TOWARD MODELING OF NITROUS OXIDE EMISSIONS FOLLOWING PRECIPITATION, URINE, AND FECES DEPOSITION ON BEEF CATTLE FEEDYARD SURFACES

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HIGHLIGHTS

- Nitrous oxide is a greenhouse gas emitted from feedyard pen surfaces.
- Experiments were conducted to quantify nitrous oxide emissions from precipitation, urine, and feces.
- Nitrous oxide emissions from urine were about 30% of those from equal amounts of precipitation.
- Regression equations were developed for empirical modeling of emissions.

ABSTRACT. *The amount of moisture deposited annually as urine (~320 mm) and feces (~95 mm) on typical semi-arid Texas beef cattle feedyard pens is considerable compared to the regional 470 mm mean annual precipitation. Precipitation is a primary factor affecting nitrous oxide (N_2O) emissions from manure, but specific effects of urine and feces deposition are unknown. The objectives of this research were to (1) quantify N_2O emissions following precipitation, urine, and feces deposition on a dry feedyard manure surface, and (2) develop equations for future empirical modeling of these emissions. Four experiments (Exp.) were conducted using recirculating flux chambers to quantify N_2O emissions. Exp. 1 had treatments (TRT) of water (W), artificial urine (AU), and two urines collected from beef cattle fed high-quality forage (FU) or corn-based concentrate (CU). Exp. 2 had TRT of W, AU, and two feces levels (Fx1 and Fx2). In Exp. 3, N_2O emissions were quantified from fresh feces pats. In Exp. 4, the effect of rainfall pH on N_2O emissions was evaluated. Results from Exp. 1 showed that the W TRT had the highest mean cumulative N_2O emission, while AU, FU, and CU ranged from 31.0% to 70.0% of W on an equal volume-applied basis. There was little correlation between N_2O emissions and urine or water nitrogen (N) content. In Exp. 2, W again had the highest cumulative N_2O. Cumulative N_2O emissions expressed per unit of water added were 29.0, 3.8, 4.5, and 5.1 mg N kg^{-1} water added for W, AU, Fx1, and Fx2, respectively. In Exp. 3, fresh feces pats emitted no direct N_2O, but N_2O originated from the dry manure beneath the feces pat due to wetting. In Exp. 4, the highest N_2O emissions occurred at pH 5 and pH 8, with lower emissions at pH 6 and pH 7. This research has shown that the addition of moisture to the pen surface from urine and feces contributes considerably to N_2O emissions as compared to precipitation alone. The following recommendations were developed for future empirical modeling purposes: (1) N_2O emissions from urine should be calculated as 32.7% of those emissions from the equivalent mass deposition of water, and (2) N_2O emissions resulting from the mass of water in feces should be calculated as 15.6% of those emissions from the equivalent mass deposition of water.*

Keywords. *Beef cattle, Greenhouse gas, Manure, Nitrous oxide, Urine, Precipitation.*

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There has been a growing concern with the emissions of greenhouse gases (GHG) from animal agriculture (Redding et al., 2015; Waldrip et al., 2016; Wiedemann et al., 2017). The two GHG of most concern from animal feeding operations are nitrous oxide (N_2O) and methane (CH_4). Because N_2O has a 100-year global warming potential (GWP) that is 265 times higher than carbon dioxide (IPCC, 2014), it can be of concern even at low emission rates.

More than six million beef and dairy cattle are housed in open-lot pens in the Southern High Plains of the U.S. Within a typical 150 d cattle finishing period, manure accumulates on the earthen surfaces within the pens and is scraped and

removed one to two times per year, followed by land application to nearby crops. Manure typically reaches a depth of 75 to 100 mm before being removed. Open-lot pens are subject to varying pen surface moisture conditions that depend on the amount and timing of precipitation events, as well as urination by cattle.

Regional long-term mean annual precipitation in the Texas Panhandle is 470 mm, as measured at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (Colaizzi et al., 2017). The annual precipitation over the past 23 years has been highly variable, ranging from 136 mm in 2014 to 658 mm in 2004 (Colaizzi et al., 2017). The mean Class A pan evaporation of 2600 mm greatly exceeds precipitation; thus, the area is subject to prolonged dry periods. The earthen-surfaced pens are dry most of the year, with a manure dry matter (DM) content of ~80% to 90%.

Emissions of N_2O from manure and soil are affected by moisture content (Luo et al., 2013; Baral et al., 2016; Waldrip et al., 2017). Nitrous oxide emissions have been studied from urine patches in pasture systems (Forrestal et al., 2017; Rochette et al., 2014). In previous research, we demonstrated that precipitation on a dry feedyard surface results in N_2O emissions that can last for several weeks (Parker et al., 2017a, 2017b).

In addition to precipitation, there is also moisture applied to the pens daily in the form of urination and defecation by cattle. Haynes and Williams (1993) reported that cattle urinate 10 to 12 times per day, with 1.6 to 2.2 L per event. The surface area of urine patches has been shown to vary from 0.16 to 0.49 m^2 (Williams and Haynes, 1994), while Saarijarvi and Virkajarvi (2009) reported a mean urine patch area of 0.35 m^2 from the average urination event of 2.4 L for dairy cows. Misselbrook et al. (2016) reported that mature beef cows on pasture urinated about 13.7 L d^{-1}, with a mean of 7.6 urination events per day and mean urination volume of 1.8 L per event. Similar urine output was reported in a chamber calorimetry study in which beef steers (374 kg live weight) fed a steam-flaked corn-based finishing diet urinated an average of 13.2 L d^{-1} (range = 4.3 to 25.5 L d^{-1}, SD = 5.3 L d^{-1}) (Jennings et al., 2018). Fecal output in the same study averaged 4.4 kg d^{-1} (range = 3.2 to 6.0 kg d^{-1}, SD = 0.74 kg d^{-1}), and the mass ratio of feces to urine excretion averaged 0.40 (range = 0.17 to 0.99, SD = 0.19). Total manure (feces plus urine) excretion for the Jennings et al. (2018) study was 17.6 kg d^{-1}, which compares favorably to the typical excretion of 22 kg d^{-1} reported for beef steers (ASABE, 2005).

A daily urine output of 13.2 L, when applied at the typical feedyard stocking rate of one animal per 15 m^2, is equal to an annual urine application of about 320 mm over the entire pen surface under the assumption that urine is evenly deposited within the pen area. Fresh feces add another 95 mm of water annually to the pen surface, such that urine and feces together add about 415 mm of water to the pen surface, a considerable amount compared to the average annual precipitation of 470 mm.

In earlier experiments, we evaluated the effect of precipitation and temperature on N_2O emissions from an open-lot feedyard surface (Parker et al., 2017a, 2018b). That earlier research did not account for moisture addition from urine or feces deposition. Because the added moisture from urine and feces deposition could have an effect on N_2O emissions, research was conducted to study this potential effect. The specific objective of this research was to quantify N_2O emissions following urine and feces deposition on the feedyard manure surface. The findings will be used in the future development of an empirical model of annual N_2O emissions from beef feedyards in the Southern High Plains.

Materials and Methods

Four experiments (Exp.) were conducted at the USDA-ARS laboratory in Bushland, Texas. In Exp. 1 to 3, N_2O emissions were measured from simulated beef feedyard manure surfaces using recirculating-flow-through (RFT), non-steady-state (NSS) chambers housed within a non-insulated metal building. In Exp. 4, emissions were measured from dry feedyard manure using a glass jar and multiplexer system within a temperature-controlled laboratory.

Details on the construction and quality assurance procedures for the RFT-NSS chamber system of Exp. 1 to 3 can be found in Parker et al. (2017a, 2017b). Briefly, each chamber pan had 0.25 m^2 surface area. A single chamber lid was moved from pan to pan during each flux measurement (fig. 1). Sample air was recirculated in 4.3 mm i.d. polyethylene tubing between the chamber lid and a real-time N_2O

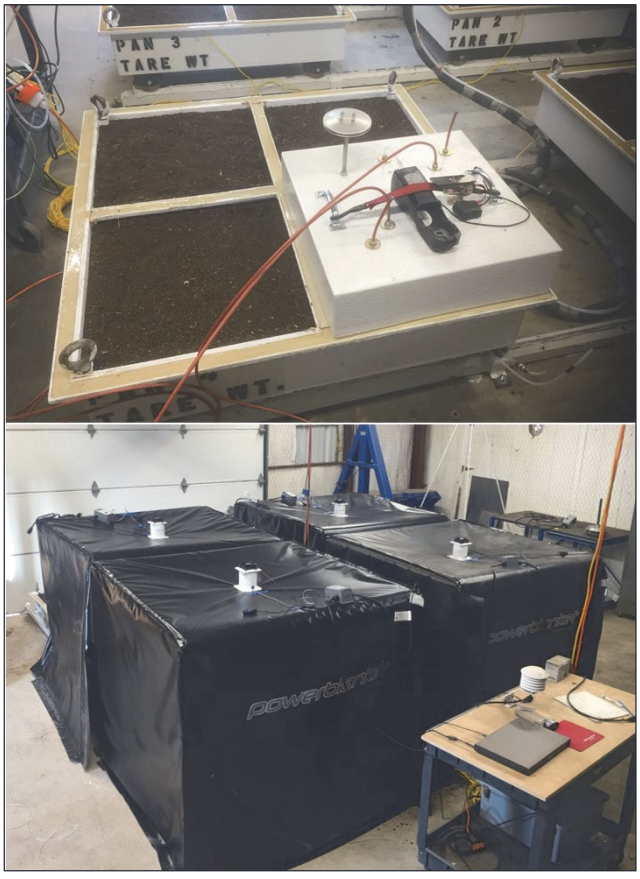

Figure 1. In Exp. 1 to 3, nitrous oxide (N_2O) emissions were measured on 0.25 m^2 pans using a portable vented lid (top) that recirculated sample air between the chamber and the analyzer. In Exp. 2 and 3, the chamber temperatures were controlled using digitally controlled hot-box heaters (bottom).

analyzer (model N_2O/CO-30-EP Enhanced Performance, Los Gatos Research, San Jose, Cal.). Chamber headspace N_2O concentrations were recorded every 1 to 2 s during each 60 s measurement period. Flux was calculated as the product of the effective headspace height and the slope of the N_2O concentration versus time curve. The slope was calculated in Microsoft Excel using linear regression for the 30 s period between 15 and 45 s after placement of the lid (Parker et al., 2017a, 2017b). Manure temperatures within the chamber (±0.1°C) were monitored using thermistors (model ACC-SEN-SDIP, Acclima, Meridian, Ida.) placed mid-depth in the manure, and ambient temperature was monitored directly above the manure surface within the flux chambers for the duration of the experiment.

In Exp. 1 to 3, each chamber pan was filled with 89 mm of native calcium carbonate soil (i.e., caliche) compacted to a dry bulk density of 1.55 Mg m^{-3}. The soil was topped with 109 mm of air-dried beef cattle feedyard manure compacted to a dry bulk density of 0.61 Mg m^{-3} with a handheld tamper.

The manure used to simulate the beef cattle feedyard surface was obtained from a commercial beef cattle feedyard with annual production of 50,000 cattle. The manure was air-dried, roughly ground with a gasoline-powered wood chipper to achieve a relatively uniform particle size, and then thoroughly mixed. Physical and chemical properties of the manure used in Exp. 1 to 4 were analyzed at a commercial laboratory (Servi-Tech Laboratories, Amarillo, Tex.) and are shown in table 1.

Total and organic N were determined by the Kjeldahl method (Sikora and Moore, 2014). Ammonium (NH_4^+) was determined by titration in accordance with Standard Method 4500-NH3. Nitrate (NO_3^-) plus nitrite (NO_2^-) was analyzed by colorimetric flow injection analysis (FIA) according to EPA Method 353.2. Phosphorus (P), potassium (K), and sulfur (S) were determined on EPA Method 3050B acid digest extracts by inductively coupled plasma atomic emission spectroscopy (ICP-AES) using AOAC Method 990.08. Water content was determined using Standard Method 2540 by loss on drying, and volatile solids were determined by loss on ignition (ASABE, 2019). Electrical conductivity and pH were determined with probe meters on 1:1 water to manure mixtures according to EPA Methods 9050 and 9045D, respectively.

Table 1. Properties of the air-dried beef cattle feedyard manure used to simulate the feedyard surface in Exp. 1 to 4. Values are means of three replicates (*n* = 3). Unless otherwise noted, all values are on a dry matter basis. Electrical conductivity and pH were measured on 1:1 water to manure mixtures by weight.

Property	Exp. 1	Exp. 2 and 3	Exp. 4
Water content (wet wt basis, g kg^{-1})	164	151	123
Organic matter (g kg^{-1})	463	452	349
Total nitrogen (N, g kg^{-1})	23.13	22.22	17.40
Organic N (g kg^{-1})	19.06	18.53	14.92
NH_4-N (g kg^{-1})	4.07	3.69	2.49
NO_3-N + NO_2-N (g kg^{-1})	0.16	0.21	0.64
Phosphorus (P, g kg^{-1})	14.57	15.54	12.00
Potassium (K, g kg^{-1})	22.95	23.23	20.47
Sulfur (S, g kg^{-1})	7.44	7.55	6.07
Electrical conductivity (S m^{-1})	1.28	0.75	1.09
pH	7.8	8.8	8.2

Exp. 1: Cattle Urine, Artificial Urine, and Water

The four treatments consisted of water (W), artificial urine (AU), and two real urines collected from beef heifers fed either a high-quality forage diet (FU) or a corn-based concentrate diet (CU). Sixteen manure-filled pans were used in Exp. 1. Three replicates per treatment were used for N_2O measurements (12 pans). An additional set of four pans, which received identical treatments, were reserved for destructive manure sampling throughout the experiment. The FU and CU urines were previously acid-treated (pH < 6) and frozen (-20°C) to prevent N losses. The forage diet consisted of 80.8% alfalfa hay, 15.0% corn silage, 0.75% dicalcium phosphate, and 3.5% premix pellets (minerals) on a DM basis, with overall crude protein (CP) content of 15.1%. The concentrate diet consisted of 71.0% dry rolled corn, 11.0% corn stalks, 7.5% corn silage, 5% soybean meal, 1.25% urea, 0.75% dicalcium phosphate, and 3.5% premix pellets, with 14.6% CP. The AU was adapted from a recipe previously shown to produce N_2O emissions similar to real urine (Kool et al., 2006). The AU used urea (12.28 g L^{-1}) and hippuric acid (0.72 g L^{-1}) as N sources, with a mixture of assorted salts (table 2). The N content of AU was set at 13.0 g L^{-1} to match that of FU (table 2). The CU had a N content of 8.0 g L^{-1}. All three urine treatments were adjusted to pH 8.1 with NaOH in order to match the W treatment. The W was Ogallala Aquifer groundwater from a drinking water well at the laboratory (pH = 8.1, 207 to 999 mg L^{-1} total dissolved solids, hardness (as $CaCO_3$) of ~241 mg L^{-1}).

Each pan received an equal amount of water or urine (1.5 kg) applied equally over the surface area of the 0.25 m^2 pan. This amount of urine is typical of a single urination event (Misselbrook et al., 2016). The treatments were applied at 0800 h on 8 August 2017. Nitrous oxide flux was subsequently measured from each pan at 1, 2, 6, 10, 16, and 24 h after water or urine addition and then at 0900 h through day 14. The ambient temperature over the 14 d period consistently exhibited a diurnal pattern, ranging from 18.8°C at night to 32.0°C during the day, with a mean of 24.0°C for the entire period.

To account for potential differences among each set of four common 0.25 m^2 pans (fig. 1), each set was initially considered a block in a randomized complete block design (RCBD), and treatments were randomly assigned such that each block received one replication of each treatment. Upon subsequent statistical analysis as an RCBD, blocking was

Table 2. Nitrogen content and pH of the three urines and water, and ingredients used to make the artificial urine for Exp. 1 (AU = artificial urine, FU = forage diet urine, and CU = concentrate diet urine, and W = water).

	AU	FU	CU	W
Total N (g L^{-1})	13.0	13.0	8.0	<0.013
pH	8.1	8.1	8.1	8.1
Ingredients				
Urea (g N L^{-1})	12.28	-	-	-
Hippuric acid (g N L^{-1})	0.72	-	-	-
$KHCO_3$ (g L^{-1})	14.0	-	-	-
KCl (g L^{-1})	10.5	-	-	-
$CaCl_2$ (g L^{-1})	0.4	-	-	-
MgCl (g L^{-1})	1.2	-	-	-
Na_2SO_4 (g L^{-1})	3.7	-	-	-

not effective (p = 0.71); therefore, the data were finally analyzed as a completely randomized design (CRD). Cumulative 14 d means among treatments were compared using post-hoc Tukey's honestly significant difference (HSD).

Manure samples were collected on days 1, 3, and 14 from the separate pan dedicated to destructive sampling. A single composite sample from 0 to 75 mm depth was analyzed for total N, NH_4, $NO_3 + NO_2$, and water content, wet weight basis (WC_{wwb}).

EXP. 2: ARTIFICIAL URINE, WATER, AND FECES

The four treatments in Exp. 2 consisted of W, AU, and two levels of wet feces (Fx1 and Fx2). Sixteen pans were used in Exp. 2, with four replicates per treatment. The amounts of W and AU were the same as Exp. 1 (1.5 kg). The AU was prepared as in Exp. 1. The Fx1 treatment received 0.60 kg of fresh feces for each 0.25 m^2 pan (2.4 kg m^{-2}), which was equal to the mass-based feces to urine excretion ratio of 0.40 reported by Jennings et al. (2018). The Fx2 treatment was twice the Fx1 amount, or 1.2 kg pan^{-1} (4.8 kg m^{-2}), equal to a feces to urine ratio of 0.80. The feces had a water content (wet weight basis) of 736 g kg^{-1} (table 3), such that Fx1 had an equivalent water application of 1.77 kg m^{-2}, and Fx2 had an equivalent water application of 3.53 kg m^{-2}.

The feces were collected from multiple fresh feces pats on the surface of a small research feedyard pen, where the beef cattle were fed a corn-based high-concentrate diet (CP = 13%). The feces were applied as a single pat for Fx1 and as two pats for Fx2, such that each pat covered 10% of the pan surface.

The treatments were applied at 0830 h on 30 January 2018. Nitrous oxide flux was subsequently measured from each pan at 1, 2, 6, 10, and 16 h after W, AU, and feces addition and then at 0930 h through day 14. Because the experiment was conducted in the winter, the pans were heated to the target temperature of 24.0°C (same mean temperature as Exp. 1 but without diurnal fluctuations) beginning four days prior to treatment application. Pan temperatures were held steady throughout the experiment. Two heating devices were used on each set of four pans (fig. 1). The ambient air surrounding each set of four chamber pans was heated using a 1.3 m × 1.3 m × 1.3 m bulk material hotbox warmer with digital temperature controller (model HB64-1440, Powerblanket, Salt Lake City, Utah). A second heater consisting of a 1400 W silicone rubber heating pad with digital temperature controller was bonded to the bottom of each set of four pans (model SRL2424X, ProTherm Industries, Hermitage, Tenn.). During flux measurements, the hotbox heater was lifted above the pans using a pulley hoist. Ventilation within the hotbox was achieved with a 12 V exhaust fan (75 mm i.d.) located at the top of each hotbox, which pulled incoming fresh air from the bottom.

To account for potential differences among each set of four common 0.25 m^2 pans (fig. 1), each set was initially considered a block in a RCBD, and treatments were randomly assigned such that each block received one replication of each treatment. Upon subsequent statistical analysis, blocking was not effective (p = 0.33); therefore, the data was finally analyzed as a CRD.

At the completion of the 14 d experiment, manure samples were collected to 76 mm depth in 12.7 mm increments from the center of each pan and analyzed for water content, total N, NH_4, $NO_3 + NO_2$, EC, and pH using the same methods as in Exp. 1. For the Fx1 and Fx2 treatments, the manure samples were collected directly beneath the center of the feces pat.

Table 3. Properties of fresh feces used in Exp. 2 and 3. Values are means of three replicates (*n* = 3). Unless otherwise noted, all values are on a dry matter basis. Electrical conductivity and pH were measured in 1:1 water to manure mixtures by weight.

Property	Value
Total N (g kg^{-1})	22.52
Organic N (g kg^{-1})	20.73
NH_4-N (g kg^{-1})	1.79
NO_3-N + NO_2-N (g kg^{-1})	<0.01
Phosphorus (g kg^{-1})	30.08
Potassium (g kg^{-1})	27.33
Sulfur (g kg^{-1})	13.28
Calcium (g kg^{-1})	122.7
Magnesium (g kg^{-1})	32.72
Water content (wet wt basis, g kg^{-1})	756
Organic matter (g kg^{-1})	799
Electrical conductivity (S m^{-1})	0.54
pH	6.9

EXP. 3: FECES ON DRY MANURE VERSUS FECES ALONE

The third experiment was conducted to determine the source of N_2O when feces were deposited on a dry manure surface. The two treatments included feces deposited on dry manure (FM) and feces alone placed on a sheet of plastic (FA). Four pans were used in Exp. 3, with two replicates per treatment. Both treatments received the same amount of feces (2.4 kg m^{-2}) applied as a single pat to 10% of the pan surface. The plastic sheet was placed at the same height as the dry manure so that the head space was the same for both treatments. A portion of the fresh feces collected prior to Exp. 2 was frozen for future use in Exp. 3. The feces were thawed and allowed to come to room temperature immediately before the experiment. The treatments were applied at 0900 h on 23 April 2018.

Nitrous oxide flux was measured immediately before feces deposition and then at 1 h, 2 h, 6 h, 1 d, 2 d, 3 d, and 4 d. The temperature of the pans was maintained at 24.0°C throughout the experiment using the heater apparatus described in Exp. 2.

EXP. 4: EFFECT OF PRECIPITATION pH

The experimental design consisted of four TRT of simulated rainfall at pH 5, 6, 7, and 8. There were 16 containers, with four replicates per TRT. Air-dried ground beef manure (220 g, WC_{wwb} = 10.84%) was placed at 100 mm depth into each of sixteen 750 mL glass containers of 75 mm diameter and 170 mm height, with 70 mm headspace. The simulated rainfall was prepared from distilled water and phosphate buffered saline (PBS, Sigma Aldrich No. P4417). The PBS solution was 0.01 M phosphate buffer, 0.0027 M potassium chloride, and 0.137 M sodium chloride with pH of 7.4. The PBS solution was adjusted to final pH with HCl or NaOH. Each container received 95 mL of simulated rainfall (equivalent to 21 mm), and the contents were thoroughly mixed, for a final manure WC_{wwb} of 37.7%. The experiment was

conducted in an air-conditioned laboratory at a target temperature of 22°C. Actual temperature fluctuated diurnally between 22°C and 25°C, peaking in late afternoon.

The treatments were applied at 1100 h on 25 March 2019. Nitrous oxide emissions were monitored starting 1 h after artificial rainfall addition and continued for 7 d. Measurements were made using a custom-made 16-port automated multiplexer system with cycles of 60 s on and 165 s off. During each 60 s sampling period, the multiplexer valves were adjusted such that the sampling container became a small RFT-NSS chamber, with headspace N_2O concentrations measured every 1 s. The recirculating airflow rate was 400 mL min^{-1} during sampling, which was the minimum airflow rate through the analytical instrument. Clean air was passed through the other containers at 40 mL min^{-1} at all other times. Flux was calculated as the product of the slope of the concentration versus time curve and the effective headspace height. Manure samples from each container were analyzed at the completion of the experiment for water content, NH_4, $NO_3 + NO_2$, and pH using the procedures described earlier.

Statistics

Statistical analyses were conducted using Excel (Microsoft Corp., Redmond, Wash.) and the PROC ANOVA procedure in SAS (SAS Institute, Cary, N.C.). Cumulative N_2O emissions were calculated in Excel by numerically integrating the area under the flux versus time curves. Post-hoc analyses of cumulative emissions were conducted used Tukey's HSD, which controls the familywise error rate at a significance level of $\alpha = 0.05$. Empirical regression models for predicting N_2O emissions were developed using Excel and the PROC REG procedure in SAS.

Results and Discussion

Exp. 1: Cattle Urine, Artificial Urine, and Water

Nitrous oxide emissions increased immediately after the addition of water or urine (fig. 2a). All treatments peaked 10 h after water or urine addition before slowly decreasing over several days. The W treatment had the highest mean initial N_2O peak (8.6 mg N m^{-2} h^{-1}), followed by FU (5.9 mg N m^{-2} h^{-1}), with similar peaks for AU (3.2 mg N m^{-2} h^{-1}) and CU (2.6 mg N m^{-2} h^{-1}) (fig. 2a). The N_2O peaks were much higher than the 0.17 mg N m^{-2} h^{-1} maximum peak reported by Di and Cameron (2012) for urine patches in grazed pasture but similar to the maximum peak of 2.38 mg N m^{-2} h^{-1} reported by Forrestal et al. (2017) for urine patches in grazed pasture. Because the first flux measurement of Di and Cameron (2012) was at least one day after urine application, it is possible they missed the maximum peak that occurred immediately after urine application, which was evident in both our research and that of Forrestal et al. (2017).

The W treatment had the highest cumulative N_2O emission after 14 d at 591.8 mg N m^{-2}, followed by FU (414.3 mg N m^{-2}), AU (193.4 mg N m^{-2}), and CU (183.6 mg N m^{-2}) ($p = 0.021$). There were two Tukey groups for cumulative emissions (fig. 2b). On an equal mass-applied basis, cumulative N_2O emissions from FU, AU, and CU were 70.0%, 32.7%, and 31.0% of W, respectively. Cumulative N_2O emissions, expressed per unit water added, were 98.6, 69.0, 32.2, and 30.6 mg N kg^{-1} water added for W, FU, AU, and CU, respectively. Of the two real urines, FU had 2.3 times higher cumulative N_2O emissions than CU. The FU treatment also had a 1.6 times higher total N (13.0 g L^{-1}) than CU (8.0 g L^{-1}), which alone suggests that the N concentration of the urine had an effect on N_2O emissions. However, the similar N_2O emissions between AU and CU, with highly different N contents, is contrary to what was expected if urine N alone was responsible for N_2O production. Our findings differ from those of Rochette et al. (2014), who reported a linear relationship between N_2O emissions and urine N rate for grazing dairy cows on pasture. Because W had the highest N_2O emissions (1.4 times higher than FU and 3.2 times higher than CU), this shows that the total N content of the urine or water was not the driving force for N_2O emissions from the feedyard manure surface. It was immediately apparent that the controlling factors for N_2O emissions from a beef

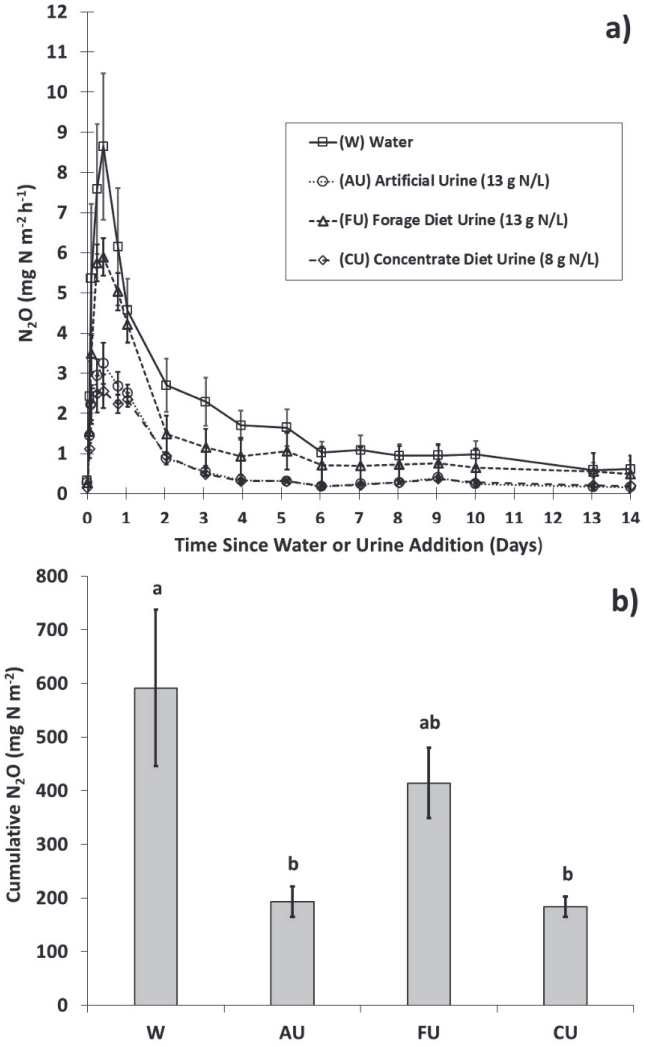

Figure 2. Nitrous oxide (N_2O, mg N m^{-2}) flux varied over time following the application of water and three types of urine to the dry beef feedlot manure surface of Exp. 1 (a, top). Each point represents the mean of three replicates. Ambient temperature fluctuated diurnally between 18.8°C and 32.0°C, with mean of 24.0°C. The letters above the bars designate Tukey groups for cumulative 14 d emissions (b, bottom). Error bars are the standard error of the mean (SEM).

feedyard manure surface are different than those for grazed pastures.

Our findings are similar to those of Redding et al. (2015), who demonstrated that there was little correlation between N_2O emissions and feedyard manure surface N content. The Redding et al. (2015) studies were based on field measurements at feedyards in different locations in Australia; thus, they were subject to varying factors such as precipitation, wind, temperature, and diet. Our highly controlled studies similarly show that there was little correlation between N_2O emissions and the N content of fresh manure added to the surface of the feedyard. Redding et al. (2015) stated that this was important because Intergovernmental Panel on Climate Change (IPCC) calculation protocols for N_2O are based on the mass of N excreted by the animal. Thus, like Redding et al. (2015), our results suggest that the IPCC protocols for estimating N_2O from beef feedyards are flawed.

Unlike studies conducted on urine patches on soil or pasture, where N_2O emissions were higher for urine than for water (Di and Cameron, 2012; Rochette et al., 2014; Forrestal et al., 2017), the results from Exp. 1 showed that N_2O emissions on a beef feedyard manure surface were greater for water than for urine (fig. 2b). It was likely not from initial pH, because all treatments had similar initial pH values yet highly differing N_2O emissions. Final manure pH values were not measured in Exp. 1, but a subsequent experiment was conducted to further assess pH effects.

This could possibly be due to activities of ammonia-oxidizing bacterial (AOB) in the enriched nitrifying environment of the feedyard manure surface. The urea in urine is hydrolyzed once it contacts the feedyard manure, which in turn increases the pH of the manure surface (Tenuta and Beauchamp, 2000). The NH_4-NH_3 equilibrium is greatly affected by pH, with NH_3 increasing and NH_4 decreasing above pH 7.5 (Fenn and Kissel, 1973). It has been shown that NH_3 can be toxic to AOB (Smith, 1964), and nitrification in N-rich soils is driven by AOB as opposed to ammonia-oxidizing archaea (AOA) (Di et al., 2009). Nicol et al. (2008) reported that the abundance of AOA increased and AOB decreased as the pH was increased from 4.9 to 7.5. In Exp. 1, the highest cumulative N_2O emissions occurred from W, which also had the lowest manure NH_4 concentration. It is possible that elevated NH_4^+ and NH_3 concentrations may have contributed to some inhibition of N_2O production, although it is unlikely that this was the primary reason.

Oxygen availability in manure varies greatly depending on manure WC, which also changes over time due to precipitation and evaporation. Based on literature values, N_2O emission factors range from 1.5% to 19% of the NH_4^+ oxidized (Rathnayake et al., 2015; Pijuan et al., 2014). Such a range in N_2O production might be explained by the different responses of N_2O-producing bioreactions (e.g., NH_2OH oxidation, denitrification) to physicochemical factors such as dissolved O_2, NH_4^+ and NO_2^- concentrations, pH, temperature, and carbon (C) availability (Groeneweg et al., 1994; Kampschreur et al., 2009; Okabe et al., 2011; Rathnayake et al., 2015). It has been reported that the genus *Nitrosomonas* is most commonly used in laboratory studies of AOB, but *Nitrosospira* seems to be the most dominant species in natural environments (Jiang and Bakken, 1999). *Nitrosomonas europaea* also appears to produce N_2O by several mechanisms. Moderate amounts of N_2O are released under full aeration, but the release increases greatly in response to O_2 limitation (Goreau et al., 1980; Remde and Conrad, 1990).

In earlier studies, we observed a second N_2O episode that peaked three to seven days after water application, but only when the temperature was greater than 31.0°C (Parker et al., 2017a). Similar to earlier experiments, in the current experiment, which was conducted at mean ambient temperature of 24.3°C, a second N_2O episode was not observed. A day after water or urine application, the total N of the manure was highest for AU and FU (fig. 3a). It follows that these two urines also had the highest N content of 13 g L^{-1}. Because W had the highest N_2O emissions, there was a negative correlation between cumulative N_2O flux and mean manure total N ($r = -0.66$, $p = 0.28$). Ammonium-N concentrations were highest in AU, followed by CU, FU, and W (fig. 3b). There was a negative correlation between cumulative N_2O flux and mean manure NH_4 concentration ($r = -0.93$, $p = 0.026$). Manure NO_3 concentrations were erratic throughout the experiment (fig. 3c). The W treatment had the highest mean manure NO_3 concentration, and cumulative N_2O flux was positively correlated with mean NO_3 concentrations ($r = 0.91$, $p = 0.034$). At no time did NO_3 concentrations fall below 0.05 g kg^{-1}. The increase in NO_3 concentration over the first three days in the W treatment suggests the occurrence of nitrification, whereas the decrease in NO_3 in CU and AU in this same time period suggests that denitrification was occurring. Because nitrification and denitrification can occur simultaneously or consecutively in manure, and both processes can produce N_2O, it is unclear whether the N_2O produced in the first few days after water or urine application was due to nitrification, denitrification, or some more complicated mechanism such as nitrifier-denitrification, heterotrophic nitrification, or coupled nitrification-denitrification (Nielsen et al., 1996; Wrage et al., 2001). Our future research will continue to address the effects of short-term events on N_2O emissions from beef feedyards and manure-applied croplands, as well as elucidate the role of soil nitrification and denitrification mechanisms associated with microbiome diversity changes in real-time N_2O emissions.

The manure water contents were similar among treatments, which was to be expected because all treatments received the same amount of liquid (fig. 3d). At the completion of the experiment, the water contents of all treatments were slightly less than their pre-application values of 164 g kg^{-1}, an indication that most of the applied water or urine had evaporated during the 14 d experiment.

Exp. 2: Artificial Urine, Water, and Feces

In Exp. 2, N_2O emissions peaked 6 to 24 h after water, urine, or feces addition to dry manure (fig. 4a). The W treatment had the highest mean initial N_2O peak (3.7 mg N m^{-2} h^{-1}), followed by Fx2 (1.3 mg N m^{-2} h^{-1}), Fx1 (0.52 mg N m^{-2} h^{-1}), and AU (0.32 mg N m^{-2} h^{-1}). The W treatment had the highest cumulative N_2O emission of 173.8 mg N m^{-2}, followed by AU (23.1 mg N m^{-2}), Fx2 (18.1 mg N m^{-2}), and Fx1 (8.0 mg N m^{-2}) ($p = 0.0002$). There were two Tukey groups, with W significantly larger than the other three treatments (fig. 4b).

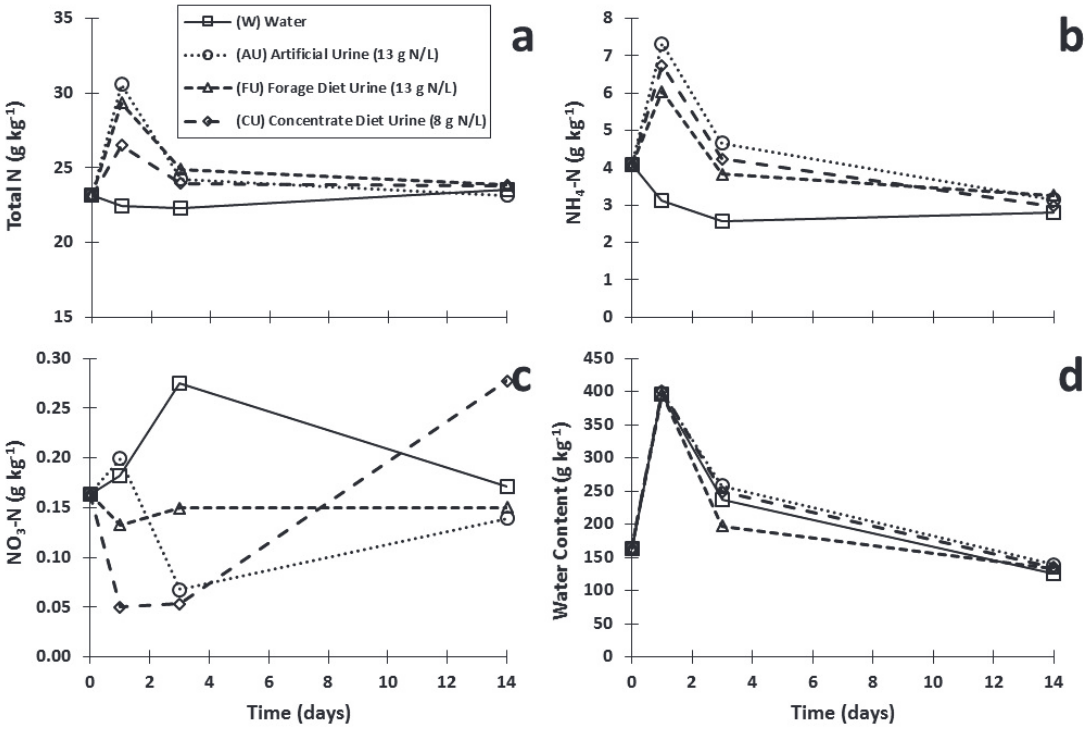

Figure 3. Plots of manure nutrient concentrations over time for Exp. 1. Manure samples were collected from a separate pan dedicated to destructive sampling. Each point is from a single composite sample from 0 to 75 mm depth.

On a daily excretion basis, cumulative N_2O emissions from feces were 35% of those from urine. Chadwick et al. (2018) reported similar lower emissions for feces than for urine. On an equal mass-applied basis, cumulative N_2O emissions from AU were 13.3% of W. Cumulative N_2O emissions expressed per unit water addition were 29.0, 3.8, 4.5, and 5.1 mg N kg^{-1} water for W, AU, Fx1, and Fx2, respectively.

In Exp. 2, the cumulative N_2O for W of 173.8 mg N m^{-2} was much lower than the 591.8 mg N m^{-2} of Exp. 1. Similarly, the cumulative N_2O for AU in Exp. 2 of 23.1 mg N m^{-2} was much lower than the 193.4 mg N m^{-2} of Exp. 1. It is unlikely that this was due to differences in the dry manure, as the chemical characteristics, particularly the N contents, were similar among the two experiments (table 2). The primary difference between the two experiments was the temperatures used. Although both experiments had the same mean temperature of 24.0°C, the ambient temperature in Exp. 1 fluctuated daily between about 18.8°C and 32.0°C, whereas the temperature in Exp. 2 was maintained at a steady 24.0°C. Thus, N_2O emissions were higher in Exp. 1 when temperatures fluctuated diurnally than in Exp. 2 when they were steady, most likely due to higher microbial activity with the fluctuating temperatures. In other words, because the formation of N_2O was nonlinear with temperature, as demonstrated by Abdalla et al. (2009) in Arrhenius plots of denitrification and temperature, the absolute value of N_2O production was greater above the mean temperature of 24.0°C than below. In earlier studies, we observed similar differences in N_2O emissions between experiments with diurnal temperature fluctuations (Parker et al., 2017a) and those with constant temperatures (Parker et al., 2018b).

The results of Exp. 1 and 2 were similar in that urine had considerably less cumulative N_2O emissions than water, even though the amount of liquid applied to dry manure was the same. In Exp. 1, AU was 32.7% of W, whereas in Exp. 2, AU was only 13.3% of W. Further research is warranted to investigate the effect of diurnal temperature fluctuations on N_2O emissions.

At the completion of the experiment, AU had the highest total N near the manure surface but had similar total N concentrations as other treatments at depth (fig. 5a). Ammonium-N concentrations were also highest within AU, and the differences were more pronounced with depth below 45 mm (fig. 5b). Manure NO_3 concentrations were variable, as indicated by the large error bars, with no distinct differences among treatments (fig. 5c). Manure water content was higher near the surface in Fx1 and Fx2 than in W or AU. Even though W and AU received more liquid application, it was apparent that most of the water either evaporated or was transported below the 45 mm manure depth (fig. 5d). All of the treatments had near-surface manure moisture contents lower than the initial manure, demonstrating the strong evaporative demand in this semi-arid region. Manure EC was highest in AU, a result of the addition of salts with the artificial urine application (fig. 5e). The near-surface pH was higher in Fx1 and Fx2 than in either W or AU (fig. 5f). These same manure samples also had higher water contents; thus, one possibility for the higher near-surface pH was that urea may have been hydrolyzed from water addition, thereby increasing the pH of the manure surface (Tenuta and Beauchamp, 2000).

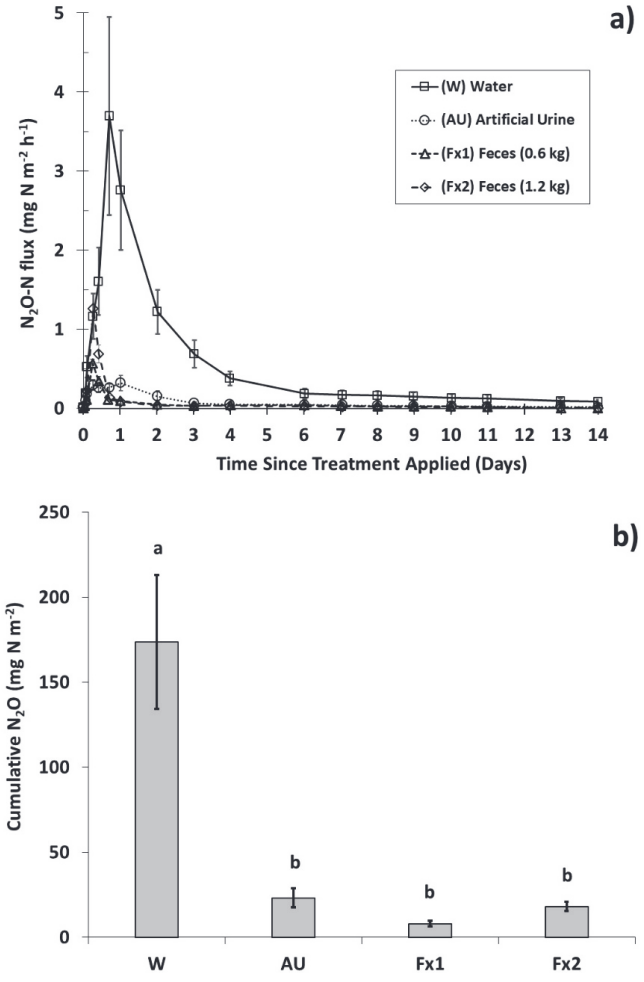

Figure 4. Nitrous oxide (N_2O, mg N m^{-2}) flux varied over time following the application of water, artificial urine, or feces to the dry beef feedlot manure surface of Exp. 2 (a, top). Each point represents the mean of four replications (n = 4). The steady ambient temperature was 24.0°C. The letters above the bars designate Tukey groups for cumulative 14 d emissions (b, bottom). Error bars are the standard error of the mean.

Exp. 3: Feces on Dry Manure versus Feces Alone

In Exp. 3, N_2O emissions peaked at 6 h for the feces on dry manure (FM), with a cumulative N_2O flux of 3.6 mg N m^{-2} after four days (fig. 6a). N_2O fluxes were zero to slightly negative for the feces alone (FA), with a cumulative N_2O flux of -0.21 mg N m^{-2} after four days ($p = 0.032$). The negative N_2O flux was likely the result of ambient N_2O being absorbed across the air-water interface in the wet feces (Heincke and Kaupenjohann, 1999). The Tukey groups for cumulative emissions are shown in figure 6b.

The manure directly beneath the feces pats was moist at the completion of the experiment. Manure water content was not measured in this experiment, but as noted in Exp. 2, the water content of the manure directly beneath the feces pats was about 60 g kg^{-1} higher than the manure farther away from the feces pats (fig. 5d). Because N_2O was not emitted from the fresh feces, it was apparent that N_2O was produced from the wetting of the dry manure beneath the feces pats. In earlier experiments, we determined that N_2O production from dry feedyard manure was linearly correlated with water addition (Parker et al., 2017a, 2017b).

Exp. 4: Effect of Precipitation pH

Nitrous oxide emissions increased after simulated rainfall addition in all pH treatments. Emissions peaked at 17 h after adding water and then declined and peaked again at 48 to 54 h (fig. 7a). A somewhat similar two-peak phenomenon was observed in earlier research but never at this cooler temperature of 22°C to 25°C, and in previous experiments the second peak occurred between three to seven days after water addition (Parker et al., 2017a, 2018b). It is probable that the occurrence of the two peaks in Exp. 4 was more related to diurnal temperature fluctuation in the laboratory. There was a 3°C daily fluctuation in manure temperature with a peak near 1700 h (late afternoon), which corresponded with the time of the second N_2O peak.

The pH 5 and pH 8 treatments had the highest cumulative N_2O emissions, with lower emissions at pH 6 and pH 7. There was a significant, almost 2-fold decrease in cumulative N_2O emissions between pH 5 and pH 6 (fig. 7b). This is contrary to previously published research for soils, where a decrease in soil pH generally leads to lower overall nitrification and N_2O production (Dancer et al., 1973; Kyveryga et al., 2004; Paul and Clark, 1989; Ste-Marie and Pare, 1999). In soils, a decrease in N_2O at low pH has been partially attributed to low soil organic C content (Simek and Cooper, 2002); however, unlike most soils, manure is not limited by organic C availability.

Groeneweg et al. (1994) reported that maximum NH_3 oxidation rates occurred between pH 6.7 and pH 7.0, while the optimum aerobic N_2O production from AOB in enriched N media occurred at pH 5.6 to pH 6.5 (Jiang and Bakken, 1999). Those studies support our findings of N_2O production at pH 5 and pH 8, but the cause for the large differences in N_2O emissions between pH 5 and pH 6 in the current research has yet to be determined.

Cumulative N_2O emissions after 7 d were 2832, 1447, 2008, and 2376 mg N m^{-2} for pH 5, pH 6, pH 7, and pH 8, respectively ($p = 0.011$). There were two Tukey groups for cumulative emissions (fig. 7b). The only statistical difference, and the greatest difference in magnitude of cumulative N_2O emissions, was between pH 5 and pH 6. The N_2O emissions were statistically equal in the pH 6 to pH 8 range, although there was a visual trend of increasing N_2O emissions with increasing pH in this range. These results indicate the importance of rainfall pH on N_2O emissions, especially in areas where pH varies between 5 and 6. In the 1980s, the pH of rainfall in the Texas cattle-feeding region was reported between 6.3 and 6.5 (Smith et al., 1984; Sharpley et al., 1985), but observations since 2007 have shown average rainfall pH closer to 6.0, with some annual observations as low as 5.5 (NADP, 2019). Thus, small differences in rainfall pH could have a considerable effect on feedyard N_2O emissions in the region.

At the completion of the experiment, there were no statistical differences in manure properties among the four treatments (table 4). The pH of the manure increased slightly over time. All four treatments had similar ending manure pH values of 8.4, an indication of the high buffering capacity of the manure (Woodbury et al., 2001; Parker et al., 2005; Cole et al., 2009; Varel et al., 2010).

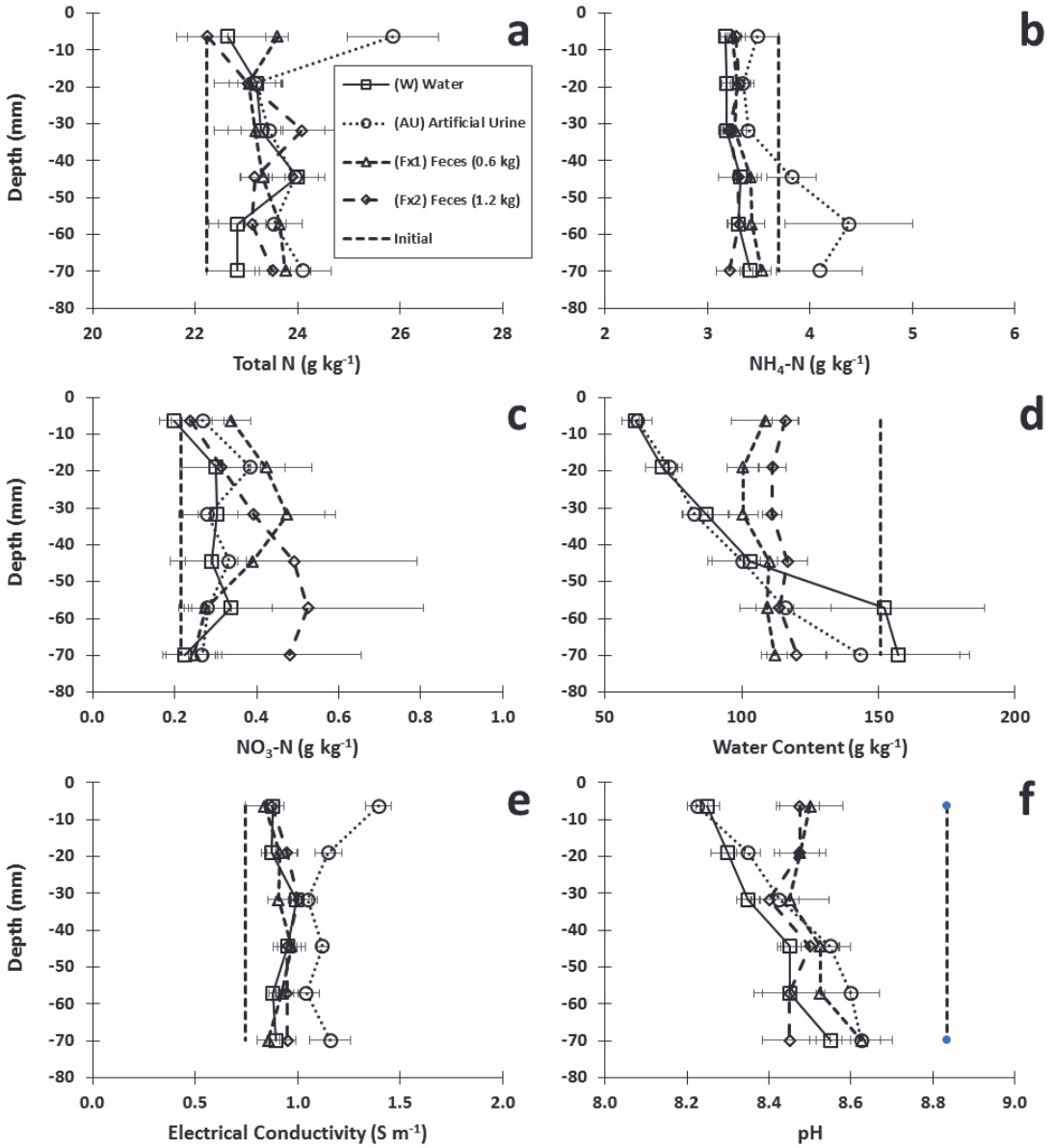

Figure 5. Plots of manure nutrient concentrations at varying depths as measured at the completion of Exp. 2. Each point represents the mean of four replications (n = 4). Error bars are the standard error of the mean (SEM). Vertical dashed lines are initial manure concentrations, prior to application of treatments.

The water content increased in all four treatments, as expected due to the adding of water. Nitrate + nitrite concentrations decreased over time, but there were no statistical differences among the four treatments at the completion of the experiment. Ammonium concentrations decreased over the same period, but again there were no statistical differences among the treatments at the completion of the experiment.

Modeling N_2O Emissions from Urine and Feces

We recommend that the empirical modeling of N_2O emissions due to water excretion in urine and feces be conducted according to the following two-step process. The first step is to predict the amount of water excreted in the urine and feces. The second step is to predict N_2O emissions based on the calculated water excretion by applying reduction factors, as we have shown in these experiments that the N_2O emitted from urine and feces is less than N_2O from water alone.

Step 1: Predict Amount of Water Excreted in Urine and Feces

The excretion of urine by cattle is positively correlated with drinking water intake (Petersson et al., 1988; Murphy, 1992). Maximum daily air temperature (MDAT) is the primary factor affecting drinking water intake by feedyard cattle in the Southern High Plains (Parker and Brown, 2003). Parker et al. (2000) showed that feedyard drinking water intake in the region is steady at MDAT below 20°C and then increases linearly above 20°C such that each 1°C increase in MDAT increases drinking water intake by 1.7 kg d^{-1}. Spek et al. (2012) determined that there was a linear relationship between urine output and water intake in dairy cows, with 94% of water intake being excreted as urine after meeting maintenance water requirements. For modeling purposes, we assumed that a similar relationship exists for beef cattle, such that urine excretion increases linearly above MDAT of

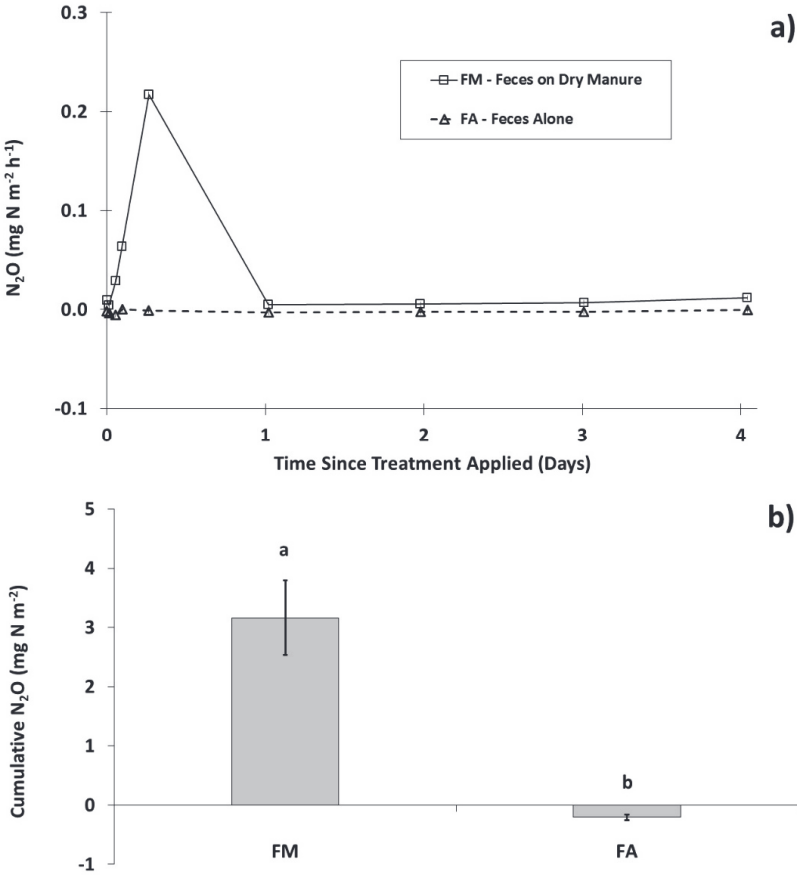

Figure 6. Nitrous oxide (N_2O, mg N m^{-2}) flux varied over time following the application of feces on dry manure (FM) or feces alone (FA) in Exp. 3 (a, top). Each point represents the mean of two replications (*n* = 2). The steady ambient temperature was 24.0°C. The letters above the bars designate Tukey groups for cumulative 4 d emissions (b, bottom). Error bars are the standard error of the mean (SEM).

20°C and that each 1°C increase leads to a 1.6 kg animal^{-1} d^{-1} (e.g., 94% of 1.7 kg) increase in urinary water excreted.

Jennings et al. (2018) reported water excreted in urine (13.2 kg d^{-1}) and feces (3.3 kg d^{-1}) from 374 kg steers maintained at ambient temperature of 24°C in a respiration calorimetry trial, for a total water excretion of 16.5 kg d^{-1}. Using this baseline point, and the linear relationship between water excretion and MDAT presented above, a model of urine and feces water excretion versus MDAT was formulated. Due to limited data suggesting otherwise, we assumed that the water excreted in feces did not change with temperature. The resulting empirical water excretion model is shown in figure 8, and the regression equations are presented in equations 1 to 5:

$$WET = 10.10 \text{ for } MDAT < 20°C \quad (1)$$

$$WET = 1.60 \times MDAT - 21.90 \text{ for } MDAT \geq 20°C \quad (2)$$

$$WEU = 6.80 \text{ for } MDAT < 20°C \quad (3)$$

$$WEU = 1.60 \times MDAT - 25.20 \text{ for } MDAT \geq 20°C \quad (4)$$

$$WEF = 3.30 \text{ for all } MDAT \quad (5)$$

where WET is the total water excreted in urine and feces (kg animal^{-1} d^{-1}), WEU is the water excreted in urine (kg animal^{-1} d^{-1}), WEF is the water excreted in feces (kg animal^{-1} d^{-1}), and MDAT is the maximum daily air temperature (°C).

The water excretion model was based on data from 374 kg steers. Drinking water intake and subsequent urine output vary with animal size, and animal size varies greatly during the growing phase (Parker and Brown, 2003). Future model adjustments can be made for different animal sizes as additional data become available,

In the absence of either MDAT or average daily air temperature (ADAT), but where one or the other is known, the relationships shown in equations 6 and 7 were derived from long-term regional weather data:

$$ADAT = 0.905 \times MDAT - 6.053 \quad (r^2 = 0.94) \quad (6)$$

$$MDAT = 1.033 \times ADAT + 7.652 \quad (r^2 = 0.94) \quad (7)$$

where ADAT is the average daily air temperature (°C), and MDAT is the maximum daily air temperature (°C).

Step 2: Predict N_2O Emissions from Water Excreted in Urine and Feces

Based on earlier research (Parker et al., 2017a, 2018a, 2018b), we developed regression equations for predicting N_2O emissions as a function of water addition and average daily manure temperature (ADMT). If ADMT is unavailable, it can be estimated using ADAT (eq. 8):

$$ADMT = 0.0122 \times ADAT^2 + 0.618 \times ADAT + 3.769 \quad (r^2 = 0.92) \quad (8)$$

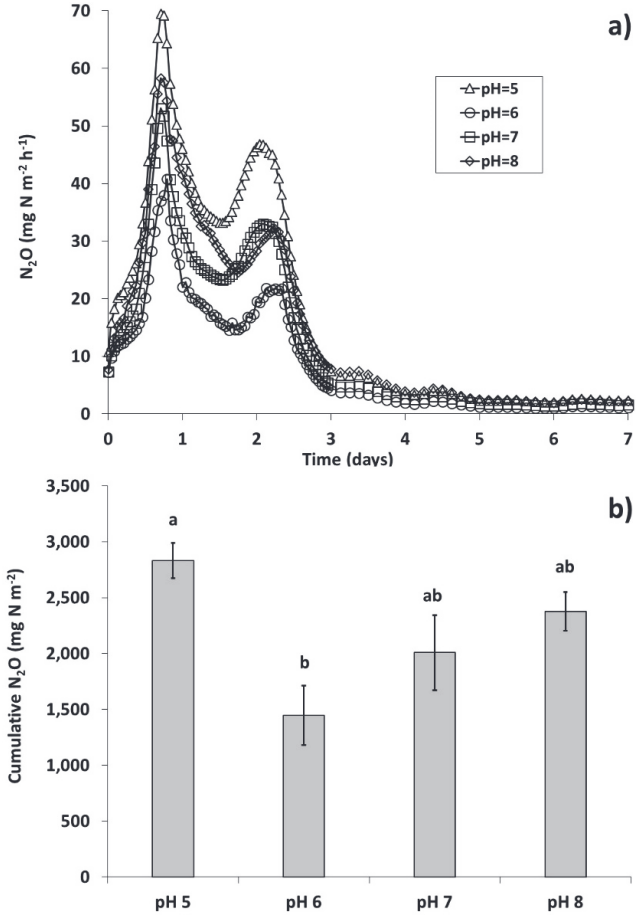

Figure 7. In Exp. 4, N_2O flux varied over time following the application of simulated rainfall at varying pH (a, top). Each point represents the mean of four replications (n = 4). The letters above the bars designate Tukey groups for cumulative 7 d emissions (b, bottom). Error bars are the standard error of the mean (SEM).

Table 4. Properties of manure at beginning and completion of Exp. 4. Unless otherwise noted, all values are on a dry matter basis; pH was measured on 1:1 water to manure mixtures. Means with different letters in the same column are significantly different (p < 0.05).

Treatment	Water Content, (wet wt basis, g kg^{-1})	NH_4-N (g kg^{-1})	NO_3-N + NO_2-N (g kg^{-1})	pH
Initial	123 b	2.49 a	0.64 a	8.2 b
pH 5	297 a	2.00 b	0.46 b	8.4 a
pH 6	295 a	2.04 b	0.46 b	8.4 a
pH 7	293 a	2.00 b	0.46 b	8.4 a
pH 8	287 a	2.04 b	0.46 b	8.4 a

where ADMT is the average daily manure temperature (°C), and ADAT is the average daily air temperature (°C). The relationships in equations 6, 7, and 8 were developed from 22 years of daily weather data (1996 to 2017) in the Amarillo, Texas, area.

Emissions due to urine and feces deposition can be estimated using reduction factors because, as shown earlier, the N_2O emitted from urine and feces is less than the N_2O from water alone. The selection of a urine reduction factor (URF) is somewhat subjective, as we demonstrated in Exp. 1 where N_2O emissions from urine range from 31.0% to 70.0% of those from an equivalent mass of water. For the purpose of modeling N_2O emissions from feedyards where beef cattle are

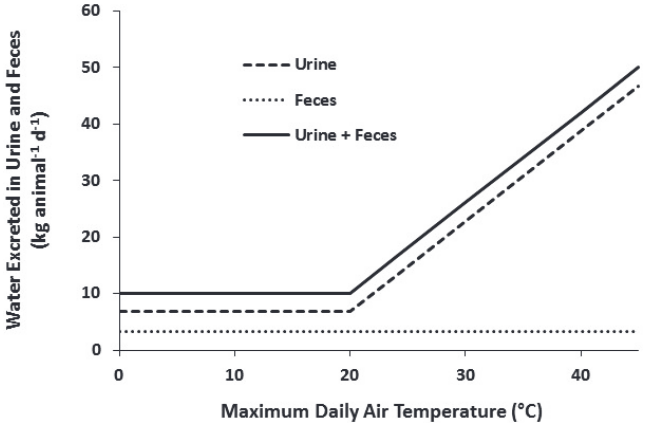

Figure 8. Empirical model of water excreted in urine and feces as a function of maximum daily temperature. The model was developed from urine and feces excretion data for 374 kg feeder steers fed a corn-based concentrate diet (Jennings et al., 2018) and drinking water intake data from a commercial feedyard (Parker et al., 2000).

fed a corn-based high-concentrate diet, we recommend a URF of 0.327, such that N_2O emissions from urine are 32.7% of those from an equivalent mass of water. Based on the findings of Exp. 2, we recommend a feces reduction factor (FRF) of 0.156, such that N_2O emissions from the water in feces are 15.6% of those from an equivalent mass of water alone.

Emissions of N_2O have been shown to be highly dependent on temperature, with different N_2O production rates at breakpoints of 31.0°C and 38.1°C (Parker et al., 2018b). Thus, regression equations were developed for each of the temperature breakpoints (eqs. 9 to 14).

For 0.0°C < ADMT < 31.0°C:

$$E_U = \text{URF} \times (3.008 \times \text{ADMT}) \times \text{WEU} / \text{SR} \quad (9)$$

$$E_F = \text{FRF} \times (3.008 \times \text{ADMT}) \times \text{WEF} / \text{SR} \quad (10)$$

For 31.0°C ≤ ADMT < 38.1°C:

$$E_U = \text{URF} \times (9.316 \times \text{ADMT} - 123.689) \times \text{WEU} / \text{SR} \quad (11)$$

$$E_F = \text{FRF} \times (9.316 \times \text{ADMT} - 123.689) \times \text{WEF} / \text{SR} \quad (12)$$

For 38.1°C ≤ ADMT ≤ 46.2°C:

$$E_U = \text{URF} \times (-10.728 \times \text{ADMT} + 639.961) \times \text{WEU} / \text{SR} \quad (13)$$

$$E_F = \text{FRF} \times (-10.728 \times \text{ADMT} + 639.961) \times \text{WEF} / \text{SR} \quad (14)$$

where E_U is the cumulative N_2O emissions from urine (mg N m^{-2}) over a 20 d period, E_F is the cumulative N_2O emissions from feces (mg N m^{-2}) over a 20 d period, URF is the urine reduction factor, FRF is the feces reduction factor, ADMT is the average daily manure temperature (°C), WEU is the water excreted in urine (kg animal^{-1} d^{-1}), WEF is the water excreted in feces (kg animal^{-1} d^{-1}), and SR is the stocking rate (~15 m^2 animal^{-1}). Note that WEU and WEF (kg animal^{-1} d^{-1}), when divided by the stocking rate (m^2 animal^{-1}), give the effective water application (in units of mm d^{-1}).

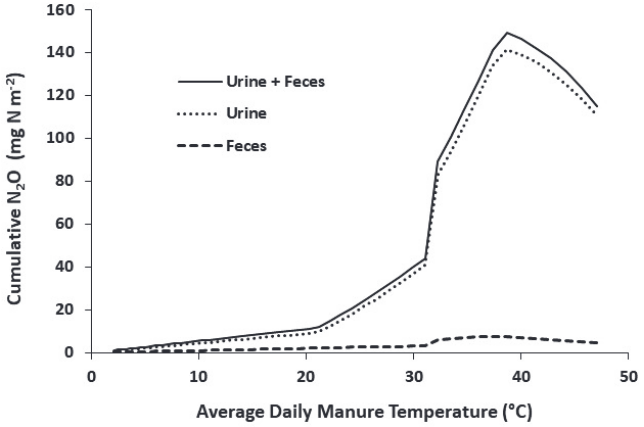

Figure 9. Cumulative 20 d N_2O emissions (mg N m^{-2}) from the feedyard pen surface as caused by the daily excretion of urine and feces. Emissions were predicted using equations 1 to 14 using data derived from 374 kg steers.

Using equations 9 to 14, the modeled cumulative N_2O emissions for different ADMT are shown in figure 9. There were breakpoints in N_2O emissions near ADMT of 21°C (coinciding with increases in drinking water intake and urinary excretion) and 31.0°C and 38.1°C (coinciding with differences in N_2O production rates.

Future Research

In earlier research, we developed empirical equations for N_2O emissions based on amount of rainfall and manure temperature (Parker et al., 2017a, 2018b). A simple preliminary empirical model was also developed based on these two parameters. The model used 22 years of daily climatological data to predict annual N_2O emissions (Parker et al., 2018a).

In the current research, we developed empirical equations for estimating N_2O emissions due to the deposition of fresh urine and feces on the feedyard pen surface. These new equations will be added to the preliminary empirical model to better estimate daily and annual N_2O emissions from beef cattle feedyards using daily weather data. The final empirical model will be validated and compared to recently collected field N_2O emissions data from commercial feedyards in the Texas Panhandle (Parker et al., 2019).

Conclusions

The following conclusions were drawn from this research:

Annual urine deposition onto beef cattle feedyard manure surfaces in the semi-arid Texas region adds about 320 mm $year^{-1}$ of water, as compared to average annual precipitation of 470 mm. Cumulative N_2O emissions for urine deposited on a dry feedyard manure surface ranged from 31% to 70% of those from an equal mass of water. Thus, annual N_2O emissions resulting from urine deposition would be 22% to 49% above that caused by precipitation.

Annual feces deposition onto beef cattle feedyard manure surfaces adds the equivalent of 95 mm $year^{-1}$ of water. Emissions from fresh feces were the result of wetting of the dry manure below the feces pat, and not directly from the feces pat. Cumulative N_2O emissions from the water in feces deposited on a dry feedyard manure surface were 15.5% of those from an equal mass of water. Thus, annual N_2O emissions resulting from feces deposition would be about 3% above that caused by precipitation.

For empirical modeling purposes, we recommend that N_2O emissions be estimated in a two-step process that first involves predicting the amount of water excreted in urine and feces, followed by predicting N_2O emissions using urine and feces reduction factors of 0.327 and 0.156, respectively. Both of these steps are highly dependent on temperature.

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