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CASE STUDY: Seasonal and Spatial Distribution of Ambient Ammonia Concentrations Measured at a Large Open-Lot Dairy

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ABSTRACT

The volatilization of NH_3 from dairy production facilities is not only a loss of valuable N, but also an air quality concern because NH_3 plays a role in the formation of airborne particulate matter, which can be a health hazard. The ambient NH_3 concentrations over several seasons at 3 locations (open lots, compost yard, lagoon) throughout a large open-lot dairy were determined, as well as the spatial distribution of NH_3 over the open-lot area. There was a significant main effect of location ($P < 0.0001$), which followed the trend of lot > lagoon = compost > background, with averages of 0.58, 0.33, 0.30, and 0.04 mg NH_3/m^3, respectively. The effect of weather and lot conditions on the spatial distribution of NH_3 across the lots was evident, with lower concentrations and less spatial variability in winter months when the lots were frozen compared with wetter warmer months. Lower NH_3 concentrations and less spatial variability were also measured when manure stockpiles were removed from the open lots and the lots were dry. Significantly greater NH_3 concentrations were generated in the lot area versus the compost and lagoon areas, which were not significantly different. Because the lots are greater in size by a factor of approximately 6, it is evident that NH_3 emissions from this sector of the dairy contribute the greatest amount of NH_3 to the atmosphere.

Key words: ammonia, confined animal feeding operation, dairy, emission, particulate matter

INTRODUCTION

Intensification of animal production has led to larger confined animal-feeding operations, resulting in the creation of large and concentrated NH_3 sources. In the United States, manure from livestock operations accounts for the majority of the anthropogenic sources of NH_3 emissions, and dairy cows are one of the largest livestock sources (Battye et al., 1994; US Environmental Protection Agency, 2000). In the atmosphere, NH_3 primarily reacts to form ammonium sulfate and ammonium nitrate aerosols, which are regulated as part of the US Environmental Protection Agency National Ambient Air Quality Standards for particulate matter with an aerodynamic diameter less than 2.5 µm because they are considered to be a human health concern. Because NH_3 is highly correlated with particulate matter less than 2.5 µm formation, it is anticipated that NH_3 emissions from confined animal-feeding operations in the United States may be regulated in the near future.

The state of Idaho has recently experienced rapid growth of the dairy industry. The number of milk cows has increased by approximately 80% in the past decade, with a 110% increase in milk production (USDA National Agricultural Statistics Service, 2007). Idaho is the second largest milk producer in the 12 western states and has become the third largest milk-producing state in the United States. In 2006, there were 477,193 milking cows in Idaho, with 71% of these being located in the Magic Valley of southern Idaho (United Dairymen of Idaho, 2007). Although this region has benefited economically from the growth of the dairy industry, there is much concern regarding the

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impact of concentrated dairy production facilities, which can be upward of 10,000 animals per operation, on regional air quality.

At present, there is a scarcity of scientifically derived information on various climatic and production factors that affect NH_3 emissions from dairy operations. Management practices such as animal housing, manure handling, and manure storage can all affect NH_3 emissions from a given production facility. Additionally, climatic conditions can have a large influence on the seasonal variability of emissions. Monteny and Erisman (1998), in a review of research on NH_3 emissions from dairy buildings, concluded that the important influencing parameters were urea concentration of the urine, urease activity, pH, temperature, air velocity, and floor area. They also indicated that rainfall and efficiency of yard cleaning might be 2 additional factors important for outdoor yard areas.

Average NH_3 emissions measured at free-stall dairies during summer months in Wisconsin and Washington ranged from 35 to 40 kg NH_3/cow per year (Rumburg et al., 2008; Flesch et al., 2009) compared with 7.3 kg NH_3/cow per year measured at an open-lot dairy in Texas during the summer (Mukhtar et al., 2008). Ammonia emissions measured at various locations on an open-lot dairy indicated that in the summer, the lots contributed 63% of total emissions and the lagoon contributed 30%, and in winter, the lots contributed 95% of the total NH_3 emissions (Mukhtar et al., 2008). Estimated NH_3 emissions during summer months can be as much as 10 times those of winter months, largely because of temperature differences (Pinder et al., 2004; Mukhtar et al., 2008; Flesch et al., 2009).

Because limited information is available regarding the contribution of various components of a production facility (i.e., animal housing vs. manure handling and storage) and the seasonal effects on NH_3 concentrations in these areas, the objective of this study was to measure the ambient NH_3 concentrations over several seasons at locations throughout a large open-lot dairy to determine the contribution of each area to total NH_3 generated. In addition, we identified lot conditions and management practices that could influence the distribution of NH_3 across the lots, with the intent of understanding management practices that could be used to reduce ambient NH_3 concentrations.

MATERIALS AND METHODS

Study Site and Design

The dairy used in this study was a privately owned commercial dairy in southern Idaho, in a rural location, with approximately 10,000 milking cows and a stocking density of 60 m^2/cow (Figure 1). This dairy was similar in configuration to most open-lot production facilities in southern Idaho. The operation consisted of 24 open-lot pens (the main 20 lots were considered in this study), 2 milking parlors, a hospital barn, a maternity barn, a manure solid separator, a lagoon (liquid storage pond), and a compost yard. The lot area included in the study was approximately 59 ha, and the compost and lagoon areas were both 10 ha. Each lot had a loafing shed and 2 windbreaks. Wash water from the milking parlor and runoff from the open lots were retained in the lagoon to the east of the pens, and solid manure from the pens was composted in an area northwest of the facility. Manure was scraped or vacuumed from feed alleys daily and placed into cells near the solid separator. The open-lot pens were harrowed daily when dry. The facility was surrounded by irrigated cropland on 3 sides and open range to the north.

Passive NH_3 samplers (Ogawa USA Inc., Pompano Beach, FL) were installed at 3 locations on the dairy (center of lots, lagoon, compost yard) and at 1 off-dairy location (0.6 km south of the dairy) for background concentration, with 4 replicate traps in each location. Samplers placed at the central lot and background locations were approximately 2 m above the ground. The samplers at the composting site were placed on poles, approximately 2 m from the top of the windrow, at a central location in the compost area. Samplers were placed on a flotation device at the northwest corner of the lagoon at approximately 0.5 m above the lagoon surface. To determine the spatial distribution of NH_3 across the 20 open lots, 36 samplers were installed in a grid across 18 of the lots and were attached to the ends of the windbreaks (about 2.5 m) so that all but 2 lots had 2 samplers per lot (Figure 1).

All the samplers were deployed on Monday and collected on Friday, with an average deployment time of 4 d during each month of the year beginning in March 2008 and continuing through February 2009. During the month of December, no samplers were placed at the center lot or background locations. The lagoon was emptied in November and remained either empty or frozen for the remainder of the study period; therefore, NH_3 samplers were deployed only from March to October at this location. The compost yard was cleaned out in October and remained empty until February, when new manure was brought in for composting; therefore, samplers were not deployed from October through January at this location. Additionally, for 7 of the 12 mo, 3 extra sets of samplers (3 replicates) were placed at the center lot location and collected daily to determine if there was saturation of the traps when left out over a 4-d period.

Details regarding passive sampler design and calculation of NH_3 concentrations can be found in Roadman et al. (2003). Concentrations from passive samplers are time-averaged concentrations for the amount of time the sampler was exposed to the air and were calculated with the following equation: mg NH_3-N/m^3 = [(mg NH_3-N) × (1 × 10^6 cm^3/m^3)]/[(min deployed) × (31.1 cm^3/min)], where mg NH_3-N was the mass of NH_3 extracted from the filters and 31.1 cm^3/min was a rate constant used to calculate diffusion to the trap (Roadman et al., 2003).

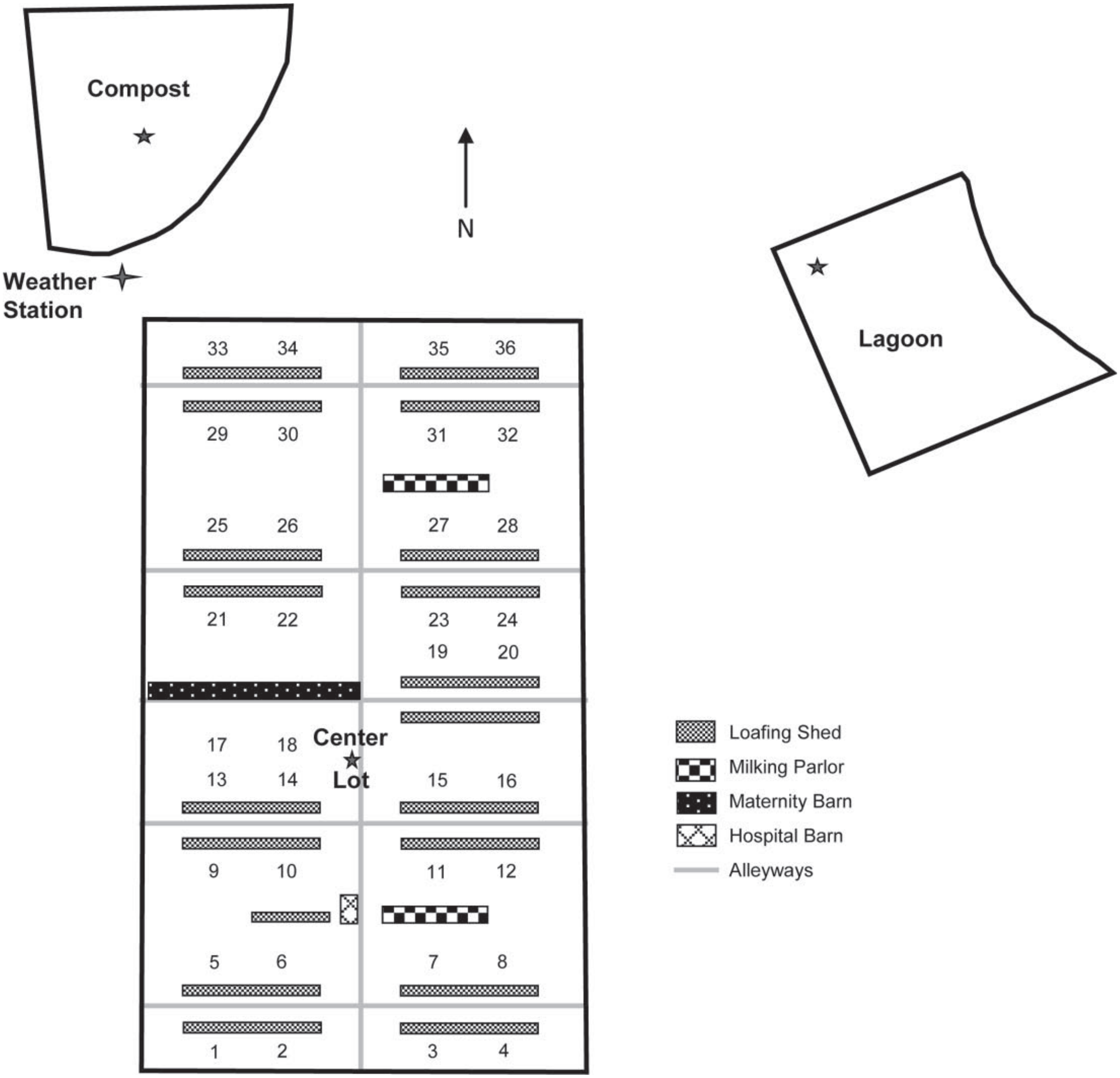

Figure 1. Diagram of the open-lot dairy used in the present study and the sampling locations.

A meteorological station was located northwest of the pens and recorded air temperature, wind direction, wind speed, solar radiation, and relative humidity during the experimental period. Measurements for wind speed, air temperature, and humidity were made at 2 m. All meteorological instruments were interfaced to a Campbell Scientific 21X Micrologger (Logan, UT), which recorded data in 15-min increments. Ambient weather data at the farm over the experimental period are shown in Table 1.

Ammonia Sampler Preparation and Analysis

The disassembled components of the passive samplers were thoroughly cleaned before each use (to avoid contamination and carryover) by rinsing with deionized water, soaking in a 1 *M* HCl bath, rinsing again with deionized water, and then air-drying in a clean hood. The filters (which trap NH_3) were prepared by impregnating a clean filter with 100 µL of 2% (wt/vol) citric acid to saturate the filters (Ogawa USA Inc.) and drying before assembling the samplers. Assembled samplers were then placed into airtight containers and transported to the field for deployment. Immediately after collection in the field, samplers were placed back into the airtight

Table 1. Ambient weather data measured at the open-lot dairy over the study period[1]

Date	Wind speed, m/s	Wind direction, °	Air temperature maximum, °C	Air temperature minimum, °C	Humidity, %	Solar radiation, W/m²
3/17/08 to 3/21/08	2.45	229	14.0	−3.9	73.6	174
4/21/08 to 4/25/08	3.15	185	17.8	−6.9	54.2	76
5/19/08 to 5/23/08	4.30	217	31.4	3.6	56.4	243
6/16/08 to 6/20/08	2.09	195	32.7	8.7	39.7	352
7/28/08 to 8/1/08	1.61	181	32.8	12.1	48.0	339
8/18/08 to 8/22/08	1.95	197	37.3	7.8	44.1	259
9/21/08 to 9/26/08	1.77	150	28.7	0.8	50.7	183
10/27/08 to 10/31/08	2.34	100	25.4	1.3	38.1	135
11/17/08 to 11/21/08	2.66	122	19.5	−0.5	60.7	109
12/15/08 to 12/19/08	3.83	114	1.6	−20.5	81.3	70
1/27/09 to 1/30/09	3.76	138	1.6	−9.1	84.6	133
2/23/09 to 2/27/09	3.03	192	11.6	−5.7	77.5	105

[1]Wind speed, wind direction, humidity, and solar radiation values are average values.

containers and then transported to the laboratory. The filters were carefully removed from the samplers with clean forceps and transferred to 15-mL centrifuge tubes, where they were extracted with 5 mL of 1 *M* KCl for 30 min with the extractant analyzed for NH_4-N via flow injection analysis using a Quickchem 8500 instrument (Lachat Instruments, Milwaukee, WI).

Geostatistical Analysis

The NH_3 concentrations across the lots were analyzed using ArcGIS Geostatistical Analyst (ESRI, 2001) and semivariogram models, and prediction surfaces were generated using ordinary Kriging. Data from each month were tested for normal distribution using the histogram and Normal QQ-Plot functions, and global trends were determined using the Trend Analysis function before generation of the semivariograms and prediction surfaces. When data were not normally distributed, data were log-transformed before analysis, and any global trends were removed before the generation of the semivariograms and prediction surfaces. Cross-validation of models was performed, and models with the lowest mean prediction error and root mean square SE closest to zero were chosen as the best-fit models.

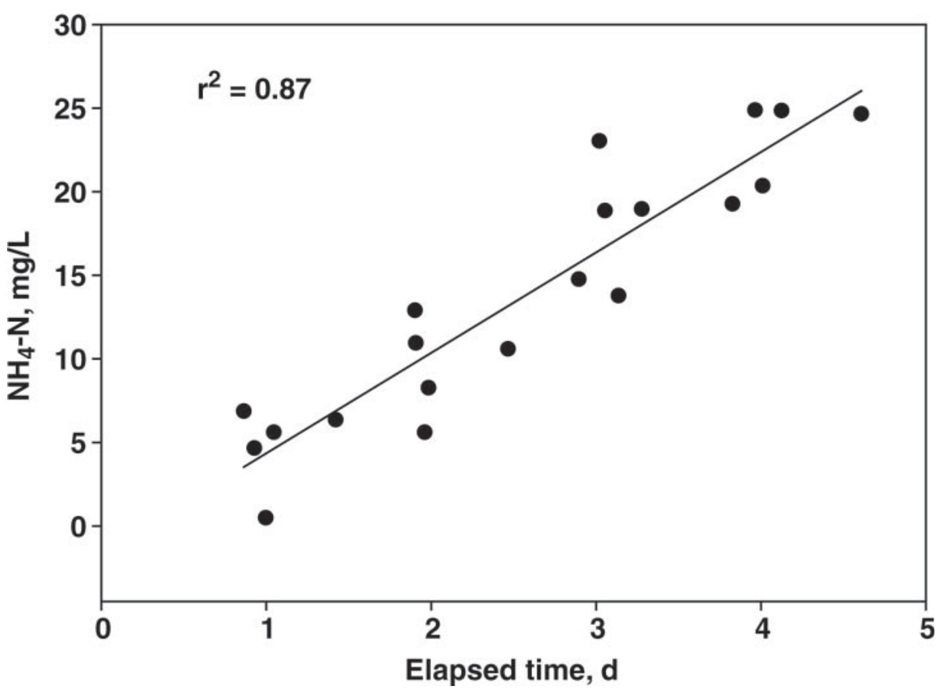

Figure 2. Ammonium concentrations measured on traps over the 4-d deployment period.

Statistical Analysis

Ammonia concentrations measured at the 4 locations were tested for normality using the Shapiro-Wilk test with the CAPABILITY procedure (SAS Institute, 2004). The data for NH_3 concentrations by location (March through September) were analyzed using the one-way ANOVA procedure (SAS Institute, 2004), with location as the main effect. Means separation was carried out using the difference of the least squares means with Tukey-Kramer adjustment and an α-level of 0.05. Pearson correlation coefficients were calculated for NH_3 concentration, wind speed, wind direction, temperature, and humidity using the CORR procedure (SAS Institute, 2004). Statements of statistical significance were based on $P < 0.05$ unless otherwise stated.

RESULTS AND DISCUSSION

Average wind speed at the dairy ranged from 1.61 to 4.30 m/s, with lower wind speeds in July through September and the greatest wind speed in May (Table 1). Wind direction tended to be from the west with a shift to the east at night. During the months of October through December, the wind was mainly from the east. Maximum air temperatures ranged from 1.6 to 37.3°C and were coldest in December and January and warmest in August. Minimum air temperatures ranged from −20.5 to 12.1°C, with temperatures below zero from November through April. Average humidity ranged from 38 to 85% and the solar radiation ranged from 70 to 352 W/m^2.

One potential drawback to deploying the NH_3 samplers for an extended period of time is the possibility that the traps could be saturated during this time period and therefore underestimate the concentration of NH_3. Roadman et al. (2003) determined optimal deployment times for NH_3 samplers based on atmospheric NH_3 concentrations. As NH_3 concentrations measured at a typical open-lot dairy can vary from 0.01 to 10 ppm by volume (unpublished data), calculations by Roadman et al. (2003) suggest that optimal deployment times for the traps would range from <1 to 10 d. To determine if traps were being saturated or if there was a decrease in sorption over time, extra samplers were placed at the center lot location, where concentrations tended to be greatest, and were collected on a daily basis. There was a linear increase in NH_4-N extracted from the traps over the 4-d period ($r^2 = 0.87$; Figure 2), with no indication of a plateau. Therefore, it is highly unlikely that deployment of the NH_3 samplers at this facility would result in NH_3 concentrations great enough to saturate the traps over this time period. The linear increase in NH_4-N deposition on the traps also indicated that the ambient NH_3 concentrations each day, over a given 4-d period, were similar. This result was not unexpected because the traps were located centrally in the lots and animal activity and climatic conditions were fairly consistent over the 4-d sampling periods.

Ammonia Concentrations Determined by Location

Ammonia concentrations were determined at the center lot and background each month except during December (Table 2). The ambient average NH_3 at the center lot ranged from 0.21 (January) to 0.89 (November) mg NH_3/m^3, and background NH_3 concentrations ranged from 0.01 to 0.06 mg NH_3/m^3. The ambient average NH_3 concentration at the lagoon ranged from 0.24 (March and April) to 0.53 (August) mg NH_3/m^3. The ambient average NH_3 concentrations at the composting yard ranged from 0.20 (May) to 1.08 (February) mg NH_3/m^3.

Because there was a complete data set for all locations only from March through September, this subset of data was used to determine the effect of location on ambient average NH_3 concentrations. There was a significant main effect of location ($P < 0.0001$), which followed the trend of lot > lagoon = compost > background, with averages of 0.58, 0.33, 0.30, and 0.04 mg NH_3/m^3, respectively. Both the lagoon and mature compost released less NH_3 than the lots, which was expected because most NH_3 emissions are derived from the urea content of the livestock urine, which is hydrolyzed to NH_3 by the enzyme urease present in livestock feces and soils. Because the majority of urea is likely converted to NH_3 in the soils of the lots where it is excreted, as well as in feed lanes where there is mixing of urine and feces, a smaller source is available for volatilization in the lagoon and compost areas. The exception to this was in February, when fresh manure (mix of straw with urine and feces) was windrowed in the compost area, resulting in seemingly greater NH_3 concentrations than in the center lot location. Additionally, in July the concentrations at the lot and compost area were similar, which is likely because new manure was brought into the compost yard at this time and the windrows were being turned during the measurement period.

Mount et al. (2002) measured NH_3 concentrations over a concrete yard housing milk cows and slurry lagoons and found that concentrations measured at the concrete yard were an order of magnitude greater than those measured at the slurry lagoon. Mukhtar et al. (2008) reported that

Table 2. Ambient average NH_3 concentrations[1] (and SD) measured by month at the center lot, lagoon, compost, and background locations of the open-lot dairy

Date	Center lot	Lagoon	Compost	Background
2008				
March	0.69 (0.05)	0.24 (0.03)	0.22 (0.02)	0.04 (0.001)
April	0.56 (0.05)	0.24 (0.02)	0.22 (0.02)	0.04 (0.007)
May	0.62 (0.13)	0.37 (0.12)	0.20 (0.07)	0.01 (0.009)
June	0.70 (0.08)	0.37 (0.02)	0.32 (0.14)	0.05 (0.001)
July	0.57 (0.03)	0.47 (0.06)	0.60 (0.05)	0.05 (0.006)
August	0.67 (0.05)	0.53 (0.04)	0.49 (0.04)	0.06 (0.006)
September	0.60 (0.12)	0.25 (0.01)	0.21 (0.05)	0.02 (0.009)
October	0.79 (0.12)	0.28 (0.11)	—	0.06 (0.005)
November	0.89 (0.14)	—	—	0.06 (0.002)
December	—	—	—	—
2009				
January	0.21 (0.05)	—	—	0.04 (0.009)
February	0.49 (0.07)	—	1.08 (0.15)	0.04 (0.007)

[1]Average NH_3 concentration expressed as mg NH_3/m^3.

Table 3. The range, mean (and SD), and median NH_3 concentrations measured across the lots of the dairy and the standard mean prediction error (SMPE) and root standard mean prediction error (RSMPE) for prediction surfaces and lot conditions for each month

	Across-lot NH_3 concentration, mg/m^3			Model fit		
Date	Range	Mean (SD)	Median	SMPE	RSMPE	Lot condition
2008						
March	0.25 to 0.65	0.41 (0.11)	0.39	0.0001	0.79	Lots partially frozen, some wet areas at east central pens, manure piles present
April	0.31 to 0.87	0.58 (0.18)	0.60	0.0045	0.92	Lots very wet with standing water in several pens along eastern edge, manure piles present
May	0.22 to 0.66	0.42 (0.12)	0.42	0.0008	0.80	All pens were cleaned out and manure piles removed, lots were dry
June	0.27 to 0.82	0.59 (0.13)	0.59	0.0004	1.12	Lots were dry, some buildup of manure piles
July	0.34 to 0.90	0.57 (0.13)	0.56	0.0026	0.83	Lots were dry, manure piles were present, lots on eastern side (lower and central) were cleaned and had new soil
August	0.31 to 0.87	0.56 (0.14)	0.56	0.0015	0.88	Lots were dry, some buildup of manure piles
September	0.20 to 1.03	0.50 (0.17)	0.48	0.0045	1.10	Lots were dry, some buildup of manure piles
October	0.12 to 1.09	0.57 (0.24)	0.53	<0.0001	1.06	Lots were wet and some areas were very muddy, manure piles present
November	0.01 to 1.02	0.58 (0.20)	0.56	0.0001	0.86	Lots were wet and some areas were very muddy, manure piles present
December	0.04 to 0.37	0.11 (0.06)	0.11	−0.0057	1.19	Lots were frozen over
2009						
January	0.08 to 0.48	0.24 (0.09)	0.23	0.0019	0.95	Lots were frozen over
February	0.19 to 0.56	0.39 (0.09)	0.39	<0.0001	0.99	Lots were mostly frozen, some thawing with standing water in some places

the contribution of the lots on a dairy to total NH_3 emissions was 63%, compared with only 30% from the lagoon. This is similar to the present study in which there was a 48% contribution from the lots and a 27% contribution from the lagoon (of combined concentrations at the 3 locations). The lot value was somewhat lower in the present study, but this was due to the inclusion of the composting area, which also contributed approximately 25% of the combined NH_3 concentrations. Excluding the compost area, the emission rate was 63% from the lot and 36% from the lagoon. In the present study, concentrations were measured, as opposed to calculating emission factors (because of the nature of the sampling device), but concentrations would parallel differences in emission fluxes because all samplers were deployed at the same time under the same weather conditions. However, total load of NH_3 would also be influenced by the size of the source area, which would enhance the contribution from the lots versus the compost (10 ha) and lagoon (10 ha) because of the greater size of the lot area (59 ha).

Spatial Variability of Ammonia in the Open Lots

The average ambient NH_3 concentration measured across the lots is presented in Table 3, along with the range and median concentration values. The average ambient NH_3 concentration ranged from 0.11 (December) to 0.59 (June) mg NH_3/m^3, with median values very close to the mean, indicating that the data were fairly normally distributed. The average NH_3 concentration across the lots was similar to or less than the concentration measured at the center lot location (Table 2). Figure 3 shows the prediction surfaces for NH_3 concentration across the lots for each month generated using the ordinary Kriging function of ArcGIS Geostatistical Analyst. There was a very good model fit each month, as indicated by standard mean prediction errors close to zero (range −0.0057 to 0.0045) and root square mean prediction errors close to 1 (range 0.79 to 1.19; Table 3).

The effect of weather and lot conditions on the spatial distribution of NH_3 across the lots is very evident (Figure 3). In months when the lots were frozen (December through February), concentrations tended to be lower and more uniform than when conditions were above freezing. In fact, there was a strong positive correlation between the average maxi-

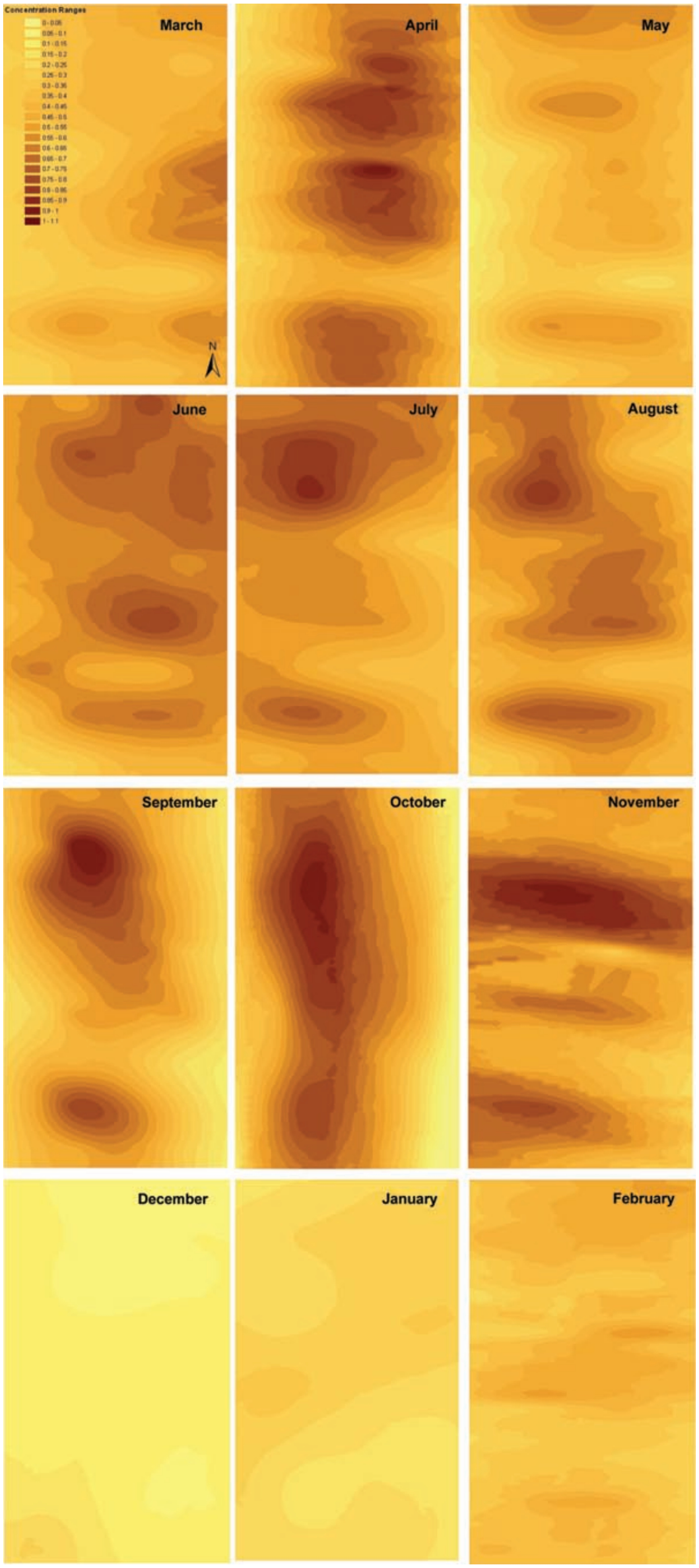

Figure 3. Predicted surfaces of NH_3 concentrations across the open-lot area for each month.

mum air temperature and average NH_3 concentration ($r^2 = 0.79$, $P = 0.002$). Flesch et al. (2009) reported a 2- to 6-fold decrease in emissions from free-stall dairy barns in winter compared with summer months. This decrease was attributed to lower temperatures, which slowed the chemical and biological reactions that led to NH_3 production from urine and feces and reduced ventilation rate in the barns. Mukhtar et al. (2008) reported that NH_3 emissions in winter were approximately 2-fold lower than summer emissions on an open-lot dairy. Although ambient weather conditions would have an effect on NH_3 emission rates from the lots, the average concentration measured at the lots in the present study was approximately 2-fold lower in the winter (December through February) than in summer (June through August), which is similar to other reported decreases.

Lot management and lot conditions also had an effect on NH_3 concentrations. In March and April, when the eastern edge lots had very wet areas and, in some cases, standing water in the eastern corners of the lots, NH_3 concentrations tended to be higher in these areas. This also occurred in October and November, when lots were wet and muddy, and some of the highest NH_3 concentrations were measured then. Hutchinson et al. (1982) reported the highest emission rates of NH_3 when beef feedlots had been wet and were drying rapidly, which would be somewhat similar to the trends in the present study. Although temperatures are not necessarily high in March and April (maximum of 14 and 18°C, respectively), the lots had been wet, and high wind speed and low relative humidity tends to dry the surface quickly, which would create an environment favorable for microbial transformations of N and increased NH_3 volatilization. Mukhtar et al. (2008) also reported that summer NH_3 emission rates from dry areas of open lots were significantly lower than those from all other areas.

In May, all the manure piles were removed from the lots and conditions were dry, which resulted in a lower and much more uniform distribution of NH_3 across the lots. Misselbrook et al. (2006) reported that scraping and removing manure from concrete yards significantly decreased NH_3 emission rates in winter. Mukhtar et al. (2008) reported that NH_3 emissions from an open-lot dairy had high spatial variability, with higher rates in areas with higher animal activity and greater manure loading. As manure stockpiles built up over June and July, an increase in NH_3 concentrations and a more uneven distribution of NH_3 across the lots could be seen (Figure 3). It is interesting to note that in July, the lots on the south and central eastern side were cleaned out and new topsoil was brought into those lots, resulting in lower NH_3 concentrations in these areas.

In summary, significantly greater NH_3 concentrations were generated in the lot area versus the compost and lagoon areas, which were not significantly different. Because the lots were greater in size by a factor of approximately 6, it is evident that NH_3 emissions from this sector of the dairy contributed the greatest amount of NH_3 to the atmosphere. The spatial distribution of NH_3 across the lots was heavily influenced by climatic conditions and lot management practices. Average NH_3 concentrations tended to be lower and more uniform in months when the lots were frozen (winter) and when all the stockpiles of manure had been removed (May) and lots were dry. Lower concentrations were also measured in lot areas in July where manure was removed and new topsoil added. Therefore, frequent manure removal from lots would be a good management practice for reducing NH_3 losses. However, concentrations could be greater where manure is stored or applied if it is not incorporated into the soil (Leytem et al., 2009). Good drainage of the lots is also an important management practice because concentrations of NH_3 were elevated when lots were wet and had standing water. These conditions tend to favor NH_3 formation, which, when coupled with windy conditions, can lead to large NH_3 losses. Additionally, measuring NH_3 concentrations with passive samplers provided results comparable to other studies, indicating that passive samplers are an affordable method for measuring NH_3 at animal production facilities.

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