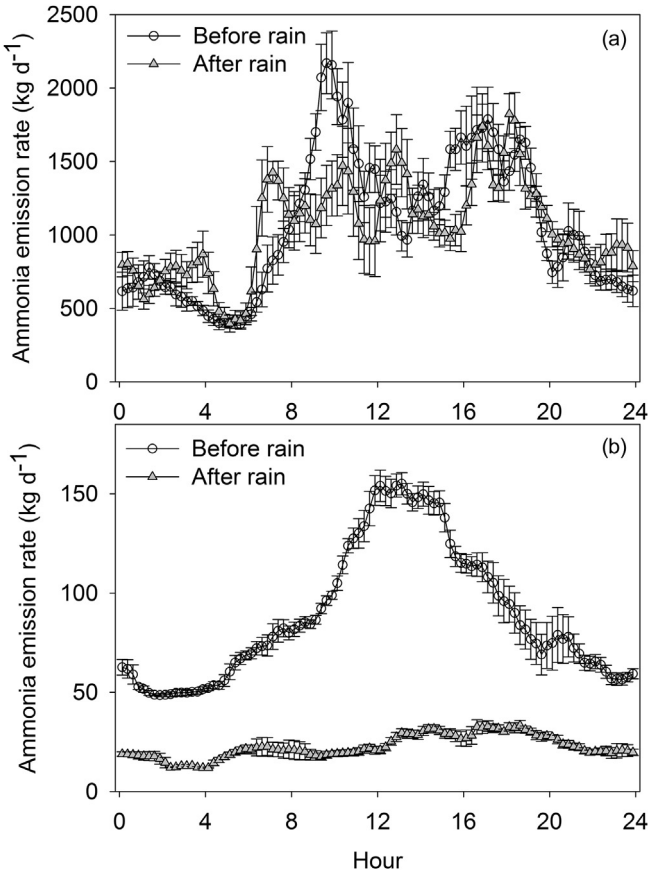

Fig. 4. Composite diel ammonia emission rate for the open lot (a) and the lagoons (b). Note that the y-axes of the two panels are different. Each quarter-hour emission rate was calculated with a three-point running average of 15-min emission rates. Error bars are the standard error for each quarter-hour mean (n from 14 to 24).

midmorning and midafternoon. This pattern of emissions in the dairy contrasts with the pattern observed in open lot and freestall dairies and in beef cattle feedyards (Harper et al., 2009; Leytem et al., 2011; Todd et al., 2011), where emissions generally correlated with air temperature and had a single midday maximum. We speculated that the diel emission pattern at the dairy open lot was related to milking schedule and the movement of cows between corrals and milking parlor, and how the interplay of occupied and temporarily empty corrals affected the NH_3 source footprint. No effect on diel emissions of the rain on DOY 222 was apparent. We expect that deposited urine would be the major source of emissions from the open lot surface, and that source would be the same before or after the rain. Sometimes, excessive wetness of manure can suppress NH_3 emission; however, the open lot was well-drained and only a few low spots had standing water. On average, 1061 kg NH_3 were emitted daily from the open lot (Table 3). Per capita emission rate (PCER) of NH_3 averaged 304 g animal^{-1} d^{-1} (based on the entire herd). Ammonia-N loss from the open lot was 41% of N intake.

The magnitude of NH_3 fluxes from the lagoons was similar to that from the open lot prior to the rain on DOY 222 (Fig. 3b). Flux densities ranged from 18 to 118 μg m^{-2} s^{-1} and averaged 58 μg m^{-2} s^{-1}. However, after the rain on DOY 222 and adjustment of the OPL path on DOY 224, fluxes were much less than before the rain, with flux densities in a narrow range between 5 and 28 μg m^{-2} s^{-1}. Several things could have contributed to this change. The influx of runoff water to the lagoons diluted the ammonium concentration in the lagoon water by half (from 286 to 136 mg L^{-1}). The cross-lagoon position of the laser path meant that the third lagoon had a greater influence on the footprint contributing NH_3 during the prevailing southerly wind directions. Since it is designed as an overflow lagoon, we speculated that emissions from the third lagoon were less than from the other lagoons. A follow-up study at the same lagoon system in 2010 that used multiple OPL that allowed us to separate lagoon emissions showed that mean flux from the third lagoon was two-thirds that from the first two lagoons.

Mean 15-min lagoon NH_3 emission rates ranged from 49 to 155 kg d^{-1} before the rain on DOY 222, about an order of magnitude less than open lot emission rates (Fig. 4b). After the rain, 15-min emission rates were much less, ranging from 12 to 33 kg d^{-1}. The lagoons lost on average 59 kg NH_3 d^{-1} during the study. Ammonia PCER from the lagoons averaged 17 g cow^{-1} d^{-1}, or 2% of N intake (Table 3). Ammonia emissions from the lagoons had a pattern correlated with air temperature, with minimum emissions during early morning and a midday maximum (Fig. 4b). McGinn et al. (2008) found a similar pattern of emissions from a dairy lagoon in Alberta, closely correlated with lagoon surface temperature. Daily NH_3 flux in that summer-long study, which used a method similar to ours, averaged 59 μg m^{-2} s^{-1}, a flux similar to what we found before the rain.

3.5. Ammonia emissions in context and annualized estimates

Our observed NH_3 PCER for the dairy (321 g cow^{-1} d^{-1}) was near the upper range reported in the literature. For example, Bjorneberg

Table 3
Mean NH_3 flux density, emission rate, per capita emission rate (PCER), and the fraction of N intake lost as NH_3–N from either the open lot or lagoons. Standard deviations in parentheses.

Source	Flux density ($\mu g\ m^{-2}\ s^{-1}$)	Emission rate ($kg\ d^{-1}$)	PCER ($g\ cow^{-1}\ d^{-1}$)	Fraction of N intake (%)
Open lot	55 (19)	1061 (252)	304	41
Lagoons	37 (39)	59 (39)	17	2

et al. (2009), working in an open lot dairy in Idaho, found that seasonal PCER ranged from 40 (winter) to 250 g $cow^{-1}\ d^{-1}$ (spring), and averaged 190 g $cow^{-1}\ d^{-1}$ during summer. From another study at an open lot dairy in Idaho, PCER ranged from 80 to 200 g $cow^{-1}\ d^{-1}$ throughout the year, and annually averaged 130 g $cow^{-1}\ d^{-1}$ (Leytem et al., 2011). Cassel et al. (2005a), using a meteorological mass balance method, reported that PCER averaged 61 g $cow^{-1}\ d^{-1}$ during winter; the California dairy housed milking cows in freestalls, and dry cows and calves in an open lot. At a hybrid freestall-open lot dairy with less manure flushing, Cassel et al. (2005b) found that PCER was 124 g $cow^{-1}\ d^{-1}$. At another California open lot dairy with a mixed cattle population, summertime PCER was either 141 or 199 g $cow^{-1}\ d^{-1}$, depending on whether passive samplers or open path Fourier transform infrared spectroscopy was used to measure NH_3 concentration (Moore et al., 2014). In a Wisconsin study of whole farm ammonia emissions from three dairy farms with freestall barns, summertime PCER ranged from 93 to 100 g $cow^{-1}\ d^{-1}$ (Flesch et al., 2009). Our studies were conducted during late summer when NH_3 emission rates would be expected to be greatest. Also, cows at the dairy were from the production herd only; heifer calves were not present, so that the herd was composed of larger milking cows or pregnant dry cows, which would increase per capita N intake and NH_3 emissions compared with farms that included heifer calves (Cassel et al., 2005a; Moore et al., 2014).

Summer NH_3 emission from open lot-freestall housing and wastewater pond areas of a dairy in Idaho (332 g $cow^{-1}\ d^{-1}$; Leytem et al., 2013) was similar to what we found (321 g $cow^{-1}\ d^{-1}$). However, the emissions from the two sources were partitioned differently; 33% of NH_3 was lost from housing in Idaho, compared with 95% in New Mexico (this study). This difference most likely reflects the different manure management practices of the two production systems. Leytem et al. (2013) reported that much of the urinary N in the Idaho freestall barns was flushed to the wastewater ponds, compared with an open lot where deposited urine remains on the pen surface. Feeding alleys were flushed less than twice a day during the first four days at the New Mexico dairy, and intermittently after the rain damaged the pumping system. But even with alley flushing, most of the excreted N was deposited on the open lot. Also, solids were separated at the lagoon, further reducing the N load to the lagoon system. Emission sources were also partitioned differently at Wisconsin freestall dairies. Flesch et al. (2009) found that about one-third of NH_3 emissions came from freestall housing on two dairy farms during summer, while Harper et al. (2009) found that freestall housing was the source for about one-third to one-half of summertime NH_3 emissions.

Studies of open lot dairies have shown that the source of most summer emissions is the open lot. At an open lot dairy in eastern Texas, 63% of summertime NH_3 emissions were from the open lot and 37% from lagoons (Mukhtar et al., 2008). In Idaho, Bjorneberg et al. (2009) and Leytem et al. (2011) found that 88% and 70%, respectively, of summer emissions were from the open lot. Our results were in close agreement with Moore et al. (2014), who found that corral emissions at an open lot dairy during summer were either 95% or 89% of total farm emissions, based on either passive sampler or open path measurements of concentration.

Mukhtar et al. (2008) found that wintertime NH_3 emissions from an open lot dairy in eastern Texas were 53% of summertime emissions. Wintertime ammonia emissions in open lot beef cattle feedyards averaged 59% of summertime emissions, and the mean of winter and summer emissions closely approximated the annual emissions (Todd et al., 2008, 2011). We chose to use 59% for the ratio of winter to summer emissions because conditions at High Plains open lot dairies are more similar to High Plains feedyards than eastern Texas dairies. Applying this to our observed summertime PCER of 321 g $cow^{-1}\ d^{-1}$, we estimated that winter and annual NH_3 PCER for the dairy were 189 and 255 g $cow^{-1}\ d^{-1}$, respectively. For a range of reasonable N intakes of 700 to 600 g N $cow^{-1}\ d^{-1}$, N lost as NH_3 on an annual basis from the open lot would range from about 30 to 35% of fed N, respectively.

3.6. Dairy N balance

Daily N intake for all cows in the dairy was 2139 kg d^{-1}. Milk N was 406 kg d^{-1}, or 19% of N intake (Fig. 5). Ammonia-N lost to the atmosphere from the open lot and lagoons was 922 kg d^{-1}, or 43% of N intake. Nitrogen retained in cows was 43 kg d^{-1}, estimated as 2% of N intake (Castillo et al., 2000). The residual of the N balance, partitioned to manure on the open lot surface, separated solids and lagoon water, was 768 kg d^{-1}, or 36% of N intake. The sum of the NH_3 loss and this residual manure was the calculated excreted N, which was 79% of N intake.

The residual term of any balance equation will accumulate the errors of all the other terms. We wanted to get another estimate of excreted N to check against the residual, and also to partition excreted N into urine and feces fractions. To do this, we used the meta-analysis equations of Castillo et al. (2000), that estimate milk N, urine N and feces N as a function of N intake (Table 4). Estimated milk N on a per capita basis (weighted by milking and fresh cow

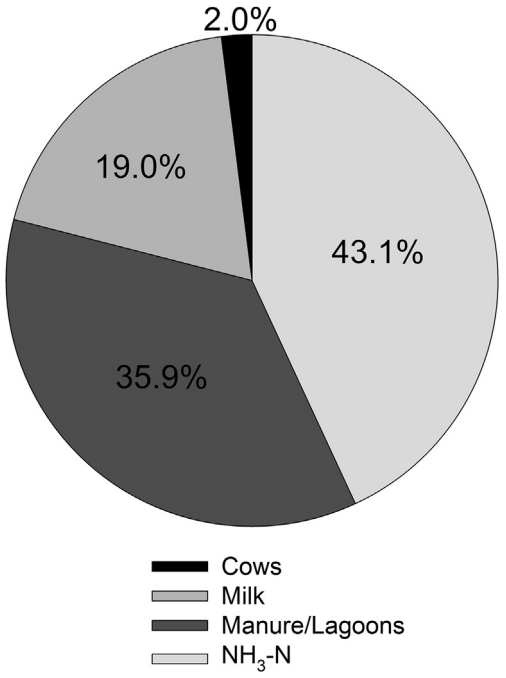

Fig. 5. Nitrogen partitioning at the New Mexico dairy. Daily N input was 2139 kg d^{-1}. Milk N and NH_3–N were measured, N partitioned to cows estimated as 2% of N intake (Castillo et al., 2000), and N partitioned to manure and lagoons was the residual of the N balance.

Table 4
Feed nitrogen partitioned on per capita basis to cow class. The N intake values for each cow class were measured. Other values were estimated as functions of N intake (Castillo et al., 2000).

Cow class	Intake	Milk[a]	Cow[a]	Urine[a]	Feces[a]	Total excreted[a]
	g N cow^{-1} d^{-1}					
Milking	701	155	14	337	202	539
Fresh	576	137	12	253	173	426
Dry (close)	325	0	7	98	124	221
Dry (far)	293	0	6	91	111	202
Weighted mean[b]	612	123[c]	12	282	183	465

[a] Estimated as functions of N intake (Castillo et al., 2000).
[b] Means in this row are weighted by the population of each cow class.
[c] The weighted mean of milk N using only milking and fresh cow classes was 153 g N cow^{-1} d^{-1}.

populations) was 153 g N cow^{-1} d^{-1}, within 6% of the actual milk N of 145 g N cow^{-1} d^{-1}. The weighted (by all cow class populations) mean of per capita urine N and feces N was 282 and 183 g N cow^{-1} d^{-1}, respectively. Total excreted N was estimated to be 465 g N cow^{-1} d^{-1}, which was 76% of N intake, only three percentage points lower than when the residual term was used for excreted N. Using these two estimates of excreted N, from 55 to 57% of excreted N was lost as NH_3. Based on the estimate of urine N for the herd (282 g cow^{-1} d^{-1}), NH_3 loss was 94% of the urine N. We expected to see NH_3 loss fractions like these during summer. For example, Cole et al. (2009) reported that almost all artificial urine N was lost within 72 h of application on a feedyard manure corral surface. Cole and Todd (2009) estimated that 79% of urinary N was volatilized as NH_3 at a commercial open lot feedyard over a year. It is likely that most NH_3 lost from this dairy during the study had its source as urinary N.

3.7. NH_3 emission intensity

The NH_3 emission intensity during this summertime study, defined as the mass of NH_3 lost per unit of milk production, was 13.7 g NH_3 kg^{-1} milk. Leytem et al. (2013) reported an annualized NH_3 emission intensity of 6 g NH_3 kg^{-1} milk at a freestall barn/open lot dairy in Idaho that had similar summer emissions to those we report here. When we estimated an annualized PCER (255 g NH_3 cow^{-1} d^{-1}), the NH_3 emission intensity decreased to 10.9 g NH_3 kg^{-1} milk. Milk production at this New Mexico dairy was 14% less than that reported at the Idaho dairy, which partly contributed to the greater NH_3 emission intensity that we observed.

4. Conclusions

Ammonia emissions from the open lot dairy were among the higher values of reported dairy emissions. Three factors largely contributed to these higher emissions. First, our measurements were made during late summer, a time in the annual cycle when maximum NH_3 emissions are expected. Second, the herd was composed of adult cows in the production herd, either lactating or soon to be lactating, so that N intake and excretion were high. Third, manure management during the study consisted of irregular flushing of the feeding alley, which transported some manure to the lagoon system; however, most N was excreted on the corral surface, where conditions were conducive to rapid volatilization.

Housing and manure handling affect the sources and magnitude of NH_3 loss. We observed that most NH_3 was emitted from the open lot (95%), which contrasted with studies that found smaller percentages of NH_3 emitted from dairies that handled manure more intensively. Frequent and effective manure management practices, such as flushing or scraping can transfer manure N from housing to other stores. But careful management is still needed to ensure that losses from these potential sources are minimized.

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