THESIS

PRACTICAL STRATEGIES FOR REDUCING AMMONIA VOLATILIZATION FROM FEEDLOTS ALONG COLORADO'S FRONT RANGE

Submitted by

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ABSTRACT

PRACTICAL STRATEGIES FOR REDUCING AMMONIA VOLATILIZATION FROM FEEDLOTS ALONG COLORADO'S FRONT RANGE

The Rocky Mountain National Park (RMNP) Initiative is a collaboration between state and federal agencies that has committed to achieving a 50% reduction (from 2004 levels) in N deposition in RMNP by 2032; current levels of N deposition have caused measureable changes in aquatic and terrestrial alpine ecosystems in the park. Northeastern Colorado, a region with a high concentration of livestock production, is likely one of the top two contributors to N deposition in RMNP. Reducing ammonia volatilization from Colorado's livestock sector will be important to achieving N deposition reduction goals in RMNP. To advance understanding of N loss from Colorado's feedlots, studies were done to examine: 1) the potential of reducing ammonia volatilization through lowering crude protein content in feedlot diets, 2) the effect of water sprinkling (a commonly prescribed dust control practice) on ammonia volatilization, and 3) the upper bound of ammonia flux from feedlot pen surfaces in Colorado.

Two types of alternative feedlot diets – Oscillating N and Reduced N – were compared to a Control diet treatment and assessed for their effect on cattle performance

and ammonia volatilization from pen surfaces. Intact pen surface samples were collected from November to March during a feeding trial from the three different diet treatments. Ammonia volatilization was measured under controlled conditions using a laboratory chamber system. The Reduced N diet (11.62% CP) significantly reduced cumulative 7-day ammonia emissions by 21 to 40% compared to the Control diet (13.5% CP). Average daily ammonia flux from Control diet samples ranged from 7.1 to 9.4 g NH_3 m^{-2} d^{-1}, while Reduced N diet samples had an average daily ammonia flux of 3.7 to 7.0 g NH_3 m^{-2} d^{-1}. There was no difference between the Oscillating N diet (11.62% CP 3 days/week and 13.5% CP 4 days/week) and the Control diet. Cattle performance (average daily gain) was not affected.

A common feedlot practice to control dust and address frequent complaints from neighboring property owners and communities is to sprinkle the pen surface with water. Many feedlot operators have infrastructure in place – either solid set sprinklers on fencelines or water trucks that drive down the alleys – to sprinkle regularly during hot, dry conditions. The mechanics of ammonia volatilization suggest that watering could potentially increase N loss, but several studies suggest that water may have a suppressive effect on volatilization rates. Paired samples were taken from visibly obvious urine patches at a commercial feedlot in northeastern Colorado during July and August. In the laboratory, 5 mm of water – a typical amount of water applied for dust control – was applied to one sample from each pair, chosen randomly. Ammonia volatilization was then measured in a laboratory chamber system. Volatilization on the first day of measurement was 39.04 g NH_3 m^{-2} d^{-1} for watered samples and 28.58 g NH_3 m^{-2} d^{-1} for unwatered – a reduction of 27%. There was no difference in emissions on days 2 through 7 of measurement. This suggests that not only are N losses not exacerbated by this common dust control technique, but water application could be an effective co-BMP for reducing ammonia volatilization from the pen surface as well. By sampling urine patches during mid-summer very high ammonia fluxes (i.e. 50 g NH_3 m^{-2} d^{-1}) were captured that will be useful for parameterizing models for simulating patterns of ammonia losses from feedlots.

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CHAPTER I

INTRODUCTION: AMMONIA EMISSIONS FROM BEEF CATTLE FEEDLOTS: IMPLICATIONS FOR COLORADO'S FRONT RANGE

Colorado's Front Range is a rapidly growing urban corridor located at the abrupt transition between the Great Plains and the Rocky Mountains. Competition for space and resources on the Front Range is fierce, the stakeholders are diverse, and the ecological and economic health of Colorado depends on working together to generate science-based solutions to complex problems. In the last 20 years, nitrogen (N) deposition at Niwot Ridge near Rocky Mountain National Park (RMNP) at the eastern edge of the Rocky Mountains, a long term ecological research site, has increased by about 200% while deposition at sites in central and western Colorado has remained stable (Elser et al., 2009). Ecological impacts of increased deposition are evident in the alpine ecosystems of RMNP (Baron et al., 2000; Elser et al., 2009). While attribution of the source of deposited N is still highly uncertain, about half is believed to originate from metro Denver, agricultural regions of northeastern Colorado, and from within RMNP; the other half comes from other parts of Colorado and outside of the state. (Malm et al., 2009).

In the Colorado Front Range, prevailing winds are generally westerly (downslope); however, easterly (upslope) winds occur throughout the year with the potential to bring pollution from urban and agricultural areas into sensitive alpine areas such as RMNP (Malm et al., 2009). Upslope conditions are most common in RMNP during April, representing about 40% of hours, and least frequent during December, accounting for slightly more than 20% of hours (Malm et al., 2009). More importantly, however, for N deposition in RMNP, is the association between easterly winds and precipitation events. During precipitating hours at the gaseous pollutant monitoring site in RMNP, about half of the winds were from the east (Malm et al., 2009). Hours characterized by upslope conditions and precipitation events are most likely to occur in the winter and spring, whereas summer precipitation events are more likely to be associated with westerly winds (Malm et al., 2009). Deposition events in RMNP generally reflect the trends one would expect based on these wind patterns, associated mostly with upslope conditions in the spring, and with more varied (but more likely westerly) wind patterns in the summer. Malm et al. (2009) reported on source attribution for the spring and summer of 2006 using back trajectory modeling and found that wet deposition of ammonium accounted for nearly 35% of deposition during both seasons. Correspondingly, about a third of all N deposition in RMNP in the spring originated in northeastern Colorado, and nearly half of those emissions are attributed to the livestock sector, which ultimately accounts for an estimated 15% (one of two largest sources identified, along with mobile sources, also 15%) of all N deposition reaching RMNP in the spring of 2006 (Malm et al. 2009). In the spring, N deposition appears to be highly episodic; one multi- day precipitation event dominated the overall seasonal deposition totals. Summer deposition was more varied with western Colorado and local (within RMNP) sources playing larger roles than northeastern Colorado.

Beginning in 2004 the National Park Service, the U.S. Environmental Protection Agency, and the Colorado Department of Public Health and the Environment began working together as the Rocky Mountain National Park Initiative along with the scientific community and industry groups to address N deposition issues facing RMNP. In 2007, this group adopted a Nitrogen Deposition Reduction Plan that set a management goal of reducing deposition from 3.1 kg N ha^{-1} yr^{-1} to 1.5 kg N ha^{-1} yr-^{1} by 2032 (2007). The interim management goal was to achieve a reduction of 13% to 2.7 kg N ha^{-1} yr^{-1} by 2012 (2007). In 2010, a contingency plan was adopted to outline a plan of action for achieving deposition reductions in the event that interim goals are not met (2010). The Agriculture Air Quality Technical Workgroup of the RMNP Initiative submitted a supporting document to the 2010 Contingency Plan outlining best management practices (BMPs) that could be part of a plan of action for achieving deposition reduction targets if the 2012 goal is not met (2009).

Ammonia Volatilization from Feedlots

Colorado's eastern plains are a highly productive agricultural region. In 2007, Weld County, CO ranked second in the U.S. in total sales of cattle and calves and first for sheep and goats (USDA, 2007). There are nearly a million cattle on feed in Colorado with about 600,000 head in animal feeding operations (AFOs) within about 180 km of the eastern slope of the Rocky Mountains (J. Ham, personal communication). Nitrogen in animal feed that exceeds the animal's needs is deposited on an AFO's pen surface in urine and manure in the form of urea and undigested organic N, respectively (Varel, 1997). In feedlot systems, more than 85% of fed N is excreted as urea and organic N (Kissinger et al., 2007). Urea is quickly hydrolyzed by the enzyme urease to form ammonium and ammonia in a two step process where urea is first broken down into one mole of ammoniacal-N species and carbamate (Eq.1.1), and then carbamate spontaneously degrades to give a second mole of ammoniacal-N species and carbon dioxide (Eq.1.2).

$$NH_2(CO)NH_2 + H_2O \xrightarrow{urease} 1\,NH_3/NH_4^+ + NH_2(CO)OH \qquad (1.1)$$

$$NH_2(CO)OH \rightarrow 1\,NH_3\,/NH_4^+ + CO_2 \qquad (1.2)$$

(Béline et al., 1998; Kaminskaia and Kostić, 1997). The form of the ammoniacal-N species produced depends upon pH (Eq.1.3) The enzyme urease is present in manure and soil, so in CAFOs where animals defecate and urinate in the same space, hydrolysis of urine-urea happens in hours to days after excretion (Béline et al., 1998; Hristov et al., 2011; James et al., 1999; Stewart, 1970). Organic N in manure breaks down to ammonium more slowly through microbial processes that take months (Béline et al., 1998; Hristov et al., 2011). The ammonium ion does not volatilize, but exists in an equilibrium with ammonia, which is susceptible to volatilization, in the soil solution

$$C_{NH_4^+(aq)} \overset{pH,temp}{\Longleftrightarrow} C_{NH_3(aq)} \qquad (1.3)$$

where $C_{NH_4^+(aq)}$ is the concentration of ammoniacal N in the form of ammonium in the aqueous phase of the soil solution (kg m^{-3}), and $C_{NH_3(aq)}$ is the concentration of ammoniacal N in the form of ammonia in the aqueous phase of the soil solution (kg m^{-3}). This equilibrium is controlled by a pH- and temperature-dependent equilibrium constant (K_a). Ammonia in the aqueous phase of the soil solution exists in equilibrium with ammonia in the gaseous phase of the soil solution

$$C_{NH_3\ (aq)} \overset{temp}{\Longleftrightarrow} C_{NH_3(g)} \qquad (1.4)$$

where $C_{NH_3(g)}$ is the concentration of ammoniacal N in the form of ammonia in the gaseous phase of the soil solution (kg m^{-3}). This equilibrium is controlled by the temperature dependent Henry's Constant (K_H). Ammonia from the gaseous phase of the soil solution volatilizes to the atmosphere by overcoming resistance from the boundary layer. Resistance is controlled by concentration of ammonia ions at the boundary layer (in turn governed by initial supply N to the soil system and Eq. 1 and 2), characteristics of the surface crusts, and meteorological characteristics of the ambient air. More alkaline conditions promote the dissociation of ammonium into ammonia. Higher temperatures favor NH_3*(g)* in the soil solution. Influx of NH_4^+*(aq)* into the soil solution pushes Eq. 1.3 and in turn Eq. 1.4 to the right. Formation of a surface crust increases the resistance to convective mass transfer, while high windspeeds in the ambient air promotes it (Ni, 1999; Wu et al., 2003). Overall, ammonia volatilization can be described by

$$J_{vola}(t) = h_m \left(\frac{K_a\ K_H}{10^{-pH}}\ C^0_{NH_4^+(aq)} - C^{air}_{NH_3(g)} \right) \qquad (1.5)$$

where $J_{vola}(t)$ is the vertical flux of ammoniacal N at time t (kg $ha^{-1}s^{-1}$), h_m is the average mass transfer coefficient for ammonia transport across an ammonia concentration boundary layer at the soil surface, $C^0_{NH_4^+(aq)}$ is the initial concentration of ammoniacal N in the form of ammonium ion in the soil solution (g L^{-1}), and $C^{air}_{NH_3(g)}$ is the background concentration of ammoniacal N in the form of ammonia in the air (g L^{-1}) (Wu et al., 2003).

Once ammonia enters the atmosphere, it can react with atmospheric acids, such as nitric and sulfuric acid, to form fine particulate matter (i.e., aerosols), also known as $PM_{2.5}$. These aerosol forms of nitrogen can be carried away by air currents and deposited elsewhere. Aerosol nitrogen typically has a lifetime of 1 to 15 days (Aneja et al., 2008), which is ample time for long distance transport. The findings of Malm et al. (2009) indicate that significant transport of reduced nitrogen species from the livestock feeding areas of northeastern Colorado to RMNP is occurring, and that BMPs that can address NH_3 emissions at seasonal or shorter timescales may be appropriate to significantly reduce N deposition in Colorado's Front Range alpine ecosystems.

Management Strategies to Reduce Volatilization from Feedlots

Feedlot operators on Colorado's Front Range need BMPs that are operationally practical and economically feasible and that specifically address the unique challenges of this region. Ammonia lost from most animal feeding operations is a general long-term concern due to the lost fertilizer value of feedlot outputs, environmental impacts, and human health impacts (Ndegwa et al., 2008). However, most areas with high concentration of animals on feed are surrounded largely by croplands that could benefit from atmospheric deposition of N from feedlot sources (Ndegwa et al., 2008). This is not the case on the Front Range of Colorado. Due to unique seasonal weather patterns and the proximity of a large number of animals on feed to sensitive alpine ecosystems, the concern about ammonia loss from Front Range feedlots is both unique and urgent.

General strategies that may apply well to other feeding regions do not adequately address the particular situation in Colorado. In fact, very little research on controlling ammonia loss from beef cattle feedlots has been done aside from investigating the effect of reducing total N excreted through dietary manipulations. Several studies have found that reducing the dietary crude protein of feedlot cattle diets reduces N losses by volatilization (Archibeque et al., 2007; Cole et al., 2006; Cole et al., 2005; Erickson and Klopfenstein, 2001; Todd et al., 2006; Todd et al., 2009; Todd et al., 2008). The two largest bodies of work on dietary manipulations use strategies with vastly different scales to evaluate diet effects on N losses. One group (Erickson and Klopfenstein, 2001; Todd et al., 2009; Todd et al., 2008) uses mass balance micrometeorological techniques at whole feedlot scales to integrate over large areas and reflect real field conditions. Erickson and Klopfenstein (2001) reduced N inputs by 10-20% and reported a corresponding reduction of N losses by 15-33% in a mass balance study in Nebraska. Using tower-based measurements in Texas, a 35% increase in ammonia emissions was found when diet CP increased from 12.2% to 16.3% (Todd et al., 2009), and a 10-64% increase in N loss was associated with a 15-26% increase in feed CP content (Todd et al., 2008). The other group (Archibeque et al., 2007; Cole et al., 2005; Todd et al., 2006) used collections of urine and fecal material as inputs into laboratory systems to provide power for testing treatment effects and achieve replication. While both of these strategies are important, they certainly have their limitations. Whole feedlot-scale measurements lack statistical rigor, and homogenized replicates of fresh urine and feces collections lack field relevance. In Chapter II of this volume, the effect of dietary manipulations on N loss is measured from intact feedlot surface cores in a replicated laboratory chamber system, a technique that is field relevant as well as statistically rigorous.

Another strategy for reducing emissions from open lots is the use of urease inhibitors that block the action of the enzyme responsible for the hydrolysis of urea. In a laboratory experiment, application of the urease inhibitor NBPT every eight days at the rate of 1 and 2 kg ha^{-1} to simulated feedlot soils reduced ammonia volatilization by 49% and 66% respectively (Parker et al., 2005). These results are promising; however, these types of chemicals can be costly, and their effect on livestock or soils onto which manure may be applied as fertilizer remains uninvestigated. Other strategies using amendments have been proposed for use in lagoons and slurries such as using strong acids to reduce the pH to a point where there simply is no non-ionized ammonia in solution (Ndegwa et al., 2008). Several of these types of studies have shown promise for reducing ammonia emissions, but these types of amendments are not practical for use in the presence of livestock.

Several studies have noted that precipitation events seem to depress ammonia emissions (Hutchinson et al., 1982; Saarijärvi et al., 2006; Todd et al., 2005; Whitehead and Raistrick, 1991). Two of these studies were season- or years-long campaigns to quantify ammonia emissions from cattle feedlots in Colorado (Hutchinson et al., 1982) and Texas (Todd et al., 2005). Both of these studies noted that emissions were relatively consistent and within an expected range except for measurements taken directly following or during a precipitation event, when emissions were much lower than would otherwise be expected. Whitehead and Raistrick (1991) applied synthetic urine and two depths of simulated rainfall to soil columns (taken from grazed grasslands). Ammonia emissions from columns receiving 2 mm of water were significantly suppressed after 2 hours, but not after 24 hours. Emissions from columns receiving 12 mm of water were suppressed by 81% after 2 hours and 33% after 24 hours. Two rainfall regimes – two small precipitation events within 24 hours and one larger event – were simulated on urine patches in a pasture in Finland, and both regimes resulted in significantly reduced emissions over the 199 hour measurement window (Saarijärvi et al., 2006). In Chapter III of this volume, the potential for operationalizing water's suppressive effects as a co-BMP in a feedlot situation is investigated by adding a 5mm depth of water to intact feedlot surface cores in a laboratory chamber system.

This thesis assesses effects of dietary N manipulation and water application for dust control on N volatilization from feedlot surfaces by using a laboratory chamber system to measure NH_3 emissions from intact feedlot pen surface cores. Specifically, the objectives were to:

1. Determine if a reduced CP diet in feedlot cattle caused a corresponding reduction in NH_3 emissions from the pen surface;
2. Investigate the effect of using periodic water application as a dust control strategy on ammonia emissions from cattle feedlot surfaces; and
3. Examine the upper bound of potential ammonia volatilization from feedlots in Colorado.

Both practices investigated showed significant reductions in ammonia emissions. Dietary N manipulation is a long-term strategy to reduce N inputs and losses from feedlot systems, with the potential to curb ammonia emissions while improving a feedlot's economic bottom-line. Water application to feedlot surfaces via (often) existing infrastructure for dust control also suppresses ammonia emission. Water application has a short-term suppressive effect and could be a co-BMP for ammonia reduction. Both strategies could be important components of a much larger Colorado strategy to protect the integrity of RMNP as well as the viability of a vibrant agricultural sector.

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CHAPTER II

INFLUENCE OF REDUCED N DIETS ON AMMONIA EMISSIONS FROM CATTLE FEEDLOT PENS

SUMMARY

Ammonia emissions from cattle feedlots on Colorado's Front Range can potentially be transported to the eastern slope of the Rocky Mountains and deposited in alpine environments where excess nitrogen can affect ecosystem function. Reducing crude protein in livestock diets may lower ammonia emissions and reduce agriculture's contribution to nitrogen deposition in mountain ecosystems. A feeding trial was conducted with crossbred steers at the Southeastern Colorado Research Center in Lamar, Colorado from December 2009 to March 2010. Three diet treatments were investigated: Reduced (11.62% crude protein), Oscillating (13.5% crude protein 4 days/wk and 11.62% crude protein 3 days/wk) and Control (13.5% crude protein). Intact soil core samples (n=36 per sampling date) were collected from the pen surfaces on three dates corresponding to 45, 92, and 148 days into the feeding cycle. Four pens from each diet treatment were sampled. Cores were placed into flow-through laboratory chambers for seven days, and ammonia emissions were trapped in acid bubblers that were refreshed every 24 hours. Average daily ammonia emissions for the Control diet ranged from 7.1 to 9.4 g NH_3 m^{-2} d^{-1}; average daily emission for the Oscillating diet ranged from 6.2 to 8.7 g NH_3 m^{-2} d^{-1}; and average daily emission for the Reduced diet ranged from 3.7 to 7.0

g NH_3 m^{-2} d^{-1}. Ammonia emissions from the Reduced N treatment were significantly lower (21 to 40%) than from the Control diet on the first two sample dates. There was no significant difference between the Oscillating and Control treatments. Cattle on different diet treatments showed no significant differences in their average daily gains. Reducing crude protein in cattle diets may be an effective method for reducing ammonia emissions from feedlot pens.

INTRODUCTION

One of the most promising strategies for reducing NH_3 emissions to the atmosphere from beef cattle feedlots is reducing the proportion of fed N that is excreted to the pen surface, which involves formulating diets to stimulate physiological N retention mechanisms in cattle. Optimizing animal performance and feed efficiency requires determining dietary protein levels above which animal production metrics do not improve. While feeding dietary protein above that level generally does not hurt the animal, it is less efficient – increasing feed costs without increasing profits, and increasing N content of animal excretions. Protein provided in excess of an animal's needs is broken down into individual amino acids which are de-aminated, creating free ammonia, and quickly converted to urea by the liver (Reynolds and Kristensen, 2008; Stewart and Smith, 2005). For animals being fed near the critical point where increasing dietary protein content will not produce additional gains in production, that urea will be recycled to the digestive tract and utilized for ruminal microbial growth, increasing overall nitrogen efficiency. As the protein in the diet increases, recycling of urea decreases, and more urea-nitrogen is lost to the environment through excretion in the urine (Piatkowski and Voigt, 1986; Stewart and Smith, 2005). Feeding systems in the United States tend to ignore the contribution of urea recycling to a ruminant's overall N budget thereby overestimating N requirements and contributing to unnecessarily high losses of N from these systems (Hristov et al., 2011).

Using a pen mass balance approach at beef feedlots, Kissinger et al. (2007) found that only 12% of all fed N is retained by cattle, the rest is excreted to the pen surface, and 67% of excreted N is volatilized as ammonia. Overall, 60% of fed N was lost to the atmosphere as ammonia (Kissinger et al., 2007). Todd et al. (2005) compared estimates of N losses using micrometeorological techniques and N:P ratio analysis and reported an overall annual estimate of 50% of fed N lost as ammonia. Using an inverse dispersion technique, Flesh et al. (2007) reported a 64% loss of fed N. Other studies report similar findings (Baum and Ham, 2009; Cole et al., 2006; Todd et al., 2008). Winter/spring ammonia losses of fed N were 12 – 53% lower than summer/fall losses (Kissinger, 2007; Todd et al., 2005; Todd et al., 2008). Absolute flux of ammonia from feedyards measured using a variety of techniques and in a variety of locations around the United States ranges from 2.89 to 5.8 g m^{-2} d^{-1} in the winter, 6.02 to 7.81 g m^{-2} d^{-1} in the summer, and 5 to 6.8 g m^{-2} d^{-1} on an annual basis (Baum and Ham, 2009; Flesch et al., 2007; Staebler et al., 2009; Todd et al., 2005; Todd et al., 2008).

One way to mitigate N losses from feedlot systems is by manipulating protein (N) content of the feed. By reducing dietary protein content to match animal needs more closely, more urea recycling is stimulated, overall feed efficiency improves, and N losses are minimized. Using a mass balance approach, Erickson et al. (2000) reported a 15-33% reduction in N loss in a phase feeding study in Nebraska that reduced N inputs by 10-

20% with no associated negative impacts on cattle performance. Using micrometeorological techniques, Todd et al. (2009) demonstrated a 35% increase in ammonia emissions when the diet at one feedyard was supplemented with distillers grains for a 16.3% crude protein (CP) feed compared to 12.2% CP at a comparable feedyard not using distillers grains. Using tower-based measurements from a commercial Texas feedlot as inputs into an inverse dispersion model, and feed grab samples, Todd et al. (2008) demonstrated a relationship between increasing CP in the diet and increased NH_3-N losses. Throughout three summer and winter campaigns, feed N increased between 15 and 26%, while NH_3-N loss increased 10-64% (Todd et al., 2008). While micrometeorological techniques can integrate over large areas, the size of the minimum sampling area makes it impossible to study treatment effects like diet manipulation with a statistically-based design (e.g., randomized block). Like all field-based methods, there are challenges in using this measurement technique to compare treatments because of a lack of control of other factors (e.g., temperature).

Animal scientists often collect the urine and feces directly from livestock and measure the ammonia emissions in the laboratory. Studies by Cole et al. (2005) showed nitrogen loss from beef cattle urine and feces was reduced 60-200% by feeding an 11.5% crude protein (CP) diet compared to a 13% crude protein diet. Todd et al. (2006) measured emissions from artificial feedlot surfaces in the field and in laboratory chambers using urine and fecal material collected from an experimental feedlot in Texas. Steers were fed 11.5% and 13.0% CP diets and significant decreases in ammonia losses were measured with the 11.5% CP diet in both the in vitro field trials and in the laboratory. Loss reduction has also been reported from urine and feces in laboratory chambers from livestock receiving a diet with oscillating crude protein (Archibeque et al., 2007a) . Cole et al. (2006) conducted a phase-feeding trial to compare several levels of dietary crude protein and the timing of feeding different diets. When animals were switched from a 13% CP diet to an 11.5% CP diet for the finishing phase, volatilization losses were reduced, but animal performance was adversely impacted. However, the group that was fed the 11.5% CP diet throughout the feeding trial showed a 25% decrease in N loss to volatilization with no impact on animal performance (Cole et al., 2006). While laboratory flux methods achieve a controlled environment for comparing ammonia loss among diet treatments, previous studies have been done using disturbed samples of mixed manure and urine that does not replicate the physio-chemical conditions of a feedlot pen surface.

Although there has been limited research of diet effects on ammonia emissions from beef cattle, there have been no statistically-based studies that directly link dietary changes to ammonia volatilization from open-lot feedlot pens. Thus, the main objective of this project was to determine if a reduced CP diet in feedlot cattle causes a corresponding reduction in NH_3 emissions from the pen surface. This study used direct laboratory measurements of intact-core surface samples from three diet treatments (Control, Reduced CP, and Oscillating CP) to make statistical comparisons among treatments. Additionally, this study compared measurements from the laboratory system to calculated N retention and excretion in animals fed the three different diet treatments.

METHODS

Feeding Trial

The feeding trial began in November of 2009 at the Colorado State University Southeastern Colorado Research Center in Lamar, CO. Monthly average temperature in Lamar during November 2009 to March 2010 ranged from -4 to 9^{0}C. A nearby weather station recorded 11.7, 0, 8.4, 11.4, and 33.8 mm of precipitation for the months of November 2009 through March 2010. These precipitation data are likely to be low, since the rain gauges in use typically do not detect snowfall accurately. Average monthly precipitation in this area is about 10 mm November to February and about 25 mm in March.

The study was conducted with 84 crossbred steers blocked by weight and fed one of three treatment diets. Stocking density was 12 m^2 $head^{-1}$. Diet treatments included in this study were:

- Control: traditional starting and step-up diets through 21 days followed by a 13.5% crude protein (CP), 3.50% crude protein extract (CPE) from non-protein nitrogen (NPN) through slaughter
- Oscillating N: traditional starting and step-up diets through 21 days followed by alternating an 11.62% CP, 1.55% CPE from NPN diet with control diet from 22 days through slaughter (the Reduced diet was fed every Wednesday, Thursday and Sunday and the Control diet was fed every Monday, Tuesday, Friday and Saturday)

- Reduced N: traditional starting and step-up diets through 21 days then 11.62% CP, 1.55% CPE from NPN from day 22 through slaughter.

All treatments were applied to a 77% steam-flaked corn-based diet. Urea and ground corn were used to modify dietary CP concentrations. Additional detail on the diet composition can be found in Westover et al. (2011). Cattle were implanted with 20 mg trenbolone acetate and 4 mg estradiol. The cattle were weighed on days 31, 74, and 107. Average daily gain was calculated for periods between weigh-days.

<u>Pen Sampling</u>

Pen surface samples were taken from three locations in each of 12 pens (4 per diet treatment) on days 45, 92, and 148 of the feeding trial. Due to frequent precipitation and low wintertime evaporation rates, the pen surface was wet, "muddy," and well-mixed on all sampling dates. Samples were taken from the center of the pen in three different locations; Rep 1 was taken 0.3 m from the concrete apron near the feed bunk; Rep 2 was taken from approximately the middle of the pen; Rep 3 was taken at the rear of the pen near the electrical fence (Fig. 1). A steel cylinder 12.7 cm in diameter and 4 cm deep was randomly placed on the pen surface in the respective sampling locations. The cylinder was pushed by hand into the surface, and the sample and cylinder was removed from the pen surface. Under typical feedlot conditions, a pneumatic or hammer driver would be used to drive the cylinder into the hard-packed surface, but due to the wet conditions, this was not necessary for any of the sampling dates in this study. Excess soil was eliminated from the bottom of the sample and outsides of the cylinder. The sample and drive cylinder were double bagged in labeled 8 mil low density polyethylene (LDPE) bags and sealed to prevent any ammonia flux. All samples were frozen within 8 hours of initial collection and stored for analysis.

Flux Chamber System

All samples were evaluated for N loss using an ammonia flux chamber system at Colorado State University, Fort Collins, Colorado. The twelve chamber, flow-through design is built around modified vacuum desiccators about 15 cm in diameter. Modifications to the desiccators and general system design are described in Vaillant (2007). Ammonia-free air at room temperature (about $22^{0}C$) and controlled humidity (dewpoint temperature of $12^{0}C$) was routed into each chamber at a rate of 5 L min^{-1} (6.7 chamber volumes per min.). Laboratory measurements showed this flow rate produced an aerodynamic conductance similar to that observed under field conditions (Vaillant, 2007). Temperature and humidity of the supply air were monitored using an Onset U23 sensor (Onset Computer Corp., Bourne, MA, USA). The air flowed into the top of chamber and was spatially diffused using a ported manifold. Air exited through the side of the chamber and was routed through a short section of Teflon tubing to a 500-ml acid bubbler bottle containing about 100 ml 0.1 M phosphorous acid. All samples ran in the system for seven days. The acid bubblers were changed daily and stored in a refrigerator for analysis. At the conclusion of each 7-day measurement run, the acid solutions were decanted into a graduated cylinder to record the final volume of acid solution. Thirty milliliters of sample were stored until the NH_3 concentration of the acid solution was measured using a Flow Injection Analyzer by the salicylate method (FIAlab Instruments, Bellvue, Washington, USA).

Because ammonia volatilization is strongly dependent on environmental conditions, especially temperature, the flux rates from the chamber system were not expected to represent actual fluxes from the feedlot pens in winter at Lamar, CO. However, the repeatable environmental conditions attainable in the laboratory provided a means to evaluate how expected differences in excreted N among treatments might affect NH_3 flux from intact cores. In a sense, the chamber data are a top-down method to detect differences in the surface physio-chemistry of NH_3 volatilization caused by differences in cattle diets.

Soil Analysis

Small samples of the soil core surface were taken before and after evaluation in the chamber system for pH measurement using a microelectrode (Model No. MI-410, Microelectrodes Inc., Bedford, New Hampshire, USA). After the flux measurements were completed, all core samples were frozen pending soil analysis. Frozen samples were quartered, and one quarter of each sample was acidified using 2% acetic acid to prevent further ammonia volatilization. Samples were quartered in order to increase surface area for acidification. They were then air dried and sealed in 8 mil LDPE plastic bags. Analysis by Servitech (Dodge City, Kansas, USA) included: total N, organic N, ammonium, nitrate, organic matter, ash, and carbon: nitrogen ratio. All three reps from each pen were ground together and pooled for soil analysis.

Initial moisture content was determined by gravimetrically. Each sample was weighed prior to and following incubation in the chamber system. Samples were then frozen and divided into quarters. One quarter from each sample was used for soil analysis as described above. The remaining three quarters from nine samples from each of the three sampling dates (one from each of the three diet treatments, from each of the three pen sampling locations) were weighed frozen. They were thawed and dried at room temperature for 2 days and further oven dried at 50^0C for one day. Initial water content of nine samples was averaged to provide an estimate of the initial water content for each sampling date.

Statistical Analysis

Treatment differences on ammonia flux were analyzed using SAS 9.2 (SAS Institute, Cary, North Carolina, USA) proc mixed with a Tukey adjustment for multiple comparisons (alpha of 0.10). Cattle average daily gain was analyzed with a similar model. The initial and final pH values were compared with a paired t-test (alpha of .05). Emissions from the chamber studies were evaluated statistically comparing the cumulative fluxes over the seven-day test period and by breaking the data into three intervals: Day 1 (24 h), Days 2 and 3 (48 h), and Days 4 to 7 (96 h). This was in response to previous measurements that showed the ammonia flux in the chambers tended to change over time.

RESULTS AND DISCUSSION

The concentration of NH_3 gas at the volatilization surface strongly controls flux into the atmosphere. Gaseous NH_3 concentration is governed by the concentration of total ammoniacal N (TAN) in solution, pH, the Henry constant (K_H), and the equilibrium constant (K_a); both K_H and K_a are strong functions of temperature (Montes, 2009). Thus, the key controlling variables are pH, temperature, and TAN at the pen surface.

$$[NH_4 + NH_3]_{solution} \xleftrightarrow{K_a, pH} [NH_3]_{solution} \quad (2.1)$$

$$[NH_3]_{solution} \xleftrightarrow{K_H} [NH_3]_{gas} \quad (2.2)$$

Ammonia volatilization can be strongly affected by pH, with higher pH increasing concentrations of ammonia in the soil solution (Eq. 2.1). The pKa of ammonia/ammonium in water is 9.23.

Soil Analysis

For the first two sampling dates (Day 45 and Day 92), the surface pH before and after the chamber runs was not significantly different. For the third sampling date surface pH after the chamber runs was lower than pH measured before for all treatments ($p \leq 0.033$)(Table1). Both initial and final pH were significantly lower for the Reduced N treatment than for the other treatments for samples taken on trial day 45. All initial and final pH measurements ranged between 6.40 and 8.32 with an overall mean of 7.44. Vaillant et al. (2009) reported surface pH around 8.5 for feedlots in Kansas, Cole et al. (2009) report a yearly average surface pH of 7.7 for feedyards in Texas, and Cole and Todd (2009) observed an annual mean pH of 7.89 from air-dried manure from Texas feedlots. Working in Nebraska, Gilbertson et al. (1975) reported average pH of 7.6 and 6.6 for two different stocking densities. Measured pH levels in this study were generally lower than other published results (but not without precedent) and did not approach the low pH range that would inhibit volatilization.

Besides pH differences mentioned above, there were no significant differences among treatments for any of the pen surface chemical properties for any of the sampling dates. Organic N accounted for nearly 85% of total N, followed by ammonium; nitrate levels were below detection for all treatments and sampling dates (Table 1). Because there were no differences in sample chemical properties among treatments, data were pooled and compared among sampling dates (data not shown). Pen surface chemical nutrient concentrations were much lower overall ($p < 0.001$) on the third sampling date (trial day 148) for Total N, Organic N, Total P, and Organic Matter (%). When treatments were pooled, the one surface chemical property that did not follow this pattern was pen surface ammonium, which remained relatively constant across all sampling dates. This may indicate that during cool weather when volatilization is limited by temperature, ammonium occupies a relatively stable proportion of exchange sites. Vaillant et al. (2009) sampled pen surfaces at four different feedlots in Kansas, and organic N ranged from 500 – 22,000 mg kg^{-1}. Of the eighteen pen samples in Vaillant et al. (2009), surface organic N values were below about 5000 mg kg^{-1} in only one pen and were much more frequently in the range reported in this study.

Cole et al. (2009) measured pen surface chemical characteristics at three feedlots in Texas in all four seasons. Taking an average of spring (April) and winter (December) values, they reported Total N values 1.5 – 2 times higher than reported in this study, about 27,500 mg kg^{-1}; however, they reported an average of 2,600 mg kg^{-1} NH_4-N, which is similar to the overall mean of 2,204±589 mg kg^{-1} in this study. Vaillant et al. (2009) reported a range of 375 – 8000 mg kg^{-1} NH_4^+-N in the top 10-cm surface layer at the Kansas feedyards. In the Texas feedyards, N:P was calculated as 3.78 in the spring and 4.53 in the winter, much higher than values reported in this study, which were all near 1.00, regardless of treatment or sampling date (Cole et al., 2009). It's possible that the much higher Total N and N:P ratio in the Cole et al. (2008) study reflect the higher crude protein content of the diets (reported only as 13-14.5% overall), while the similarities in surface ammonium reflect the rapid kinetics of the physicochemical processes of urea hydrolysis.

The organic matter component of samples in this study was 26-38% (Table 1), similar to values reported for manure harvested from feedlot pens (Kissinger et al., 2007). Adams et al. (2004) measured organic matter content of pen surface manure in three trials examining effect of OM additions. For Control treatments (without OM additions) they reported OM content of 18.8, 23.5 and 27.8%. For three different diet treatments, Bierman et al. (1999) reported OM content of 28-35% in manure removed from the pen surface.

Initial moisture content of samples from trial days 45, 92, and 148 was 52.5%, 47.3%, and 42.7% respectively (data not shown). Woodbury et al. (2001) reported feedlot surface moisture content of 18.8 to 32.1% for "unconsolidated surface material" and 19.9 to 29.9% for the first 10 cm. Cole et al. (2009) reported wintertime water content of a feedlot surface as 12.7% for "loose" surface material and 23.1% for the "dry-pack" layer. Harvested manure from piles that had just been scraped from a pen surface had a moisture content of 28.2% in the winter/spring (Kissingeret al., 2007). Moisture content for this study was higher than other values reported in the literature and likely influenced ammonia flux temporal dynamics.

Ammonia Flux

Daily ammonia flux dynamics for each sampling are shown in Figure 2 and dynamics for each set of samples through the ammonia flux chamber system are shown in

Figure 3. Ammonia volatilization was influenced by the sample's initial water content and evaporative water loss throughout the course of the chamber study, so the temporal patterns showed different trends for the three sampling dates. The 2009-2010 winter around Lamar, CO was unusually wet and all sampling dates reported here exhibited "sloppy", wet conditions. Samples were loaded into the chambers with very high initial moisture content (e.g., 50 %) which likely contributed to the varied patterns. In previous studies with mostly dry samples, trends in ammonia flux exhibited an exponential or linear decrease over time with very high fluxes on the first day (Fig. 4). Data in Fig. 4 were taken from intact cores collected from urine patches at a commercial feedlot in northern Colorado during the summer. The exponential decline in flux with time seen in Fig. 4 is consistent with other feedlot ammonia measurements observed from drier cores using the chamber system. Thus, the somewhat unusual patterns observed in Figs. 2 and 3 are probably unique to wet cores. The high water content probably initially limited near surface vertical NH_3 diffusion, and, later, contributed to the formation of cracks when drying, which compromise the integrity of the surface crust and reduce resistance to mass transfer. The physical properties of the pen surface likely changed over the course of the study as hoof action continued to mix and stir the accumulated manure under the wet conditions. Deep cracks and shrinkage were observed in the cores during the chamber tests which exposed more surface area to the air and affected fluxes. Thus, the temporal dynamics of drying and cracking likely contributed to increases in flux over time seen for samples collected on Day 148, and the convex pattern observed for the Day 92 samples.

Ammonia flux from the Reduced N treatment was significantly lower than that from the Control and Oscillating treatments on two of the three sampling dates. For samples collected on day 45, the Reduced N treatment had significantly lower N loss than the Control treatment ($p=0.0018$) and the Oscillating treatment ($p=0.0122$). Average flux for the three treatments – Control, Oscillating N, and Reduced N – was 7.1, 6.2, and 3.7 g NH_3 m^{-2} d^{-1} respectively, and peak daily emission occurred on the first day of the 7 day incubation for all three treatments and was 8.1, 8.1, and 5.1 g NH_3 m^{-2} d^{-1} respectively (Table 2, Fig. 2A and 3Ai-iii). The Reduced N treatment was significantly lower for all the intervals evaluated (i.e., Day 1, Day 2-3, and Day, 4-7, Table 3).

For day 92 samples, the results are similar, with the Reduced N diet showing significantly lower emissions than the Control diet ($p=0.0155$) and the Oscillating N diet ($p=0.0932$). Average daily emissions were 9.4, 8.7, and 7.0 g NH_3 m^{-2} d^{-1} for the Control, Oscillating N, and Reduced N diets; respectively. Peak daily emissions occurred on day 4 for all treatments. The control treatment peak emission was 11.3 g NH_3 m^{-2} d^{-1}, and the Oscillating N and Reduced N treatment emissions peaked at 10.3 and 8.5 g NH_3 m^{-2} d^{-1} (Table 2, Fig. 2B and 3Bi-iii). The interval analysis showed that the differences tended to be more significant during the beginning of the seven-day test (Day 1, and Day 2-3, Table 3).

On trial day 148, trends were similar but there were not significant differences among diets. The average daily emission for the Control diet was 7.2 g NH_3 m^{-2} d^{-1}, average daily emission for the Oscillating N diet was 7.4 g NH_3 m^{-2} d^{-1}, and average daily emission for the Reduced N diet was 6.3 g NH_3 m^{-2} d^{-1}. The Oscillating N and Reduced N diets peaked on the sixth day of measurement at 9.2 and 7.1 g NH_3 m^{-2} d^{-1} while the control diet peaked on the seventh (last) day of measurement at 8.2 g NH_3 m^{-2} d^{-1}. However, it is possible that the control treatment samples actually exhibited peak emissions after our seven day measurement timeframe (Table 2, Figs. 2C and 3Ci-iii). There were no differences for any of the sub-intervals, which likely resulted from slightly higher variance among cores on this sampling date (Table 3).

Regardless of the patterns observed during the chamber tests, cumulative emissions from the Reduced N treatment were 40% and 25% lower than the Control for Day 48 and Day 92, respectively (Fig. 5). As mentioned, there were no significant differences on the last sampling date, but the absolute reduction between the Control and Reduced N treatments was 21%. Thus, the Reduced N diet seemed to have a greater effect on NH_3 emissions early in the feeding cycle and then moderate over time. This trend is most likely the result of larger differences in pen-surface ammoniacal N early in the feeding cycle. However, there is no direct evidence of changes in pen surface NH_4^+ over time (Table 1). The chemistry of the 5-cm deep cores (i.e., Table 1) may not be equivalent to that at the aqueous-air interface where NH_3 volatilization occurred. The inability to measure differences in N content among treatments may have been the result of sampling too deep. Future studies should include very shallow sampling in the top few millimeters of the pen surface.

Cumulative reductions in emissions reported here for the Reduced N diet for Day 92 and Day 148 were similar to values reported from composited surface samples and simulated feedlot surfaces at the end of the feeding cycle by Todd et al. (2006) and Cole et al. (2006). Day 45 reductions were higher than previously reported, but as mentioned, the effect seems to be more pronounced earlier in the feeding cycle. Differences between the Control and Oscillating N diets were not observed. Archibeque et al. (2007a) measured a significant 66% reduction of in vitro ammonia volatilization from fresh composite manure and urine samples from an oscillating CP treatment compared to a high CP treatment with no reduction in animal performance (Archibeque et al., 2007b). Archibeque et al. (2007a) studied an oscillating treatment that averaged 11.5% CP, and found no difference in the volatilization of ammonia or animal performance between the oscillating treatment and a moderate CP treatment with a constant 11.8% CP. In addition, the timing and the magnitude of the oscillation were considerably different, switching from 9.1% CP to 13.9% CP on a predictable 48 hour rotation (Archibeque et al., 2007a). The current study fed an 11.62% CP diet every Wednesday, Thursday, and Saturday and a 13.5% CP diet the remaining days of the week. This timing scheme was chosen to make the feeding scheme more practical for a commercial operation, but this could have negated the proposed N recycling benefits of oscillating CP by making the oscillation period irregular, thus making it difficult for the animal to adapt physiologically (Cole, 1999; Cole and Todd, 2008).

Animal Performance

Animal N retention and excretion was calculated as part of the feeding trial, providing an opportunity to compare the measurements from the laboratory chamber system against N losses that were calculated by difference (Table 2). For the Control treatment, 160 g NH_3 head^{-1} d^{-1} were excreted to the pen surface. For the Oscillating N and Reduced N treatments 148.5 and 131.7 g NH_3 head^{-1} d^{-1} were excreted respectively. N excreted as feces remained constant across the treatments, but N excreted as urine tended to decrease for the reduced and the oscillating treatments. Reduced excretion of urine-N instead of fecal-N is a reflection of increased urea recycling in the rumen in response to lower crude protein diets and is expected based on cattle physiology

(Piatkowski and Voigt, 1986; Stewart and Smith, 2005). In an extensive mass balance study of several commercial feedlots in Nebraska, Kissinger et al. (2007) reported that 62% of all excreted N is volatilized as ammonia. Using this figure, and based on the N excretion calculations (Table 3), the estimate for ammonia loss is 8.3 g NH_3 m^{-2} d^{-1} from the Control pens, 7.7 g NH_3 m^{-2} d^{-1} from the Oscillating N pens, and 6.83 g NH_3 m^{-2} d^{-1} from the Reduced N pens. These values fall within the ranges measured using the chamber system with the exception of the Reduced treatment. Kissinger et al. (2007) fed a diet with 14.3% CP. It is possible that because the volatilization mechanism depends partially on an ample supply of ammonium ions to drive the equilibrium towards ammonia, and on concentration gradients to move the ammonia to the surface layers from which volatilization occurs, the input of 11.62% CP into the system may not be great enough to drive volatilization at as great a rate as observed by Kissinger et al. (2007).

There were no differences in the feedlot performance among the three dietary crude protein treatments in this study (Table 3). Cole et al. (2006) showed similar N loss reductions with no impact on animal performance; however, studies with similar dietary CP reductions have shown reductions in animal performance metrics (Gleghorn et al., 2004). Any ammonia volatilization strategy that negatively impacts animal performance will not be a practical N loss reduction strategy for feedlot operators. Ability to maintain animal performance levels at a reduced dietary CP should be investigated further at larger scales as part of commercial feedlot trials. Additional information on animal performance and excreted N can be found in Westover (2011).

CONCLUSIONS

Reducing CP from 13.5 % to 11.62 % caused a 21 to 40 percent reduction in emissions without negatively impacting animal performance under the conditions tested. This measured reduction corresponds to calculated reductions in N excreted, particularly urinary N from cattle receiving the reduced diet. Altering cattle finishing diets to eliminate CP that exceeds the cattle's nutritional requirements for maximum growth provides an opportunity to reduce overall N losses to the atmosphere and ultimately, to decrease N transport into Colorado's alpine areas. Because N transport from the Front Range to the alpine is a seasonal phenomenon largely confined to the spring (Malm et al., 2009), the reduction measured in this study suggests a BMP of using lower N diets in April, May, and June when upslope conditions are more likely. More research is needed to determine if reductions in emissions can be sustained with lower CP diets without affecting rate of gain in feedlot cattle.

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FIGURES AND TABLES

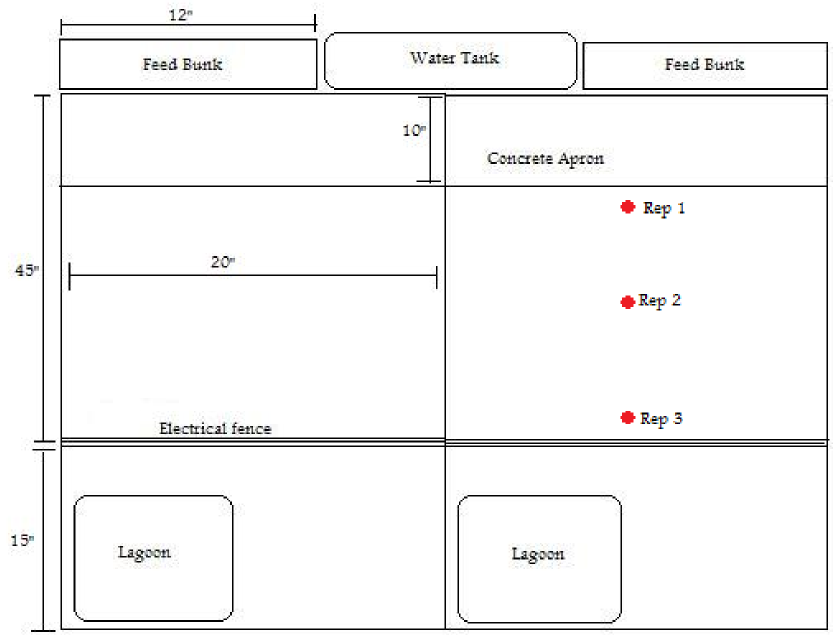

Figure 1 Feeding trial pen design and pen surface sampling scheme.

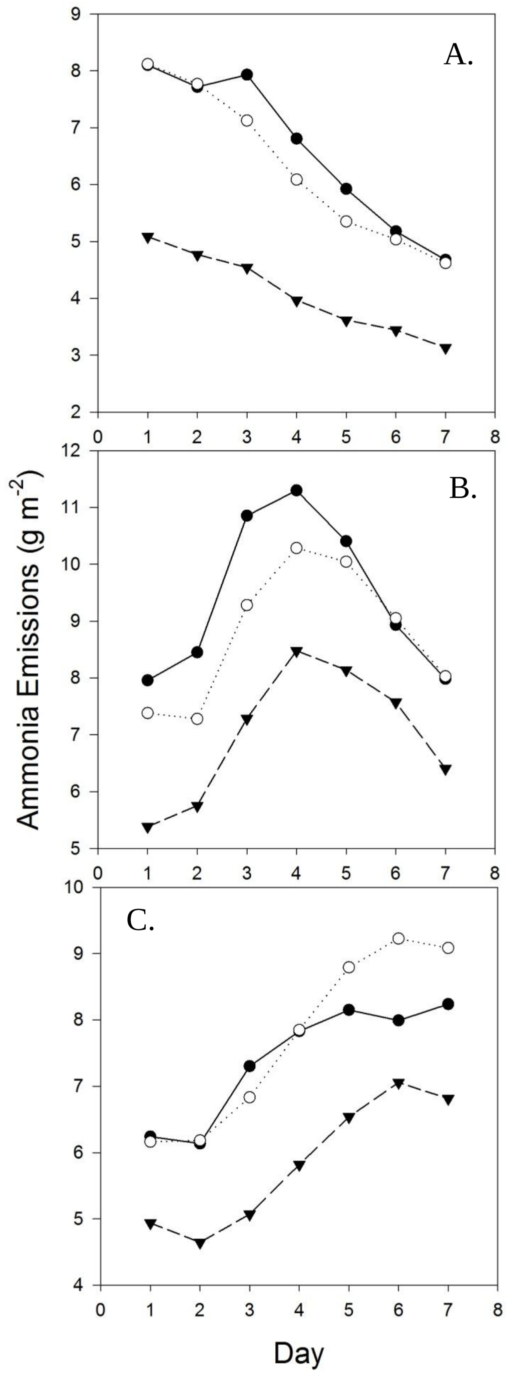

Figure 2 A. Overall ammonia flux trends during seven days of incubation in a laboratory chamber system at room temperature for samples of the pen surface taken on feeding trial day 45. Fig. 2B Samples taken on feeding trial day 92, and 2C Samples from feeding trial day 148. Open circles denote the Control diet containing 13.5% crude protein (CP), closed circles denote the Oscillating CP diet, which contained 13.5% CP four days/wk and 11.62% CP three days/wk. Closed triangles denote the reduced N diet, which contained 11.62% CP. Error bars omitted for readability. Standard deviations ranged from 1.24 to 2.54 g NH_3 m^{-2} d^{-1} for the day 45, from 1.28 to 3.06 g NH_3 m^{-2} d^{-1} for trial day 92 and from 0.60 to 2.13 g NH_3 m^{-2} d^{-1} for trial day 148.

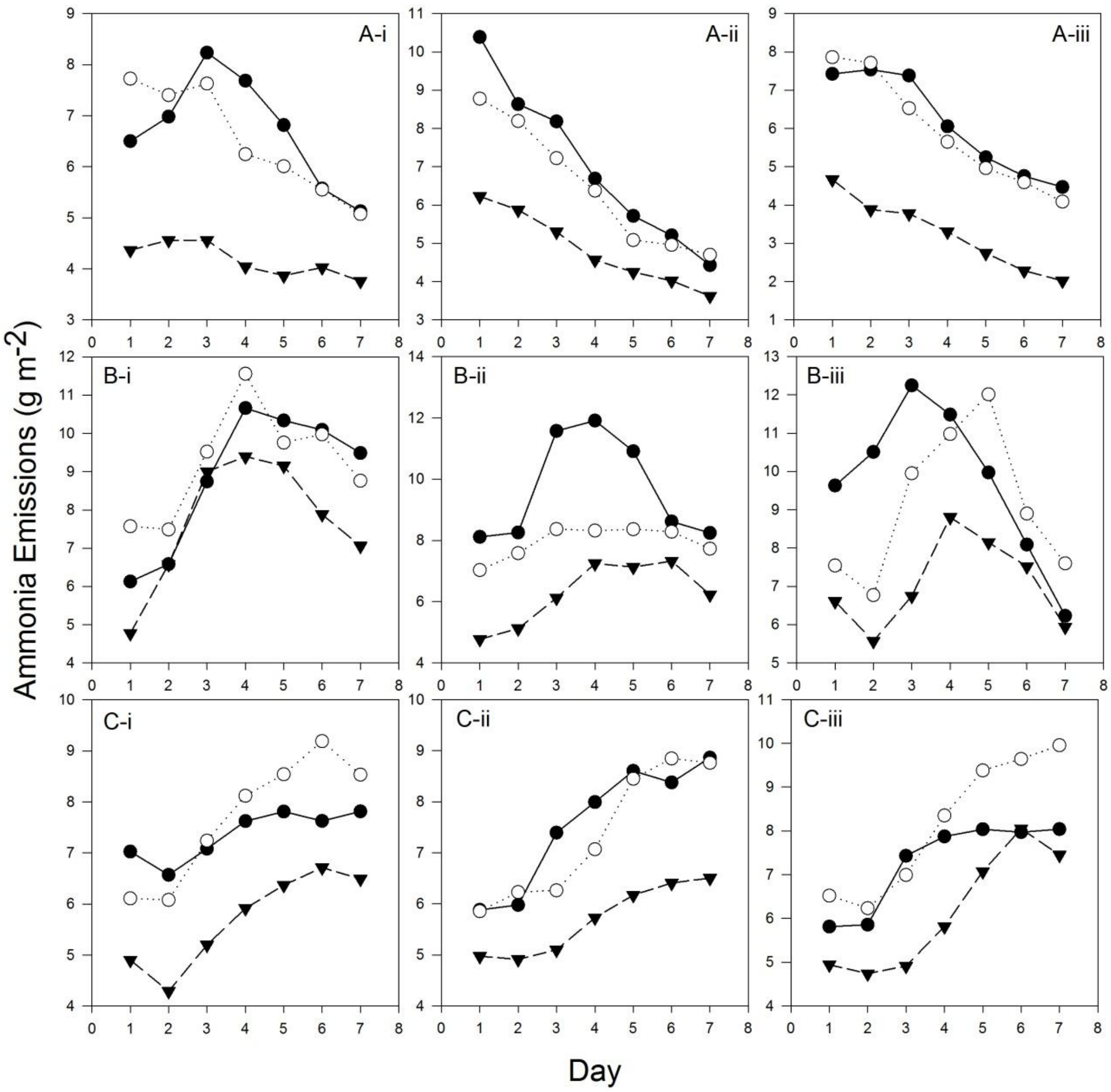

Figure 3 Ai-iii. Ammonia flux trends during seven days of incubation in a laboratory chamber system at room temperature for 3 replicate samples taken on feeding trial day 45. Bi-iii. Three replicates of samples taken on feeding trial day 92, and Ci-iii. Three replicates of samples from feeding trial day 148. Open circles denote the Control diet containing 13.5% crude protein (CP), closed circles denote the Oscillating CP diet, which contained 13.5% CP four days/wk and 11.62% CP three days/wk. Closed triangles denote the reduced N diet, which contained 11.62% CP. Error bars omitted for readability. Standard deviations ranged from 1.24 to 2.54 g NH_3 m^{-2} d^{-1} for the day 45, from 1.28 to 3.06 g NH_3 m^{-2} d^{-1} for trial day 92 and from 0.60 to 2.13 g NH_3 m^{-2} d^{-1} for trial day 148.

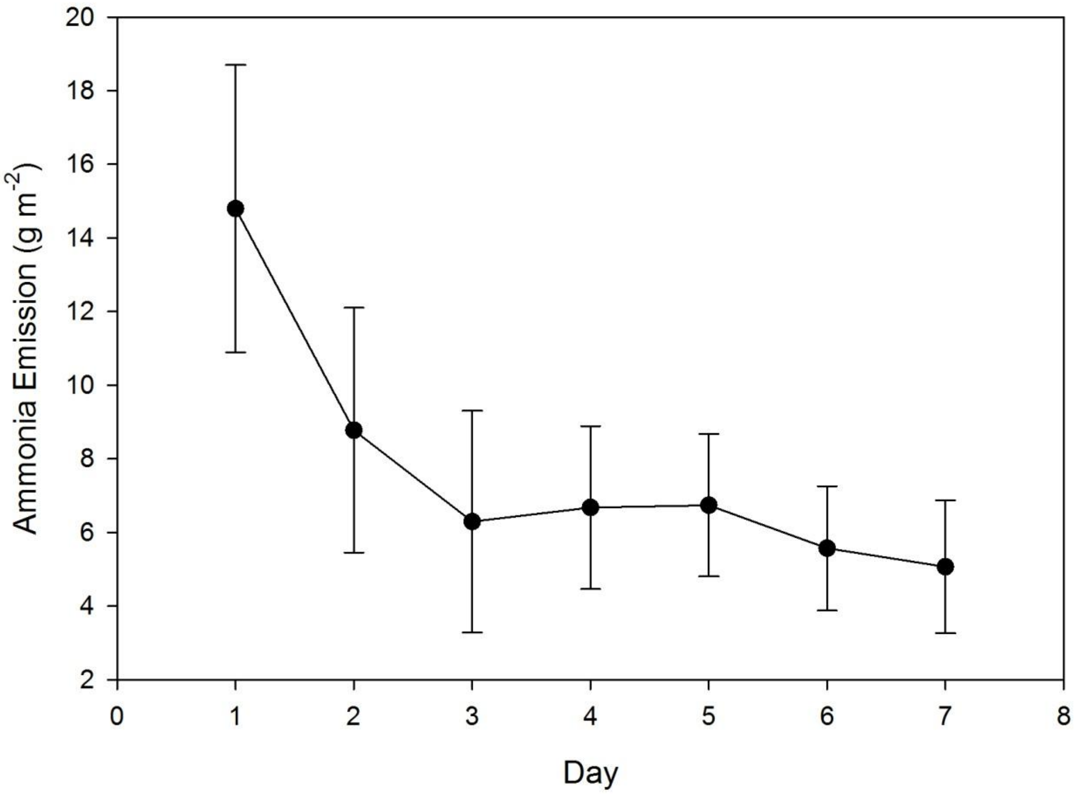

Figure 4 Example of typical ammonia flux profile from an intact feedlot pen surface sample. Samples in this study were taken during the summer from urine patches at a commercial feedlot in northern Colorado and processed and analyzed in the same way as samples in this study

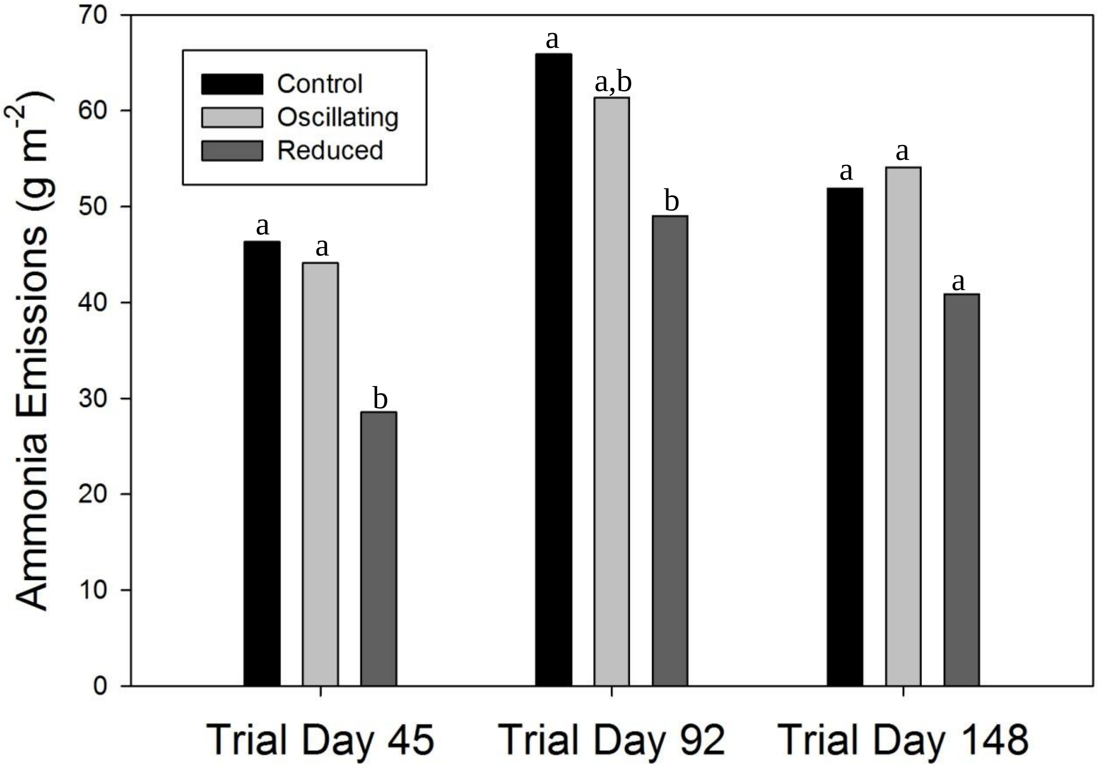

Figure 5 Cumulative ammonia emissions for each of the sampling days and each of the dietary CP treatments. Control: 13.5% CP; Oscillating: 13.5% CP 4 days/wk and 11.62% CP 3 days/wk; and Reduced: 11.62% CP. a,b indicate statistically significant differences (alpha = 0.10).

Table 1 Summary of pen surface chemical analysis (mg kg^{-1} except where indicated)

Treatment[1]	Total N	Org N	NH_4^+	NO_3^-	P	N:P	$pH^{initial}$	pH^{final}	OM (%)
Trial Day 45									
Control	15900±2960	13838±2517	2075±463	< 50	14975±2494	1.06±0.10	7.80±0.14[a]	7.83±0.12[a]	37.4±7.3
Oscillating	15775±1938	13700±1417	2050±570	< 50	14700±2333	1.01±0.11	7.83±0.14[a]	7.89±0.20[a]	36.6±5.5
Reduced	14213±1571	12538±1483	1663±225	< 50	13500±1623	1.05±0.05	7.52±0.35[b]	7.64±0.25[b]	35.6±4.5
Trial Day 92									
Control	15738±3115	13188±2626	2550±492	< 50	15325±2416	1.03±0.05	7.48±0.23	7.44±0.28	38.3±6.4
Oscillating	15400±4114	12838±2932	2550±1209	< 50	13575±3298	1.13±0.11	7.43±0.32	7.50±0.36	37.2±8.9
Reduced	15713±2376	13438±1920	2263±511	< 50	14875±1784	1.06±0.05	7.41±0.30	7.53±0.31	38.3±3.4
Trial Day 148									
Control	12063±3527	9675±3158	2363±598	< 50	11025±3663	1.11±0.11	7.30±0.20[x]	6.97±0.42[y]	27.7±9.1
Oscillating	10800±1004	8750±977	2038±390	< 50	10038±1190	1.08±0.08	7.27±0.14[x]	6.89±0.30[y]	25.7±3.4
Reduced	11650±3238	9363±2972	2288±368	< 50	10950±2838	1.06±0.06	7.17±0.19[x]	6.96±0.29[y]	28.5±7.9

[1] Treatments: Control: 13.5% CP; Oscillating: 13.5% CP fed 4 days/wk and 11.62% CP fed 3 days/wk; Reduced: 11.62% CP

[a,b] Indicate statistical difference among treatments ($\alpha = 0.05$)

[x,y] Indicate statistical difference of sample pH before ($pH^{initial}$) and after (pH^{final}) incubation in laboratory chambers ($\alpha = 0.05$)

Table 2 Effects of dietary crude protein treatments on feedlot performance.

Item[b]	Treatments[1] Control	Oscillating	Reduced
Initial wt., kg	331.1	330.3	329.0
Finish wt., kg	548.2	553.5	547.7
ADG	1.34	1.37	1.35
DMI	8.76	8.70	8.49
F:G	6.54	6.35	6.29
N retention, g	23	23.3	23.1
N excretion, g	160	148.5	131.7
Feces, g	32.1	37.4	37.1
Urine, g	127.8	111.2	94.4

[1] Treatments: Control: 13.5% CP; Oscillating: 13.5% CP fed 4 days/wk and 11.62% CP fed 3 days/wk; Reduced: 11.62% CP

[b]ADG = Average daily gain (kg d^{-1}); DMI = Daily dry matter intake (kg hd^{-1} d^{-1}); F:G = Feed to gain ratio (kg dry matter:kg gain)

Table 3 Effect of dietary crude protein treatment on ammonia emissions (g m^{-2} d^{-1}) by chamber day intervals.

Interval	Treatment[1] Control	Oscillating	Reduced
Trial Day 45			
Day 1	8.50^{a}	8.17^{a}	4.64^{b}
Days 2-3	8.40^{a}	7.27^{a}	4.25^{b}
Days 4-7	6.16^{a}	5.16^{a}	3.24^{b}
Overall	7.13^{a}	6.21^{a}	3.72^{b}
Trial Day 92			
Day 1	8.11^{a}	7.40^{a,b}	5.21^{b}
Days 2-3	9.52^{a}	8.66^{a,b}	6.27^{b}
Days 4-7	9.68^{a}	9.22^{a}	7.72^{a}
Overall	9.41^{a}	8.74^{a}	7.02^{b}
Trial Day 148			
Day 1	6.20^{a}	6.14^{a}	5.00^{a}
Days 2-3	6.58^{a}	6.21^{a}	5.29^{a}
Days 4-7	7.85^{a}	8.49^{a}	7.00^{a}
Overall	7.22^{a}	7.43^{a}	6.27^{a}

[1] Treatments: Control: 13.5% CP; Oscillating: 13.5% CP fed 4 days/wk and 11.62% CP fed 3 days/wk; Reduced: 11.62% CP

[a-c] Least squares means within a row without a common superscript differ ($P < 0.10$)

CHAPTER III

WATER APPLICATION TO CATTLE FEEDLOT PENS REDUCES AMMONIA EMISSIONS

SUMMARY

Air quality effects of large cattle feeding operations are a concern nationally due to dust and odor from the pen surfaces and from the handling and storage of manure. These are generally considered “fenceline” level issues provoking complaints from neighbors and nearby communities. Due to the proximity of Colorado’s cattle feeding region to pristine and sensitive alpine ecosystems and the transport of nitrogen (N) from feedlots to the Front Range mountains, Colorado feedlot operators are at the middle of an environmental concern with regional and national implications. To address property line dust issues feedlot operators often apply water to the pen surfaces. However, because ammonia volatilization depends on near-surface concentrations of aqueous ammonia, addressing local issues in this case may exacerbate the regional-scale nitrogen transport problems. While the mechanics of ammonia volatilization suggest that addition of water could potentially increase the rate of N loss, several studies suggest that water actually has a depressive effect on volatilization rates. It is possible, therefore, that water application is actually a BMP for addressing both property line and regional- to national-scale concerns for Colorado’s cattle feeders. The effect of water application on ammonia emissions was measured in the laboratory using intact surface cores taken from urine

patches in pens at a commercial feedlot in NE Colorado. A water application of 5 mm reduced the first day ammonia emissions by 27% ($p = 0.0004$), from 39.04 to 28.58 g NH_3 m^{-2} d^{-1}, but had no effect during the remainder of the test. These data suggest that a regime of frequent low-volume watering, using in-place feedlot infrastructure, to control dust also will reduce NH_3 losses and potentially lessen the risk of contributing to N deposition in the alpine ecosystems of Colorado. Feedlot managers can use watering as a dust control measure without concerns about increasing NH_3 emissions. Further research is required to test different frequencies and depths of water applications, and at larger scales.

INTRODUCTION

One of the top complaints from the public about AFOs is fugitive dust (Auvermann, 2003; Mukhtar and Auvermann, 2009). Dust can be a nuisance to neighbors, and complaints to state air pollution regulatory authorities or law enforcement can lead to visits from law enforcement or pollution control authorities and in particularly contentious situations, litigation (Auvermann, 2003). AFOs can also be held liable when dust decreases visibility on nearby roadways and causes accidents (Auvermann, 2003). In addition, dust can have significant health consequences for cattle and feedlot profitability, as well as for the health of feedlot workers and nearby communities (Auvermann, 2003). It is in the best interest of a feedlot to undertake dust suppression measures in order to manage these mostly property-line level conflicts. The most commonly used and recommended method of dust suppression is to increase the moisture content of the pen surface using solid set sprinklers, a traveling gun sprinkler system, or a water truck system (Amosson et al., 2008; Auvermann, 2003; Mukhtar and Auvermann, 2009). Other recommendations to control dust include: increasing stocking density (another method of increasing pen surface moisture content), proper compaction, and scraping the pen surface every 3-4 months (Mukhtar and Auvermann, 2009). To control both dust and odor, it is recommended that pen surface moisture content is managed within the range of 25-40% (Auvermann, 2003; Mukhtar and Auvermann, 2009). Ammonia volatilization depends on the concentration of aqueous NH_3 at the pen surface (Eq. 1.5), which raises concerns that water application for dust control may exacerbate the regional-scale problem of N transport to the alpine areas of Colorado. Previous work has indicated that not only does pen surface watering not exacerbate the problem, it actually suppresses ammonia volatilization on short time scales (see below). However, there are still significant concerns about the use of water, a particularly scarce resource in eastern Colorado, and with the costs of implementing a water-based dust suppression system (Amosson et al., 2008).

Several authors investigating ammonia emissions have observed that emissions are depressed immediately following a precipitation event. Hutchinson et al. (1982) measured emissions from a feedlot in northeastern Colorado using micrometeorological techniques on 13 separate dates in 1977 and 1978. Measured values were within a predictable range except for three measurement dates – on two of these dates the feedlot surface was saturated following a precipitation event, and emissions were lower than expected. Todd et al. (2005) observed that variability in ammonia flux measurements from Texas feedlots was small during their five multi-day measurement campaigns from 2002-2004 except during a campaign that encompassed at least one precipitation event that caused variability to increase by suppressing flux immediately following the rain. This has also been the subject of studies that simulate rainfall to investigate the effect of precipitation on ammonia emissions. Whitehead and Raistrick (1991) applied six different depths (0-16 mm) of simulated rainfall to soil columns (soil sampled from grassland grazed by dairy cattle) containing synthetic livestock urine either 2 or 24 hours after the application of the urine. All quantities of simulated rainfall significantly reduced ammonia emissions (by 15% for 2 mm and 81% for 12 mm for rainfall happening 2 hours after urination). The effect was much less for the simulated rainfall after 24 hours – the 12 mm rainfall reduced emissions by 33%. Saarijarvi et al. (2006) measured emissions from urine spots from dairy cows in Finland after two regimes of simulated rainfall in pasture. The first consisted of two small (5 mm) rainfall events – the first 1-6 hours after urination and the second 24-29 hours after urination. This rainfall pattern decreased emissions by half compared to the control treatment. The second regime was a single 20 mm rainfall event 1-6 hours after the urination event which resulted in one quarter of the ammonia emissions compared to the control. Despite this promising evidence, water application has never been promoted as a BMP to reduce ammonia emissions because all studies – observational and experimental – have always noted a corresponding increase in emissions during the following drying period, resulting in no perceived benefit when considering longer term emission trends. For example, Rhoades et al. (2008) measured ammonia flux at a Texas feedlot every 5 minutes March through August and calculated monthly mean fluxes. Surprisingly, the highest monthly ammonia flux occurred in April, as opposed to the much hotter mid-summer months. The authors attributed this to high April windspeeds and significant drying occurring after a wet, muddy month of March.

Despite all of these promising studies, watering effects on NH_3 emissions have not been studied under controlled conditions from actual feedlot surfaces. The laboratory system described in the previous chapter provides a good way to study this phenomena in a statistically robust way.

The majority of ammonia produced at beef CAFOs originates from the pen surface, and an overwhelming preponderance of surface emissions come from urine (Cole et al., 2009; Cole et al., 2005; Hutchinson et al., 1982; Koziel et al., 2005; Rhoades et al., 2008; Saarijärvi et al., 2006; Todd et al., 2008; Whitehead and Raistrick, 1991). Saarajarvi et al. (2006) measured emissions from fresh urine and fresh manure separately in an intensively managed pasture system and found that peak emissions from the manure pats were less than 20% of the peak emission from the urine spots. Overall, accounting for the total surface area of the pasture affected by urine and manure, urine spots were responsible for about 96% of the pasture system's total ammonia emissions (Saarijärvi et al., 2006). A similar study measuring fresh urine and fresh manure emissions separately was conducted in an open lot beef cattle feeding operation in the Texas panhandle (Koziel et al., 2005). These researchers did not estimate the total proportion of ammonia emissions emanating from urine spots, but they did find that fresh manure emits 2.5% to 13.7% as much ammonia as fresh urine (Koziel et al., 2005). Several studies using dietary manipulations to reduce overall emissions focus on changes that shift excreted N from urine to manure. Dietary studies tend to reduce the crude protein (CP) because as CP in a diet decreases, the quantity of urinary N is diminished (Bierman et al., 1999; Cole et al., 2005; Todd et al., 2006; Todd et al., 2008). Todd et al. (2006) reduced CP in beef cattle diet from 13% to 11.5% and found that for the 11.5% CP diet 66% of total N excreted was in the urine where as 73% of excreted N was urinary N for 13% CP diet. This redistribution of excreted N was associated with a 44% reduction of ammonia emissions from the 11.5% CP compared to the 13% CP diet (Todd et al., 2006). In this volume, Chapter II, a reduction of CP from 13.5% to 11.62% was associated with reducing urinary N as a percentage of total excreted N from 80% to 72%, and reducing ammonia emissions from 21 to 40%.

It is evident that the critical time to reduce ammonia emissions is immediately following any individual urination event – the decrease in flux from the surface is not linear, it is strongly exponential as is demonstrated in Chapter II, Figure 4, and this Chapter, Figures 1 and 2, as well as Todd et al. (2006) and Whitehead and Raistrick (1991). Saarijarvi et al. (2006) reported that more than 80% of the total ammonia emissions from urine spots occurs during the first 48 hours of exposure to the atmosphere. Since urine spots are the primary source of ammonia emissions from beef cattle feedlots, it is important to identify BMPs that can be agile enough to respond to new emission sources (urine spots) as they arise, especially in the springtime when there is high risk of transporting N to the high alpine areas of RMNP. This means that an operator – even an operator that has reduced emissions and improved economic efficiency through dietary manipulations – should be intervening to prevent emissions on a daily, not weekly or monthly, basis.

In addition, studies that look at seasonal emissions generally report that summertime emissions are about twice that of wintertime emissions (Hristov et al., 2011). While this work does not attempt to model overall emissions, it is a focus of this research group, and critical to a better understanding of N transport from eastern

Colorado sources to the alpine. Since earlier work (this volume, Chapter I) did not examine conditions likely to produce peak emissions, this work to test the water application BMP was carried out on samples from urine patches in July and August to examine periods of potential peak emissions.

The objectives of this study were to (1) investigate the effects of periodic water application for dust control on ammonia volatilization from feedlot surfaces, and (2) examine the upper bound of potential ammonia volatilization from feedlots in Colorado by making direct measurement from intact surface cores taken from fresh urine spots during mid-summer.

METHODS

This study was conducted at a commercial beef cattle feedlot with a capacity of about 30,000 head and a stocking density of 20 m^{-2} $head^{-1}$ located east of Greeley, CO, USA. All samples were taken from the same pen housing a group of crossbreed heifers (initial weight: 320 kg).

Flux Chamber System

All samples were evaluated for N loss using an ammonia flux chamber system at Colorado State University, Fort Collins, Colorado. The twelve chamber, flow-through design is built around modified vacuum desiccators about 15 cm in diameter. Modifications to the desiccators and general system design are described in Vaillant (2007). Ammonia-free air at a controlled humidity is routed into each chamber at a rate of 5 L/min. The air flows over the soil cores and the exhaust is routed through a short section of Teflon tubing to an acid bubbler containing about 100 ml 0.1 M phosphorous acid. All samples ran in the system for seven days.

Acid bubblers were changed daily and stored in a refrigerator for analysis. At the conclusion of each measurement run, the acid solutions were decanted into a graduated cylinder to record the final volume of acid solution. Thirty milliliters of sample were stored until the NH_3 concentration of the acid solution was measured using a Flow Injection Analyzer (FIAlab Instruments, Bellvue, Washington, USA).

Soil Sampling

Paired, intact surface samples from six obvious urine spots were taken on three sampling days in July and August of 2010. Samples were taken using stainless steel drive cylinders 12.7 cm in diameter and 4 cm deep. Though the recent urination softened the feedlot surfaces in sampling spots, a manual driver was required to drive the cylinders completely into the hard-packed surface. Urine spots used were large enough to encompass both drive cylinders easily, were visually obvious on the pen surface (i.e., darker in color), but were old enough to not have standing, pooled urine on the surface. The drive cylinders in each pair were placed no further than 5 cm apart, and every effort was made to ensure that each sample in a pair was as similar as possible to the other. Excess soil and manure was removed from the bottom and sides of each drive cylinder. Each sample was double-bagged in 8 mil low density polyethylene bags and transported back to the laboratory at Colorado State University in Fort Collins, CO, USA. Samples were loaded into a laboratory chamber system to measure surface ammonia flux within three hours of being removed from the feedlot surface.

Water Application

Immediately after loading the samples into the chamber system, 5 mm of Milli-Q water (Millipore Corporation, Bellerica, Massachusetts, USA) was applied to one randomly chosen sample from each pair, simulating a typical sprinkling for dust control event on the eastern plains of Colorado. A spray bottle was used to apply the water with the aid of a cylindrical shield to ensure that water was applied directly the sample surface. Depth applied was determined by repeated weighing of the spray bottle until a mass equivalent to 5 mm had been added. Aside from the application of the water, there were no differences in the handling and manipulation of the samples.

Soil Analysis

Following seven days of measurement in the flux chamber system, samples were removed, placed in 8 mil low density polyethylene (LDPE) bags and frozen for further analysis. Several months later, samples were partially thawed, and a sub-sample from the center of the surface of each sample was taken. Samples from each treatment from each sampling date were manually composited. Analysis by the Colorado State University Soil Testing Laboratory (Fort Collins, Colorado, USA) included total organic carbon, total nitrogen, organic nitrogen, ammonium-N, nitrate-N, % dry matter, and % organic matter.

Statistical Analysis

Treatment differences in ammonia flux for each sampling date and on soil analysis for pooled sampling dates were analyzed with SAS 9.2 (SAS Institute, Cary, North Carolina, USA) by using a paired t-test (alpha = 0.05).

RESULTS AND DISCUSSION

Ammonia Flux

The pattern of ammonia flux from samples in this study reflected the exponential decrease in emissions observed in previous work by this research group, but was very different from temporal flux patterns recorded in Chapter I of this volume. Emissions on the first day of measurement were very high and rapidly decreased, leveling and remaining consistent starting on day 3 and through the end of this study's measurement period (Fig. 1). This pattern was the same for all three sampling dates, though magnitudes of fluxes varied considerably. Pooling measurements from all three sampling dates, on the first day of measurement there was a 27% reduction of emissions due to the water addition that was highly significant ($p = .00048$). Day 2 emissions were not significantly different ($p = 0.82$) when the three sampling dates were pooled, and on days 2-7 of measurement flux from the watered samples actually tended to be slightly, but not significantly, higher than the samples that did not receive a water addition (Fig. 2). It is possible that if the measurement period had been extended long enough, the difference in cumulative emissions would have been completely negated by these small differences. This pattern of suppression of emissions immediately following a watering event are similar to other published results (Hutchinson et al., 1982; Rhoades et al., 2008; Saarijärvi et al., 2006; Todd et al., 2008; Whitehead and Raistrick, 1991). Addition of water to surface cores did not significantly reduce cumulative emissions (Fig. 3).

Taking measurements from fresh urine patches did, as expected, generate very high ammonia flux measurements compared to other measurements taken previously by our research group (this volume, Chapter I). The highest single measurement made in this experiment was 56.9 g NH_3 m^{-2} d^{-1} and came from an unwatered sample from replicate 2 (Fig.1). The highest emission from a watered sample came from the same pair and was 53.2 g NH_3 m^{-2} d^{-1}. Average emission on Day 1 for all replicates pooled was 28.6 g NH_3 m^{-2} d^{-1} for watered samples and 39.0 g NH_3 m^{-2} d^{-1} for unwatered samples. Average cumulative 7-day emissions for all replicates pooled was 78.2 g NH_3 m^{-2} for watered samples and 85.8 g NH_3 m^{-2} for unwatered samples. Variance *among* sampling dates was high, resulting in relative standard deviation (RSD) values of 57% and 50% for watered and unwatered cumulative emissions respectively, and 52% (watered) and 35% (unwatered) for Day 1 emissions. Variance *within* each sampling date was slightly smaller. Relative Standard Deviation for the cumulative emissions, watered and unwatered, for each sampling date ranged from 43-47%, with the exception of unwatered samples from sampling date 2 (28 July) that had an RSD of 27%. Day 1 measurements within each sampling date were much less predictable than days 2-7 with RSDs ranging from 5-63%. This type of variance is to be expected even from samples from fresh urine patches due to well-established high intra-pen variability related to cattle traffic around structures like the feed bunk, water tank, and central mound, individual animal physiological differences, age of urine patch at time of sampling, and soil physicochemical variability (Koziel et al., 2005).

The phenomenon of reduced emission following a precipitation event could relate to simple leaching of aqueous ammonium away from the surface layers where it is less susceptible to volatilization. If this is the case, this shallowly leached N may eventually be susceptible to deeper leaching out of the soil profile, contributing to potential groundwater contamination and N in wastewater lagoons. However, the ammonium cation is often adsorbed to soil exchange sites and remains relatively close (3 m) to the surface. (Vaillant et al., 2009). Hutchinson et al. (1982) suggests that precipitation events cause a dramatic increase in the size of the reservoir available for ammonia to exist in solution – diluting the NH_4^+ concentration and effectively decreasing the surface area of the soil water – the boundary at which volatilization occurs. The modeling work of Wu et al. (2003) suggests that both of these mechanistic explanations are at work. Shallow diffusion away from the surface creates greater diffusive resistance for NH_3 to reach the surface (h_m, Eq.1.5), and dilution of the ammonium pool decreases the concentration of gaseous NH_3 at the surface ($C^0_{NH_4^+(aq)}$, Eq. 1.5).

<u>Soil Analysis</u>

A summary of the pen surface soil analysis can be found in Table 1. Total N and Organic N were similar to the findings in this volume, Chapter II and Vaillant et al. (2009), but lower than reported by Cole et al. (2009). Ammonium-N concentration was similar to reported summertime concentration of 1,501 mg kg^{-1} and within the range of values reported by Vaillant et al. (2009), but lower than concentrations reported in this volume, Chapter II. Differences in ammonium-N concentration between this study and the study reported on in Chapter II are likely due to the increased rate of ammonia loss due to seasonal differences. Organic Matter in this study was higher than reported in Chapter II and several other reported values (Adams et al., 2004; Bierman et al., 1999; Kissinger et al., 2007), but similar to the 53.7% summertime organic matter reported by Cole et al. (2009). Because they were composite samples, statistical comparisons weren't possible within individual sampling dates. When sampling dates were combined, there were not statistical differences between treatments for: total organic carbon, total N, total organic N, ammonium-N, or nitrate-N. Percent dry matter ($p = 0.012$) and percent organic matter ($p = 0.037$) were significantly lower for watered samples compared to the unwatered samples. It is not surprising that dry matter would be lower in watered samples, since water was intentionally added to only these samples.

CONCLUSIONS

For the particular concerns of Colorado – predictable, seasonally specific transport of N from the Front Range to the alpine – our results indicate that applications of water from a sprinkling system to feedlot surfaces for dust control does not exacerbate N loss. While water is certainly a precious commodity, particularly in eastern Colorado, water sprinkling has potential as a short-term co-BMP to prevent ammonia volatilization from Colorado's Front Range feedlots during upslope conditions. This possibility is even more intriguing because many feedlot operators already have and routinely employ the infrastructure that would be required to implement this practice. Water sprinklers – either solid set in pens or as part of a mobile truck unit – are widely recommended and adopted for the control of dust at large cattle feeding operations (Auvermann, 2003; Miller and Woodbury, 2003; Razote et al., 2004; Razote et al., 2007). Further research is required in the laboratory to determine if, as these data indicate may be the case, frequent small (every 12 or 24 hours) water applications can significantly depress ammonia emissions for several days. If this is the case, pilot and field-scale experiments using tower-based measurement approaches should be performed to determine whether or not this BMP prospect translates to the feedlot operation scale.

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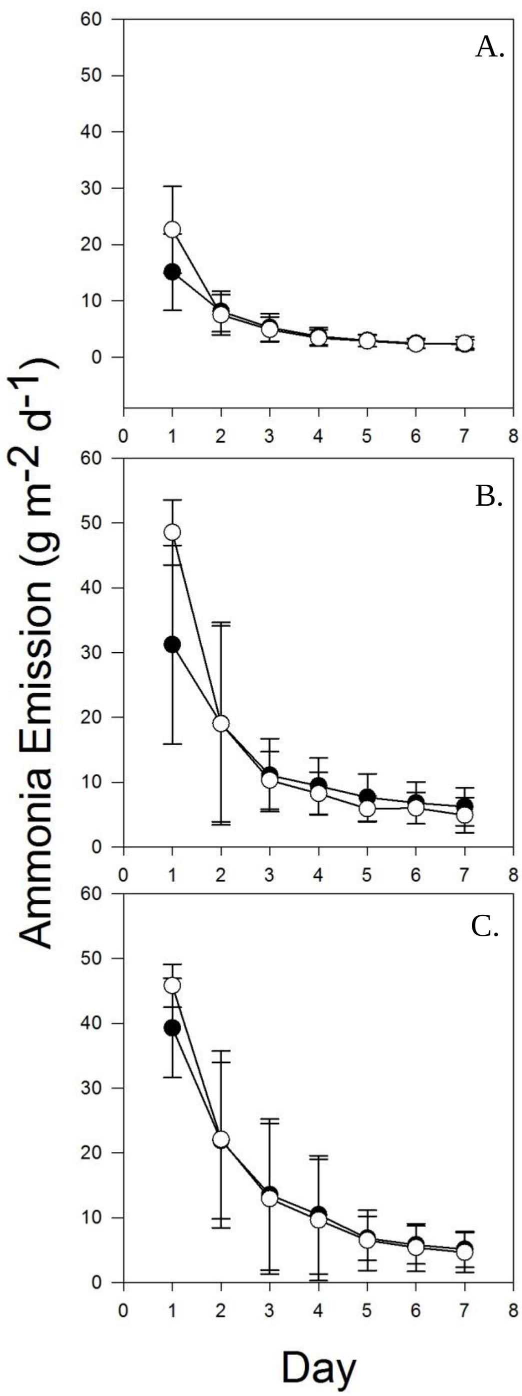

Figure 1 A.-C. Average ammonia emissions from 6 paired samples collected on 9 July 2010 (A), 28 July 2010 (B) and 19 August 2010 (C) from a commercial feedlot near Greeley, CO. Dark circles show emissions from samples that received a 5 mm water application treatment before the 7-day measurement period. Open circles show control emissions. Error bars represent one standard deviation.

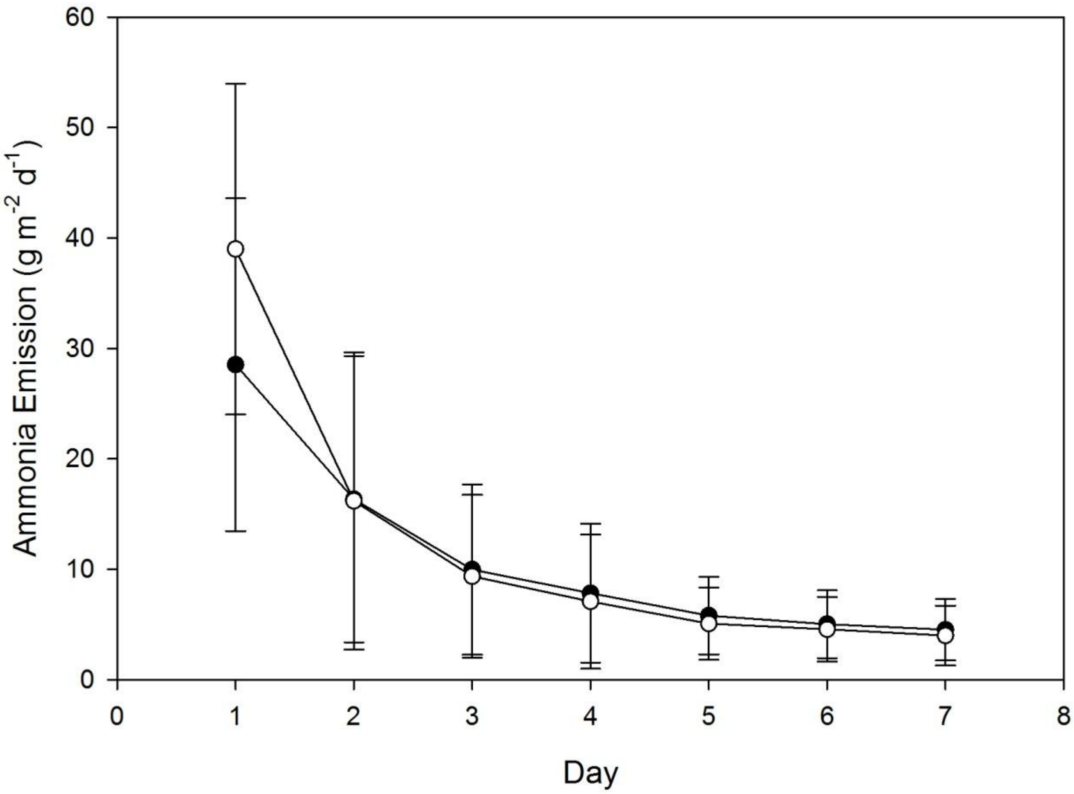

Figure 2 Ammonia emissions for all three pooled sampling dates during July and August of 2010. Dark circles show emissions from samples that received a 5 mm water application treatment prior to the 7-day measurement period. Open circles show the control treatment. Error bars represent one standard deviation.

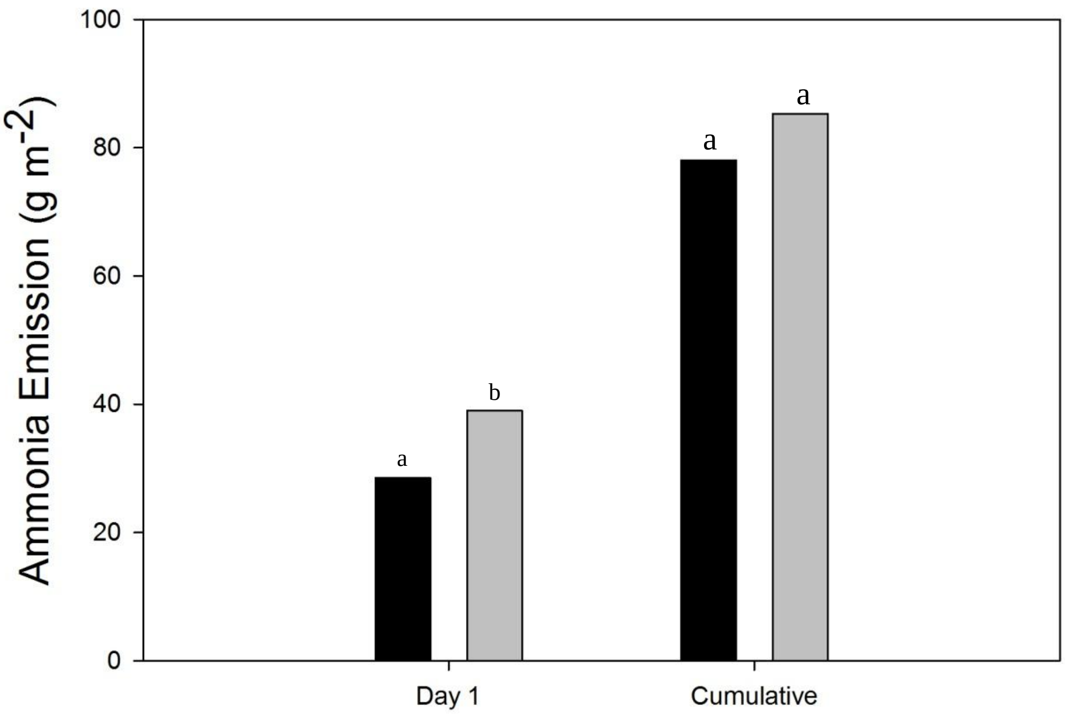

Figure 3 Effect of addition of 5 mm of water to intact feedlot surface cores taken from fresh urine patches on ammonia emissions during the first day of measurement as well as cumulative emissions during the entire seven day measurement period. Results are pooled from three different sampling dates in July and August of 2010. Dark bars are watered samples and gray bars are unwatered samples. [a,b] indicate statistically significant differences ($\alpha = 0.05$).

Table 1 Nutrient analysis of composite samples (all watered or all unwatered) from 3 sampling dates. All units are mg kg^{-1} unless otherwise noted.

Treatment[1]	TOC	Total N	Org N	NH_4-N	NO_3-N	DM (%)	OM (%)
9 July							
Watered	17600	16300	15400	970	0.9	57.85	56.0
Unwatered	17700	16300	15100	1217	1.3	64.18	52.5
28 July							
Watered	19500	16900	14400	2458	3.6	54.49	57.1
Unwatered	19200	16400	14500	1828	3.3	59.88	53.6
19 August							
Watered	16900	16200	14900	1342	1.8	64.87	60.2
Unwatered	18500	16900	15400	1502	0.6	70.51	52.4
Dates Combined							
Watered	18000±1350[a]	16467±380[a]	14900±500[a]	1590±750[a]	2.1±1.4[a]	59.1±5.3[a]	57.8±2.2[a]
Unwatered	18500±750[a]	16533±320[a]	15000±450[a]	1520±300[a]	1.7±1.4[a]	64.9±5.3[b]	52.8±0.6[b]

[1] Watered samples received a 5 mm application of water prior to a 7-day measurement period in a flux chamber system; Unwatered samples were the control.

[a,b] Indicates statistical difference among treatments using a paired t-test (alpha = 0.05)

CHAPTER IV

CONCLUSIONS: VIABLE MANAGEMENT OPTIONS FOR REDUCING AMMONIA VOLATILIZATION FROM BEEF CATTLE FEEDLOTS

Sensitive alpine ecosystems are showing fundamental stoichiometric shifts in response to nutrient inputs, which may lead to reduced phytoplankton diversity, food-web disruption, and reduced production in higher trophic levels in alpine lake ecosystems (Elser et al., 2009). Nitrogen transport to Colorado's alpine originates from many sources, but agricultural (largely livestock) emissions from northeastern Colorado are estimated to be one of the two largest sources, accounting for 15% of total N deposition in Rocky Mountain National Park in the spring and summer of 2006 (Malm et al., 2009). The Rocky Mountain National Park Initiative is a partnership of State and Federal agencies tasked with reducing N deposition in RMNP to below the ecological critical load of 1.5 kg N ha^{-1} yr^{-1} (Baron, 2006), but relatively little progress has been made and the first intermediate goal for 2012 is unlikely to be met. Feedlot operators on Colorado's Front Range need best management practices (BMPs) that are operationally practical, economically feasible and that specifically address the unique challenges of this region. Due to the proximity of a large number of animals on feed to sensitive alpine ecosystems, the concern about ammonia loss from Front Range feedlots is both unique and urgent. This thesis assessed the potential of dietary N manipulation and water application as

BMPs to reduce N volatilization from feedlot surfaces. Specifically, the objectives were to:

1. Determine if a reduced CP diet in feedlot cattle causes a corresponding reduction in NH_3 emissions from the pen surface;
2. Investigate the potential of using periodic water application as a BMP to reduce ammonia emissions from cattle feedlot surfaces; and
3. Examine the upper bound of potential ammonia volatilization from feedlots in Colorado.

Objective 1

As part of a feeding trial at Colorado State University's experimental feedlot in Lamar, CO pen surface samples were taken from three cattle receiving a control diet, a reduced N diet, and an oscillating N diet. Ammonia emissions from these samples were measured under controlled conditions using a laboratory chamber system.

- Reducing CP from 13.5 % to 11.62 % caused a 21 to 40 percent reduction in emissions – from a daily average 7.8 to 5.0 g NH_3 m^{-2} d^{-1} across all three sampling dates;
- Animal performance, measured by average daily gain, was not negatively impacted by the reduced N diet under the conditions studies;
- Reductions measured from the pen surface samples correspond to calculated reductions in N excreted, particularly urinary N from cattle receiving the reduced diet;

- There were not pen surface volatilization reductions associated with the Oscillating N diet; and
- Because N transport from the Front Range to the alpine is a seasonal phenomenon largely confined to the spring, the reduction measured in this study suggests a BMP of using lower N diets in April, May, and June when upslope conditions are most likely.
- Future studies should be conducted at a commercial feedlot scale using a variety of measurement techniques – laboratory chambers, field chambers, and micrometeorological methods – to further examine the effect of reduced CP diets on ammonia emissions and on cattle performance metrics.

<u>Objectives 2 and 3</u>

Paired pen surface samples were collected from urine spots at a commercial feedlot near Greeley, CO. From each pair, one sample was moistened with a 5 mm application of water prior to incubation in a laboratory chamber system.

- Water application reduced the first day ammonia emissions by 27% ($p = 0.0004$), from 39.04 to 28.58 g NH_3 m^{-2} d^{-1};
- As drying progressed, watered samples had slightly higher emissions than unwatered samples – seven day cumulative emissions from watered samples were 9% lower than from unwatered samples;
- Timing and location of sampling for this study were ideal to produce very high emissions – average first day emissions from unwatered samples was

39.04 g NH_3 m^{-2} d^{-1}, the highest measured so far by this research group - providing an upper-bound for future modeling work of feedlot ammonia;

- In eastern Colorado, due to its ease of implementation and low infrastructure costs, water sprinkling to prevent short-term ammonia emissions has potential as a BMP;
- Future studies using laboratory chambers should examine the effect of multiple watering events every 12 to 24 hours on delaying ammonia emissions for longer periods of time;
- The feasibility of using water (a scarce resource in eastern Colorado) to reduce ammonia emissions from feedlots should be evaluated from both an economics and a water resource perspective.

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