B. Options to Reduce Ammonia Emissions

I. Agricultural Livestock and Crop Production

Agriculture in Colorado is important to the state's economic well being, producing over $16 billion per year in farm revenue that contributes to the vitality of rural communities and helps to ensure the sustainability of America's food supply (CDA, 2005). Over the past 100 years, the agricultural industry has developed a very efficient, sophisticated system for production of meat, milk, poultry, and grain products.

Since the early 1970s, state and federal regulations and programs have directly addressed water quality protection from CAFOs and the application of commercial fertilizers. Accordingly, in the last 35 years systems designed for manure management and fertilizer application have been optimized for water quality protection purposes to comply with effluent limitations guidelines (ELGs) adopted in 1974 and 1976 by the U.S. Environmental Protection Agency (EPA). Most states, like Colorado, have surpassed EPA in requiring groundwater protection measures and nutrient balances for land application of manure and commercial fertilizer. In the past five years, changing regulatory priorities at the federal and state levels have begun to include agricultural activities in discussions related to air quality issues. For example, ammonia volatilization was considered a desirable means to remove nitrogen from manure to balance nitrogen for land application, and only recently has ammonia loss been viewed as a potential problem in terms of air quality considerations.

Research efforts to characterize ammonia emissions from animal feeding operations and agricultural fertilizer use efforts have intensified in Europe and the United States in recent years. However, little work has been done to evaluate potential abatement (control) strategies. Furthermore, the majority of investigations into abatement strategies cited in recent literature are limited to laboratory scale studies and do not reflect the complex realities of applied nitrogen management in the agricultural industry. Much of the work that has been done to investigate ammonia control strategies in animal feeding operations is limited in scope and focused on only one component of a manure management system, rather than taking a holistic systems approach. The result of this narrow focus is that little or no information exists to characterize changes in emissions from subsequent steps in the manure management system. For example, while some studies have found that frequent scraping of manure from dry lots may reduce ammonia emissions from the pen surface (Misselbrook et al., 1998), most did not assess the impact that frequent scraping may have on ammonia emissions from subsequent storage and compost piles into which the nitrogen-rich manure scrapings were deposited, nor the emissions from soils on which such scrapings were finally disposed. It is likely that the higher nitrogen content of scrapings from frequently harvested dry lots could result in comparable ammonia emissions in these subsequent stages of manure management to those resulting from storage, composting, and disposal or land application of manure harvested in a more traditional time interval. Therefore, the entire system needs to be addressed, rather than just one piece of it to achieve the most benefit from nitrogen abatement strategies.

In order to achieve ammonia reduction benefits on the farm, and in RMNP, it is imperative that sufficient research and data exist to quantify the benefit of implementing best management practices (BMPs). The complex nature of biological systems that agriculture must work with further complicates the scientific understanding of the industry. Thus, when addressing agricultural issues, consideration must be given to the holistic nature of agriculture and to both air quality and water quality issues simultaneously in order to achieve effective controls and eliminate unintended consequences.

Targeted and sufficient research requires time and resources. The research must balance water and air quality issues in a holistic systems approach while maintaining high standards of livestock productivity, animal health and production cost efficiency. For example, if EPA updates Effluent Limitation Guidelines, the rulemaking will likely embrace phosphorus limits in land application criteria, an action that will lead toward reduced manure and wastewater application rates in some watersheds (primarily in the eastern U.S.). In turn, this may increase producers' incentives to reduce nitrogen loss and strive to accurately balance nitrogen application rates. Research and development of existing regulatory requirements, and current and emerging BMPs need to properly quantify ammonia emissions from Colorado facilities in order to provide accurate and defendable results for Colorado's producers.

Quantifiable BMPs that can demonstrate ammonia reductions will more readily help the National Park Service meet its environmental protection goals at Rocky Mountain National Park and garner greater support from the agricultural industry in reducing ammonia emissions from a universe of approximately 31,000 farms and ranches in Colorado.

1. Current Agricultural Practices and Research

Farmers and ranchers use BMPs to reduce environmental impacts to water, air or land. Historically, BMPs have focused almost exclusively on reducing the amount of pollutants that make their way to ground or surface waters. BMPs addressing air pollution are limited and/or not well researched or understood in terms of its quantifiable benefit. In general, BMPs are recommended methods, structures or practices designed to prevent or reduce environmental impacts to water, air or land. BMPs are inherently voluntary, site-specific, and are applied at the local level. Many BMPs are considered standard industry practice and often provide both environmental and economic benefits to agricultural operators.

Factors influencing ammonia emissions from livestock operations include: type and size of animal; dietary nitrogen and amino acid content; nitrogen digestibility and conversion; confinement housing system; and manure handling system (Battye et al., 1994). Additional variables that influence ammonia emissions from agricultural practices include: climatic conditions, soil properties, manure properties, nitrogen application rate, application method, and timing of soil incorporation. The large number of variables, together with the complex biological nature of agricultural operations creates added complexity to the development of targeted ammonia abatement strategies for agricultural operations. Unless carefully analyzed and researched, BMPs can result in simply moving an emission source from one place to another (spatially and/or temporally) with little or no net reduction in emissions. For crop-based agricultural operations, emissions can be affected variously by similar management practices depending on environmental conditions so no single management practice will effectively reduce emissions from all production systems. For example, the efficacy of most crop CMPs will depend on the soil pH, organic matter content, and texture of the soil on a given farm such that a BMP that will work on a calcareous soil with low organic matter may not be suitable for a more acidic soil with high organic matter content. For livestock operations, the complete elimination of ammonia emissions is not possible unless there is a way to bind or permanently change the form of ammonia-nitrogen that is emitted from manure. To date, research has not validated a way to eliminate ammonia emissions from agricultural activities, nor would it be desirable as ammonia is a by-product of many natural and necessary reactions in soils without which vegetative life would not exist.

What is currently supported by research is that the quantity and rate of ammonia volatilization depends on a variety of factors such as the amount of dietary crude protein in feed rations, manure management strategies, manure and soil pH, and climate effects (temperature, relative humidity, wind speed, etc.), to name a few. In addition, ammonia emissions from livestock operations have many secondary effects such as ammonium salt formation ($PM_{2.5}$), wet and dry nitrogen deposition to surrounding vegetation, soil acidification, water eutrophication, and ecosystem change (Vitousek et al., 1997; de Boer, 2003; Krupa, 2003; Fenn et al., 2003). As with many processes, there is a trade-off to reducing ammonia emissions. For instance, by retaining ammonia in one area of the operation, it becomes more susceptible to loss later in the system. If nitrogen is retained in manure, the possibility of nitrate leaching and runoff into ground and/or surface waters increases with application to soil. Additionally, some management practices that reduce gaseous ammonia emissions, such as decreasing pH or encouraging aerobic conditions in manure, can lead to an increase in hydrogen sulfide, odor, or nitrous oxide emissions. Thus, the potential for unintended consequences must be evaluated and understood prior to implementing ammonia reduction control options.

Research on quantifiable ammonia reductions resulting from BMP implementation is limited. Results of a comprehensive scientific literature review conducted by Dr. Jessica Davis, Nichole Marcillac, Cathy Stewart, and Adrianne Elliot from Colorado State University are listed below. Agricultural producers currently use some of these BMPs. Current practices and research provide a starting point for the development of a research strategy on ammonia reduction BMPs for production agriculture. Additional research on the quantification of gaseous ammonia emissions and resulting emission reductions are still necessary prior to including the following potential BMPs in the RMNP plan as a successful emission reduction strategy for agriculture. The following information provides a basic overview of potential BMPs that have shown potential for reduction of gaseous ammonia emissions. It is important to remember that most of these BMPs require further investigation to determine their true ability to reduce emissions of ammonia from livestock and crop production. Once a particular BMP or control strategy has been scientifically determined to reduce overall ammonia emissions, it may be adopted as a BMP for air emission reduction from Colorado agriculture. Adoption of these potential BMPs before their efficacy is quantified may lead to burdens on agricultural producers without corresponding reductions in nitrogen deposition in RMNP, which could make agricultural producers less receptive to more effective BMPs proposed in the future.

The following table is a summary of research being conducted in 2006 on agricultural ammonia emissions that may be applicable to efforts at reducing nitrogen deposition in RMNP taken from the Proceedings of the Workshop on Agricultural Air Quality: State of the Science held in Potomoc, MD, in June 2006. This list is not considered to be an extensive list, but simply provides a start to identifying some of the research currently being pursued in the United States[NMM1].

Table 1. Ammonia research presented at workshop on agricultural air quality in 2006 (Aneja et al, 2006).

Topic	Authors
Emissions	

General	
Development of an easily updatable national emissions inventory	Strader and Davidson
Analyzing effects of emissions controls on ambient ammonia concentrations	Fowler et al.
Collecting emissions data from animal housing facilities nationwide (NAEMS)	Heber and Bogan
Use of lidar to measure emissions from an entire facility	Bingham et al.
Development of process-based modeling of gaseous nitrogen emissions	Beuning and VanHeyst
Results of the six-states study	Jacobson, et al.
Estimating nitrogen loss from manure using nitrogen to phosphorous ratios	Moreira
Greenhouse gas emissions from stored animal manure in cold climates	Wagner-Riddle, et al.
Predicting emissions from manure nitrogen from livestock facilities and storage	Keener and Zhao
Measurement Techniques	
Using FTIR for measuring trace gas emissions	Griffith et al.
Using a photothermal inteferometer to estimate ammonia fluxes	Avery and Plant
Using a microtunnel for measuring emissions	McDaniel et al.
Boundary layer sampling at CAFOs	Marcillac, et al.
Swine	
Analyzing effects of reduced crude protein on emissions from swine	Powers et al.
Measuring emissions from buildings and lagoons in North Carolina	Blunden et al.
Ammonia emissions and dry deposition from hog farms in North Carolina	Bajwa et al.
Relationship between ventilation control and ammonia emissions from barns	Haeussermann et al.
Assessment of biological treatments of slurry with storage-spreading system	Loyon, et al.
Emissions assessment using inverse Gaussian modeling	Martin, et al.
Spatial variations of ammonia around swine confinement operations	Pfeiffer
Evaluation of potential abatement technologies in North Carolina	Rumsey, et al.
Dry-deposition of ammonia in the vicinity of a swine production facility	Walker and Robarge
Nitrogen mass balance for fields fertilized with liquid swine waste	Whalen and DeBerardinis
Beef Cattle	
Investigation of surface boundary layer of cattle feedyards	Ham et al.
Dispersion of the ammonia plume from a beef cattle feedlot	Staebler, et al.
Dairy Cattle	
Ammonia emissions from application of dairy effluent	Beene et al.
Effects of acidifying liquid cattle manure on ammonia emissions	Berg et al.
Emissions from dairy cows, waste, and feed	Mitloehner
Seasonal and spatial emissions from an open-lot dairy operation	Mukhtar, et al.
Volatilization during and after dairy slurry field application	Pattey, et al.
Ammonia emission fluxes from dairy stalls, lagoons, and slurry application	Rumburg, et al.
Diurnal variation of ammonia from dairy manure storage pond in Idaho	Sheffield and Louks
Crops	
Uncertainty analysis	Krupa et al.
Crop-specific management related background flux rates	Model and Hellebrand
Denitrification in frozen, manure-amended soils	Phillips
Modeling	
Improving temporal resolution of ammonia models	Hutchings et al.
Analyzing ammonia fate and transport on regional levels	Dennis et al.
Investigation into the effect of terrain on dispersion models	Alfieri et al.
Evaluation of WATER9 for predicting emissions from CAFOs	Deerhake et al.
Comparison of dispersion models for ammonia emissions	Faulkner et al.
Multi-scale measurements and process based modeling of CAFO emissions	Marcillac, et al.
Evaluation of DYNAMO model	Reidy and Menzi
The role of precursors in ammonia transport in North Carolina	Scott and Aneja
Modeling transport and chemistry of ammonia in North Carolina	Wu, et al.
Deposition	
Investigation into atmospheric nitrogen reactions and deposition in China	Bowersox and Lehmann
Investigation of dry deposition near a swine facility	Walker and Robarge
Emissions and NH_4^+ concentrations in precipitation in Southeast and Midwest US	Konarik, et al.
Modeling of dry deposition of ammonia in North Carolina	Krishnan, et al.
Flux and deposition over intensively managed animal facilities in North Carolina	Phillips, et al.

Management Practices	
Use of vegetative buffers	Colletti et al.
Establishing an enviro-economic framework for evaluating BMPs	Schou et al.
Use of a bio-trickling filter for gaseous ammonia removal	Jensen and Hansen
Biofilters for ammonia abatement	Nicolai and Lefers
Abating emissions from dairy barns through feed, herd, and bedding management	Powell, et al.
Ammonia-based air permits for dairies in Idaho	Sheffield and Louks
Reduction of swine lagoon emissions using alternatives wastewater technologies	Szogi, et al.
Aerobic composting for mitigating greenhouse gas emissions from swine manure	Wagner-Riddle, et al.

Aneja, V.P., W.H. Schlesinger, R. Knighton, G. Jennings, D. Niyogi, W. Gilliam, and C.S. Duke. (eds.) 2006. Proceeding of the Workshop of Agricultural Air Quality: State of the Science. Raleigh, NC: Department of Communication Services.

Faulkner, W.B., B.W. Shaw, and R.E. Lacey. 2005. Analysis of sampling protocols for the EPA animal feeding operations consent agreement. Presented at the 2005 ASAE/CSAE Annual International Meeting held from July 17-20, 2005 at Tampa, Florid. Paper No. 054007.

Additionally, through the Consent Agreement with the EPA, the largest study ever conducted on air emissions from agricultural operations is currently underway, in which emissions will be measured from livestock facilities across the United States including swine and dairy animal feeding operations. Various institutions throughout the United States are conducting this study. For an analysis and critique of the proposed sampling protocols of this agreement, see Faulkner, et al. (2005).

Researchers at the Texas Agricultural Experiment Station, West Texas A&M University, Colorado State University, and the USDA-ARS are working to quantify ammonia emissions from beef cattle feedyards. They are evaluating surface additives; nutrition, feedyard, and manure management regimes; and land application protocols that for reducing ammonia emissions from beef cattle feeding operations.

Ammonia emission factors for open-lot and free-stall dairies are being developed at Texas A&M University, University of California, Davis, and Colorado State University. Abatement strategies for dairies are being investigated at University of Minnesota and Idaho.

Faculty at North Carolina State, Purdue, Iowa State, and the University of Minnesota continue to work to characterize ammonia emissions from swine housing facilities and manure management practices as well as evaluate proposed abatement strategies and management practices.

Again, other agencies and individuals are conducting research relevant to issues facing RMNP. In essence, additional time is needed to allow for the completion of this research and an analysis of the applicability of results to Colorado operations. In the interim, continued research that is applicable to Colorado production practices and climate are also needed before abatement strategies can be effectively employed.

A. BMPs for Crop Production

Crops can either be a sink for gaseous ammonia by plant uptake through leaves or deposition on leaf surfaces, or an ammonia source through leaf volatilization or plant residue decomposition (Sommer and Christensen, 1992). Under conditions of low soil nitrogen or high atmospheric ammonia concentrations, plants absorb ammonia through their stomata. Under conditions of high soil nitrogen or low atmospheric ammonia concentrations, plants volatilize ammonia (Sharpe and Harper, 1995). When atmospheric ammonia concentration exceeds stomatal ammonia concentration, plants absorb a proportional amount of atmospheric ammonia. Additionally, water-soluble ammonia may be stored in moist leaf surfaces (Sommer et al., 2004).

Ammonia loss from plants is due to metabolic plant processes such as nitrate reduction, atmospheric nitrogen fixation, photorespiration in leaves, and transport of nitrogen products within the cell. Ammonia uptake in natural systems, pastures (Cowling and Lockyer, 1981), and cropped lands adjacent to animal feeding operations, has been found to be significant.

Volatilization of ammonia can occur during all stages of crop production including tillage, fertility management, and plant cutout. Volatilization of ammonia may also occur at the end of the growing season when plant tissue dries, perhaps due to chlorophyll degradation.

Due to the spatial variability within the plant where these processes occur and to variability in atmospheric and soil ammonia concentrations, ammonia volatilization from cropping systems is difficult to predict (Sommer et al., 2004). However, several management practices have been suggested which have the potential to reduce overall nitrogen volatilization from crop production in Colorado and therefore impact the level of nitrogen deposition in RMNP. Some potential control options for limiting ammonia volatilization from crop production are as follows:

1. **Tillage**

   a. **Conventional Tillage**

   Ammonia emissions from cultivated systems without fertilizer additions from manure or synthetic sources are low and, therefore, there are no BMPs for ammonia emissions from tillage effects alone. Effects of fertilizer addition will be discussed below.

   b. **Conservation Tillage**

   Conservation tillage is a practice whereby crop residues are left on the soil surface from year to year rather than deep plowing the soil every year. Conservation tillage may be practiced in varying degrees, from no-till systems where all crop residues are left on the surface and subsequent crops are planted directly into the stubble, to strip-till systems where strips of land are tilled for seed and fertilizer placement while leaving crop residue between seedbeds.

   Conservation tillage has largely been adopted in areas with large losses of topsoil to wind erosion or in areas where water resources are limited. Conservation tillage practices protect topsoil from wind erosion by leaving stubble in place. Long-term, maintaining topsoil may reduce the need for nutrient addition through fertilizer as the nutrients that were historically lost with the topsoil are maintained. Also, as topsoil is maintained, organic matter levels in the top layer of the root zone (usually the top 5 cm of soil) increase, thus increasing the soil's cation exchange capacity, which allows the soil to "hold on" to soluble nutrients applied to the surface such as nitrogen. However, with conservation tillage, the organic matter levels below the top strata typically decline as crop residues are no longer turned under by deep plowing. Additional research needs to be conducted to determine whether long-term conservation tillage reduces overall nitrogen requirements of cropping systems used in Colorado.

   Well-managed conservation tillage systems maintain soil moisture better than conventional tillage systems. Because this soil moisture is not evaporated, dissolved ammonia in the soil pore spaces is less likely to be volatilized. If dissolved ammonia is better stored in conservation tillage systems, then conservation tillage may reduce overall ammonia emissions from crop production in Colorado. However, no literature was found that has characterized ammonia losses between similar yielding crop production systems managed with conventional and conservation tillage practices pointing to the need for research in this area before BMPs can be determined.

When nitrogen fertilizer is applied to systems with stubble, or surface straw, ammonia emissions increase, due to a higher urease activity in plant litter compared to the top 10 mm of soil (Sommer et al., 2004). Consequently, ammonia fertilizer should not be broadcast applied to fields where no-till conservation management practices are being employed as this could potentially increase ammonia volatilization (Sommer et al., 2004). Use of implements that move remaining residue to the side on no-till soil so that nitrogen fertilizers may be directly applied to the soil surface may reduce losses (Touchton and Hargrove, 1982), but such equipment is not currently available commercially. Furthermore, quantification of the reduction in ammonia volatilization through the use of this practice is needed to determine the impact such a practice may have on nitrogen deposition in RMNP.

It should be noted that universal adoption of conservation tillage would be in direct conflict with reducing ammonia emissions from land application of waste products from animal feeding operations through incorporation of these animal wastes into the soil. The need for agronomic land on which to spread the manure and effluent should be considered when determining BMPs for reducing nitrogen emissions from agricultural sources.

2. Fertilizer Use

a. Fertilizer Selection

Ammonia volatilization from fertilizer applied to soil typically ranges from 3 to 50% of added nitrogen, but can be much higher in some cases. Ammonia volatilization depends on multiple factors, including soil texture, cation exchange capacity (CEC), pH, moisture, type of fertilizer added, and rate of application. Urea is the most widely used fertilizer in the world, but losses from urea fertilizer are extremely high when applied to calcareous soils, which are common in eastern Colorado. For this reason, many farmers in eastern Colorado have turned to anhydrous ammonia, which typically has lower nitrogen losses on high pH soils (Asman, 1992; Potter et al, 2001; Battye et al, 1994) . However, in the Front Range counties closest to RMNP, ammonia is rarely used and is not available at most farmers' cooperatives any longer due to its high volatilization rate in calcareous soils.

Many options are available to farmers today to supply the nutrient needs of their crops. An effective BMP for reducing ammonia volatilization from crop production in Colorado is to choose the nitrogen fertilizer most appropriate for a given cropping system that will have the lowest nitrogen volatilization on the soil type to which it is being applied. If this BMP is adopted, care must be taken to match fertilizer types to the soil on which it will be applied. Fertilizers with non-precipitating anions such as ammonium nitrate or ammonium chloride should be used on calcareous soils to maximize nitrogen availability to the plants, thus reducing the amount of nitrogen available for volatilization.

Of nutrients used in crop production, nitrogen is typically the most expensive. Nitrogen lost through volatilization is nitrogen that is not useful for the producer. Therefore, for economic reasons, producers will be inclined to, and in many cases already are, practicing agronomic application and “soil–appropriate” fertilizer choices. The results of completed and future research regarding nitrogen losses of various fertilizers on eastern Colorado soils should be well disseminated throughout the agricultural community. If this is done, voluntary adoption of better fertilizer selection practices is likely to occur.

Selection of controlled release fertilizers may also reduce ammonia volatilization as nitrogen is made available to the plant over a longer period of time. If managed well, this practice may increase nitrogen utilization by the plant, thus reducing ammonia volatilization by decreasing the nitrogen gradient between the soil surface and the atmosphere. Controlled release fertilizers, however, are more expensive and may not be feasible in all production systems.

b. Fertilizer Application Rates

Ammonia volatilization from soils increases as the gradient between ammonia concentration in the air and in the soil grows (Hutchinson et al, 1972; Sharpe et al, 1988; Harper and Sharpe, 1995). Therefore, inducing higher levels of soil nitrogen than needed through over fertilization will result in greater ammonia volatilization. Fertilizer application rates should be determined based upon soil analyses (from soil samples taken throughout the root zone) as well as water analyses (in irrigated systems) and reasonable yield goals. Yield goals should be determined for each field based upon soil properties, available moisture, yield history, and management level. Once yield goals have been established and soil tests conducted, necessary fertilizer application rates can be determined through consultation with a crop consultant or use of various publications. By basing fertilizer application rates on these factors, excess nitrogen usage can be avoided, thus reducing ammonia volatilization from over fertilization. These strategies have also been proven for increasing profitability in many diverse geographic regions and cropping systems, so application of such a BMP is likely to be well received by producers.

c. Soil Acidification

Ammonia volatilization is favored by calcareous soils such as are common in eastern Colorado. Ammonia volatilization may be reduced by soil acidification (Potter et al, 2001; Chinkin et al, 2003) through use of soil amendments such as sulfur. In many production systems, lower soil pH is desirable to promote nutrient availability as well, and many producers in eastern Colorado already apply sulfur compounds to their soils such as ammonium-sulfate (21-0-0-24 is most commonly used on grasslands), sulfur-nitrate fertilizer or elemental sulfur. Care must be taken when employing this practice because over acidification can lead to problems such as aluminum toxicity. Additional research is needed to quantify the reduction in ammonia emissions achieved by soil acidification, but use of sulfur compounds in crop production on calcareous soils is a potential method to reduce ammonia emissions.

d. Urease Inhibitors

Ammonia volatilization occurs as urea nitrogen is hydrolyzed by the urease enzyme (found naturally in soils and animal feces) to form ammonia gas. Urease inhibitors slow the rate of or inhibit this reaction, thus slowing the rate of ammonia volatilization allowing the nitrogen to be retained in soils or used by plants. Use of urease inhibitors may reduce the amount of ammonia volatilized from cropping systems, especially those using urea fertilizer or animal waste (Byrnes and Freney, 1995). However, thus far the use of urease inhibitors has been found economically infeasible in many production systems due to the limited duration of urease inhibitor efficacy.

c. Fertilizer Placement

Incorporating fertilizer or manure as soon as possible into the soil will minimize the loss of ammonia (Grant, 2005). Planting and fertilizing equipment that will band fertilizer with or near seeds during and after planting, are commercially available, though they often represent a significant capital investment for producers. However, banding fertilizer below the soil surface has proven to greatly reduce ammonia volatilization from nitrogen fertilizers, both reducing detrimental environmental effects and making more applied nitrogen available for plants. In calcareous soils, placement between 5 and 7.5 cm is recommended to reduce ammonia emissions (Sommer et al., 2004). Use of subsurface fertilizer banding equipment in crop production may reduce ammonia emissions from many crop production systems in Colorado. Many producers on the Front Range are already banding their fertilizer, placing it directly into the root zone of the plants, commonly using 2x2 or 2x3 planting equipment (i.e. fertilizer is placed two inches to the side and two or three inches below the seed). Furthermore, as subsurface drip irrigation is growing in the region (an estimated 2000-3000 acres is already installed on the Front Range) producers have the ability to apply nitrogen fertilizer through the irrigation system, significantly reducing the possibility of ammonia volatilization.

3. Fertilizer Storage and Handling

Properly storing and managing commercial fertilizer can help to minimize emissions of ammonia from leaks, spills or other problems. Valves on fertilizer storage and application equipment should be regularly inspected for leaks and should be locked and secured when not in use. Storage tanks should also be regularly inspected for leaks or spills. Properly calibrated fertilizer equipment can also result in better crop utilization and fewer emissions from over application or mechanical problems.

Due to the nature of many nitrogen fertilizers, extreme caution should be taken when developing BMPs for fertilizer storage and handling to account for the safety of those handling or in the vicinity of nitrogen fertilizer storage areas.

B. BMPs for Livestock Production

1. Nutrient Management

a. Reducing Dietary Crude Protein

A number of studies have focused on the link between nitrogen intake and ammonia volatilization from animal excreta. Excess nitrogen fed to animals is excreted in the waste and readily volatilized as ammonia. For example, in dairy cattle fed typical diets, up to 70% of the nitrogen consumed is excreted (Rotz, 2004), with most of that nitrogen (60 to 70%) excreted in the urine (Misselbrook et al., 2005). Through various management techniques, this excretion amount can be reduced, but the theoretical maximum possible efficiency is 50% nitrogen retention (Rotz, 2004). Beef cattle, swine and poultry all experience similar inefficiencies in nitrogen utilization. Swine and poultry may excrete 60% of the total nitrogen consumed, and beef cattle can excrete as much as 80% (Rotz, 2004). Matching an animal's nitrogen intake to its production needs is critical in reducing nitrogen excretion.

Because nitrogen excretion is directly related to an animal's protein intake, crude protein intake needs to be targeted to an animal's needs to reduce nitrogen excretion and subsequent ammonia volatilization. Studies have shown that there is a direct link between the amount of crude protein in the diet and the amount of ammonia volatilized from pen surfaces; a reduction in crude protein in the diet leads to a reduction of ammonia volatilization (Todd et al., 2006; Frank and Swensson, 2002). Feeding less crude protein not only reduces the amount of total nitrogen in the manure, it also changes the partitioning of nitrogen between the urine and feces. Todd et al. (2006) found that steers fed a reduced crude protein diet had 27% more nitrogen in the feces, 28% less nitrogen in the urine, and 44% less total ammonia loss from the manure. Cole et al. (2005) found that at a dietary crude protein level of 11.5 to 13%, nitrogen excretion and subsequent ammonia volatilization from beef steers was reduced, while maintaining performance levels. Because urinary nitrogen contains 60 to 70% of the total nitrogen excreted (primarily as urea) (Todd et al., 2006; Rotz, 2004), it is the main component affecting ammonia volatilization. These results show that decreasing protein intake will decrease the amount of ammonia volatilized from the manure, and retain more nitrogen in the feces. Reducing the amount of ammonia volatilized from manure can have beneficial effects later in the system when manure is applied to crops by improving the nitrogen: phosphorous ratio.

Animal nutrition has been, and continues to be, studied and researched extensively because profitability for the livestock feeding industry is directly correlated to the well-being and health of the animals, and hence, how effectively animals convert nutrients fed to meat or milk. The ultimate goal of livestock operations is to employ the best-fed ration in order to efficiently convert nutrients fed to tissue protein. Furthermore, protein is usually the most expensive part of an animal's diet. As a result, most commercial cattle feeding companies hire nutritionists to monitor cattle performance and ensure that cattle diets are formulated to maximize efficiency and minimize waste. In addition, feedyards co-locate a feedmill onsite that is able to mix feed to narrow tolerances to maximize accuracy and precision, and minimize waste and costs.

In order to maximize profits, animals must be fed so as to gain weight most efficiently. If the animals are performing to their maximum level, then reducing the level of protein will reduce the efficiency of nutrient utilization and will require them to be on feed longer. This in turn would lead to greater overall nitrogen excretion and volatilization as animals would be fed longer and consume more total nutrients to achieve comparable ends even if the rate of ammonia volatilization were lower.

Altering dietary crude protein to achieve maximum efficiency is a viable BMP that would easily gain acceptance with livestock producers because of its profitability. Continued research should be conducted to further improve the nitrogen utilization of different animal species, and the results of such research should be widely disseminated through the animal feeding industry. However, adoption of a BMP to match dietary crude protein levels to animal requirements is unlikely to reduce overall nitrogen volatilization and subsequent deposition in RMNP because this practice is already widely used by producers. Adoption of a BMP to further reduce dietary crude protein in animal feeding operations may even have detrimental effects on RMNP because animals would utilize the nitrogen in their diets less effectively, requiring more time on feed and therefore emitting more nitrogen over their life cycle.

b. Phase Feeding

Phase feeding is a practice whereby animals are separated by age, sex, and/or stage of growth or production. Animals have different nutrient requirements at each stage of production, and therefore different levels of dietary crude protein are appropriate at each stage. Phase feeding allows more precise matching of dietary crude protein to animal requirements by distinguishing between animals at different production stages. For the reasons mentioned above matching of dietary crude protein to an animal's specific nutrient requirements is desirable to achieve minimum overall nitrogen excretion. Since most of the nitrogen excreted is in a form that is easily volatilized as ammonia, any reduction in nitrogen will decrease subsequent ammonia production. Therefore, phase feeding has been proposed as a BMP for reducing nitrogen volatilization from animal feeding operations.

Most of the animal feeding industry in the United States already practices phase feeding. Beef cattle are most often separated into cow/calf operations, stocker operations, and finishing operations. These operations are often geographically separated and managed by different entities. Dairy cattle are grouped with other animals of similar production stage (e.g. milking cows versus dry cows) so that rations can be adjusted for optimal efficiency. Swine are generally divided by production phase into farrowing barns, nursery barns, and grower/finisher barns. Nutrition and health are managed differently in each stage of production to ensure the highest overall efficiency. Unlike beef cattle and swine operations, poultry operations do not typically move birds as their growth stage changes. However, all the birds in a given barn typically hatch within a few days of each other so that the nutrient requirements of all birds are similar and can be managed effectively.

Again, while phase feeding is a viable option for minimizing overall nitrogen volatilization and subsequent deposition in RMNP, most animal feeding operations already employs this practice. Therefore, adoption of phase feeding as a BMP is unlikely to significantly impact the total contribution of livestock to atmospheric ammonia concentrations.

One sector of livestock production that largely does not practice phase feeding and may, therefore, realize a reduction in nitrogen volatilization by adoption of such a standard is the cow/calf sector of beef cattle production. Often, smaller cow/calf producers do not limit their calving season to the 45-60 day window encouraged by animal scientists because of the additional work and facilities required to maintain herd sires apart from their cowherds for the greater part of the year. The failure of cow/calf producers to limit their calving season leads to varying nutrient requirements of cattle in a single herd and therefore may decrease the overall nutrient utilization of a given herd. However, because cow/calf operations rely on voluntary grazing to meet the majority of their nutrient requirements, it is not expected that a significant impact could be made on nitrogen volatilization from animal feeding operations by encouraging more uniform calving seasons. Furthermore, this practice is already strongly encouraged by Extension specialists for its benefits to management ease and labor utilization.

c. Oscillating Protein Feeding for Ruminants

Research conducted by Cole (1999) found that by oscillating dietary crude protein in lamb diets, animals were able to increase nitrogen utilization resulting in lower nitrogen excretion. However in studies with beef steers, Cole et al. (2003) found that oscillating protein in the diets increased nitrogen retention, but had little effect on overall nitrogen balance compared to cattle fed a consistent protein level. Oscillating protein works by changing the animal's protein intake from a low to a high level every two days. The oscillating protein diet is a new method of feeding and needs further research, but the potential benefits in reducing ammonia appear promising.

Before protein oscillation for ruminants is considered as a BMP, extensive research should be conducted on any specie for which this management practice is being considered, taking into account current production practices and genetics of animals being fed on the Front Range of Colorado. Extrapolation of management practices from one species to another is not recommended. In addition, caution must be taken in concluding that changing dietary protein levels will not affect animal performance.

There must be enough statistical power (i.e. replication) present in a research study given the existing animal variation before it can be concluded that protein oscillation is not detrimental to animal wellbeing. Otherwise, a Type-II statistical error (whereby a significant difference in animal performance is present but not detected due to lack of enough experimental data) can lead to unintended consequences including not reducing nitrogen deposition in RMNP and reducing animal productivity thus jeopardizing many Colorado businesses.

2. Livestock Management

a. Genetic Selection

Nutrient utilization efficiency is largely dependent on genetic traits that can be enhanced by careful genetic selection. Swine and poultry producers in the United States have significantly narrowed the genetic pool of these species in the past several decades, making further gains in nutrient utilization more difficult. However, cow/calf producers still have many options available for improving nutrient utilization through selective breeding. However, unless cow/calf producers retain ownership of their animals throughout the feeding process (which only a very small percentage of cow/calf producers do today), there is little economic incentive or information feedback to select for high feed conversion efficiency when choosing animals.

While genetic selection may increase feed conversion efficiency and therefore reduce nitrogen volatilization in the long run, it is unlikely that any reduction of nitrogen deposition in RMNP would be observed by improving genetic selection for these traits in the near future. Furthermore, the expense and infeasibility of making marked changes in feed conversion efficiency industry-wide, given the expansive and independent nature of the animal feeding industry, make this option unattractive.

b. Feed Additives and Hormones

Use of feed additive and supplemental hormones in animal production has proven to greatly improve nutrient utilization, resulting in more efficient milk and meat production. In cattle, Bovine somatotropin (bst) injections are given to increase milking efficiency, and have been shown to reduce nitrogen excretion by up to 7.8% (Dunlap et al., 2000). Similar feed additives and hormones are available for all species of animals intensively grown in Colorado. Use of such products may decrease nitrogen excretion per day and/or reduce the total number of days on feed, thereby reducing overall nitrogen excretion and subsequent ammonia volatilization.

Further research should be conducted to determine the efficacy of various feed additives and/or hormones on nitrogen excretion by animal species produced in Colorado. Use of such products may prove to be an effective BMP for both reducing nitrogen deposition in RMNP and for increasing profitability of animal feeding operations. If pursued as a BMP, special consideration should be given to account for public health, public preference, and environmental concerns associated with use of such products in animal production.

3. Facility Design and Management

a. Barns

In dairy barns and enclosed swine and poultry barns, ammonia volatilization occurs soon after manure is deposited on the barn floor. The urea in urine mixes with the urease enzyme in feces and rapidly hydrolyzes to form ammonia gas. For poultry, this reaction is slightly slower, as metabolic waste is primarily excreted as uric acid, which must first be converted to urea through aerobic decomposition. The rate of the reaction is a function of mixing time, temperature, relative humidity, and pH of the manure. Each of these factors can be controlled to some degree in enclosed housing and barns.

A simple way to reduce ammonia volatilization from barn floors is by frequent removal of manure. Some studies have found that scraping of barn floors had little effect on ammonia volatilization (Kroodsma et al., 1993; Braam et al., 1997; Moreira and Satter, 2006), as scraping tends to spread and distribute manure over the barn floor surface increasing its surface area and volatilization potential (Kroodsma et al., 1993; Braam et al., 1997). Rather, flushing alleyways with fresh or recycled lagoon water was shown to remove deposited manure and reduce ammonia emissions by up to 70% immediately after flushing (Kroodsma et al., 1993). By increasing the rate of flushing from every four hours to every two hours, further ammonia reductions were seen (Kroodsma et al., 1993).

The use of flushing or scraping of manure as a BMP to reduce ammonia volatilization should be pursued cautiously. The increased water requirements for flushing should be carefully weighed as well as the increased potential for surface and groundwater pollution. Furthermore, a holistic analysis of ammonia emissions from the entire manure management system should be thoroughly researched to determine if decreased nitrogen loss through ammonia volatilization during this stage of management leads to increased emissions in subsequent stages such as manure storage, disposal, or land application. Without such research, significant amounts of capital and labor investments could be made with little net effect on ammonia volatilization.

In Colorado, approximately half of the dairies are free stall facilities with the other half using open lots. Free stall barns house animals in open barns that allow animals to move freely in open alleyways between bedded resting areas and the feeding area. Manure is deposited in the concrete lined alleyways that are regularly flushed or scraped to keep the area and cows clean. Rotz (2004) found that 16% of the total nitrogen excreted is lost from the free stall area while Moreira and Satter (2006) estimated that 37 to 43% of the total nitrogen excreted is lost from the free stall area.

Modifications to the floor surface can reduce ammonia production potential. For example, designing a 3% slope to channel urine away from feces reduces the mixing potential and ammonia volatilization by 21% compared to solid level floors (Braam et al., 1997; Zhang et al., 2005). A double-sloped floor with a urine gutter in the center that traps and channels urine away from feces was shown to reduce ammonia emissions by 50% compared to solid floors (Braam et al., 1997). Another option is to add grooves to the concrete floor that can further aid in channeling urine away from feces, thus reducing ammonia emissions. Adoption of such floor designs as BMPs or building standards in the state of Colorado or through professional organizations such as the American Society of Agricultural and Biological Engineers Standard for “Terminology and Recommendations for Free stall Dairy Housing, Free stalls, Feed Bunks, and Feeding Fences” (ASAE EP444.1, 1999) could prove to reduce nitrogen volatilization in the long term. Again, however, the resulting change in emissions from storage and disposal of urine and/or feces managed in this manner should be explored to ensure that on overall reduction in ammonia volatilization results from such management and design practices.

The use of alternative bedding materials in simulated free stall dairy barns was evaluated by Misselbrook and Powell (2005) who compared ammonia emissions from six different bedding types typically used in dairy barns in the United Kingdom including chopped straw, sand, pine shavings, chopped newspaper, chopped cornstalks, and recycled manure solids. Of these materials, sand is the most prevalent bedding material used by freestall dairies in Colorado. Several producers are also using recycled manure. Misselbrook and Powell (2005) found that physical structure and relative absorbance capacity were the two most important characteristics influencing ammonia emissions from bedding materials. The recycled manure was the most absorbent, retaining 15 times more urine than sand, which was the least absorptive and thus has the lowest ammonia emissions. Recycled manure also had the highest rate of ammonia volatilization. They hypothesized this to be because the urine stayed on the top of the manure surface where it was more susceptible to volatilization. With sand bedding, the urine percolated to the bottom of the pile, reducing the urine-air interface and decreasing ammonia emissions. Pine shavings had the second lowest ammonia volatilization rate followed by chopped straw. Chopped newspaper, chopped cornstalks, and recycled manure all had similar levels of high ammonia volatilization.

In Colorado there are approximately 100 dairies with greater than 700 milking cows. Of these 100 dairies, around half are open lot dairies and the other half are free stall dairies. Approximately 30 of the free-stall dairies use sand bedding materials while 20 use recycled manure solids. There are also approximately 150 dairies with less than 100 animals (approximately 100 open lot dairies, 20 free stall dairies, and 30 open lot/free stall hybrids). Most of these smaller producers use sand bedding. There is no known use of pine shavings, chopped newspaper, or chopped corn stalks as bedding materials in Colorado dairies.

Establishment of a BMP for bedding material may be beneficial, but emissions from bedding materials after they are disposed of should be researched and considered before adopting a BMP to ensure an overall reduction in ammonia emissions is achieved.

One of the most common manure management systems for swine production in the United States is the use of slatted or partially slatted floors that channel urine away from feces. However, an alternative to slatted floors in swine production is a deep litter system. This system uses a deep layer of bedding to separate urine and feces to reduce ammonia emissions. In the litter, a complex process of aerobic and anaerobic degradation occurs, leading to both nitrification and denitrification processes. Groenestein and Van Faassen (1996) found that deep litter bedding reduced ammonia by 50% compared to the use of slatted floors due to denitrification, however the total nitrous oxide losses were greater with deep litter systems, leading to a more negative environmental impact due to emission of greenhouse gases.

Addition of surface amendments to flooring and litter in animal barns has shown promise for reducing ammonia emissions from livestock barns. DeLaune et al. (2004) found that alum reduced ammonia emissions from poultry litter by 62% over unamended litter. Similar amendments may be considered for control of ammonia emissions from litter from swine buildings.

Heber et al (2005) found that daily spraying of soybean oil in a tunnel-ventilated swine finishing barn reduced ammonia emissions in the barn by 40% compared to a similar control building adjacent to the treatment facility. While this study should be repeated by others to verify the results and the implications on the quality of flush water from such a system analyzed, such a system appears promising.

Wet manure usually has a greater potential for ammonia volatilization than dry manure. By drying manure to less than 40% moisture content, both urease activity and ammonia loss are reduced (Sommer and Hutchings, 1995). Management practices such as the use of a manure spreader in drylots, or manure scrapers in barns speed drying of the lot or barn surface. However, caution needs to be taken when spreading wet manure, as an increase in manure surface area and air contact will increase the ammonia volatilization potential. The rate of air movement across the surface of the manure also influences the rate of ammonia volatilization by removing the ammonia produced on the surface of the manure and drawing more ammonia from deeper layers, thus allowing the process to continue. It is unclear, then, whether spreading of manure will increase or decrease overall ammonia volatilization.

The rate of ammonia production from manure is very rapid, but can be altered with variations in temperature. Below a temperature of 10º C, urease activity is very low, but activity increases exponentially at higher temperatures (Rotz, 2004; Zhang et al., 2005). At 30º C, essentially all urea in urine is hydrolyzed as ammonia within six hours of deposition to the barn floor (Muck, 1981). Smits et al. (1995) found that an increase in animal enclosure temperature from 10 to 24º C resulted in a 46% increase in ammonia emissions. By reducing the temperature in barns, ammonia volatilization can be reduced. Temperature can be controlled with swamp coolers in arid areas or naturally by allowing more natural ventilation to circulate through bans in the winter months. However, barn temperatures are generally controlled to optimize animal comfort and therefore feed conversion efficiency. Therefore, while reducing barn temperatures may decrease the amount of ammonia volatilized, it is likely that animal performance will be adversely affected thus increasing the number of days on feed.

Removing ammonia from the exit air of enclosed barns with bio-filters can reduce atmospheric ammonia emission from barns (Hilhorst et al., 2002; Melse and Ogink, 2005). Melse and Ogink (2005) reported that the use of acid scrubbers and biotrickling filters removed ammonia from the exit air or swine and poultry barns with a removal efficiency of 96 and 78%, respectively. While use of scrubbers is not currently economically feasible, biofilters are being successfully employed in some animal feeding operations in North Carolina. Research into a more economically feasible scrubbing mechanism may be helpful in reducing ammonia emissions from livestock production barns.

b. Drylots

Substantial amounts of ammonia are emitted from the surface of dry lots in beef cattle feedyards and open lot dairies. Volatile ammonia emission from dry lots can be up to 70% of the total nitrogen excreted. Increasing the frequency of pen scraping can reduce ammonia volatilization from the dry lot surface. However, additional research is needed to determine whether emissions from storage and disposal of pen scrapings are affected by the frequency of manure harvest. It is likely that higher nitrogen concentrations in more-frequently harvested manure may result in greater emissions during subsequent steps in the manure management processes if those steps are not also amended to limit ammonia volatilization.

The pH of the soil surface greatly affects the rate of ammonia volatilization. If the soil is acidic (pH below six) ammonia will be found primarily in its ionic form, ammonium, and volatilization will be low. At a higher pH (above eight) ammonia will volatilize rapidly from the soil surface. A variety of surface amendments to reduce soil pH have been tested on feedlot and dairy pen surfaces to assess the ability of amendments to decrease ammonia emissions. Aluminum sulfate (alum) has been shown to be the most effective additive in reducing the surface pH and ammonia emissions (Shi et al., 2001; DeLaune et al., 2004). In a laboratory study, Shi et al. (2001) found that alum reduced cumulative ammonia emissions by 98% over a 21-

day period. They also reported that calcium chloride was an effective amendment, reducing cumulative ammonia emissions by 77%. While surface amendment studies are successful in laboratory settings, they seem to have less success in field application, losing effectiveness over a short period of time and showing variable results. This is probably due to reapplication of manure on treated pen surfaces and animal hoof action breaking and removing the pen surface crust.

In addition to surface amendments that reduce the pH, enzymatic treatments can be used to inhibit the hydrolysis of urine urea to ammonia by the urease enzyme in feces. While enzymatic treatments are not as efficient as acidifiers in decreasing ammonia emissions, Shi et al. (2001) found that enzymatic treatment with the urease inhibitor NBPT (N-(n-butyl) thiophophoric triamide) could reduce cumulative ammonia emissions by 65%. They also found that on a benefit-to-cost ratio, the NBPT treatment to feedlot surfaces was more cost effective than alum treatment, yet it was still an expensive amendment for a producer to utilize. Varel et al. (1999) found that the addition of NBPT to cattle pen surfaces reduced the amount of ammonia volatilized by retaining the urea in the manure. After 11 days, however, they began to see hydrolysis of the urea and subsequent ammonia volatilization and by day 28 all the urea had volatilized as ammonia. It was speculated that this was due to chemical breakdown of the urease inhibitors, requiring more frequent application to maintain effectiveness. An efficient, lasting, and cost effective surface amendment to reduce ammonia emissions still needs to be found. Currently, surface amendments may be effective on a small scale, but this has little practicality in the current large-scale livestock industry.

When considering BMPs to reduce ammonia volatilization from open surfaces it should be remembered that controlling volatilization on the pen surface does not necessarily mean that volatilization is eliminated. BMPs that are recommended in the nitrogen management plan must look at the nitrogen cycle and manure management holistically, focusing on strategies that will reduce overall emissions rather than shift the problem to another stage of the system or to water quality issues from nitrogen runoff.

4. Wastewater Management

In dairies and swine operations, wastewater is often stored in lagoons where microbial treatment occurs and from whence it can be recycled to flush alleyways and barns or land applied through irrigation systems. The rate of ammonia volatilization from lagoons will vary with temperature, nutrient load, pH, the presence of a cover or crust on the surface, and the aerobic/anaerobic status (treatment) of the lagoon. After solid separation, 75% of the total nitrogen in collected manure goes into the lagoon with the liquid portion of the influent (Rotz, 2004). At a typical lagoon pH of 7.0-7.6 throughout the year, up to 60% of the total nitrogen can be volatilized as ammonia (Rotz, 2004). A portion of the remaining nitrogen in solution is either lost as nitrous oxide and nitrogen gas following nitrification/denitrification, or retained in the lagoon as nitrate or other non-gaseous nitrogen compounds (Harper et al., 2000).

Aneja et al. (2001) found a strong correlation between ambient temperature and ammonia flux from the surface of swine lagoons. Aneja et al. (2001) reported that the greatest emission of ammonia was in the summer months, which accounted for up to 60% of the total yearly flux. Safley and Westerman (1992) found similar results from dairy waste lagoons. Conversely, the lowest ammonia volatilization was observed in the winter when microbial activity in the lagoon was dormant in cold climates.

In some areas of the United States, producers are encouraged to allow ammonia volatilization from lagoons in order to reduce the nitrogen load seen by surface waters after land application of effluent. Caution should be taken when adopting BMPs to reduce nitrogen volatilization from lagoons to ensure that surface water quality is not detrimentally impacted. Where reductions of gaseous nitrogen emissions from lagoons are desirable, several ideas have been proposed to reduce ammonia volatilization from lagoons including:

a. Lagoon Acidification

If the pH of the lagoon is maintained above 8 (basic), ammonia volatilization increases and may be up to 70% of the total nitrogen entering the lagoon (Rotz, 2004). At a pH below 6 (acidic), ammonia is bound in solution in its ionic ammonium form and little ammonia volatilization will occur (Aneja et al., 2001). Achieving a low pH requires the addition of acidifying compounds such as alum, citric acid, or nitric acid to the lagoon. Positive results have been found in reducing ammonia emissions from small-scale waste confinement and laboratory studies, but large-scale studies are limited due to cost and feasibility of the method on production-scale livestock operations. In addition, low pH reduces the efficacy of anaerobic lagoons and may increase odor.

The acidic nature of treated lagoon water can be detrimental when applied to crops. Lefcourt and Meisinger (2001) showed that acidifying agents like alum have been shown to reduce ammonia volatilization from dairy slurry by 58%, but increased soluble aluminum in solution, which led to soil acidity when slurry was applied to land. The addition of zeoilite as an alternative slurry additive was shown to reduce ammonia emissions by 50% by sequestering ammonium-N, which could be a good source of slow-release nitrogen for plants. In Colorado, where soil is generally basic and has a good buffering capacity, the additional acidity of the slurry may be beneficial when applied to pre-emergent fields, but caution must be taken when applying acidic wastewater to fields where plants may be damaged and growth inhibited. Additional research should be conducted to determine the minimum pH of wastewater than may be applied to various crops cultivated in Colorado without inducing plant stress or damaging plant tissues while keeping in mind the cost, safety hazards, and possible environmental impacts associated with such practices. For example, the use of sulfuric acid to overcome pH buffering will add sulfates to the water, which are a regulated pollutant.

b. Lagoon Aeration

Most animal waste lagoons are anaerobic in nature, and therefore most nitrogen entering the lagoon is lost as volatilized ammonia or nitrous oxide due to nitrification and denitrification processes (Harper et al., 2000). Aeration of lagoons may reduce nitrogen volatilization by promoting oxidation, which converts ammonia to nitrate. Aerobic treatment of swine slurry has been shown to reduce odor and total nitrogen by 56% after four days of aeration (Sneath et al., 1992), which may decrease gaseous emissions from land application of the lagoon effluent. Even the intermittent use of aerators in swine lagoons has been shown to reduce total nitrogen and odor, and operating costs (Yang and Wang, 1999; Zhang and Zhu, 2005). However, aeration has been shown to increase ammonia emissions from aerobic lagoons under some conditions (Park et al., 2005; Amon et al, 2005).

Rarely, however, are livestock waste lagoons totally aerobic, as aeration is difficult to achieve in a livestock lagoon due to the high solids and protein content in the slurry (Cumby, 1987) and costly energy inputs for aerators.

Reports on the efficacy of aeration at reducing ammonia emissions are mixed. Rumburg et al. (2004) installed commercial aerators in a dairy lagoon and found no change in ammonia emissions stating that the aerators failed to introduce enough oxygen into the lagoon to degrade the ammonia. Due to the high oxygen demand of the nutrient rich solids in a lagoon, it is difficult to provide enough oxygen (1-2 mg/L) to achieve proper aeration in a waste lagoon (Cumby, 1987; Rumburg et al., 2004). The process of aeration can even be counter-productive, raising the pH of the lagoon, and actually inhibiting nitrifying bacteria and promoting ammonia volatilization (Zhang and Zhu, 2003). More research will be needed to determine the conditions under which aeration reduces gaseous nitrogen volatilization before it can be effectively employed in Colorado to reduce ammonia emissions from livestock operations.

c. Stratified Lagoons

Ammonia volatilization may be reduced by use of a facultative or stratified lagoon, which has an aerobic top layer to reduce ammonia and odor emissions, and an anaerobic bottom layer to promote microbial breakdown of solids and nutrients. Stratification is achieved by mechanical circulation/aeration of the top layers of the lagoon or can occur naturally in swine lagoons where solids are low, in secondary dairy lagoons, or overflow lagoons with low solids content and nutrient load (Cumby, 1987). According to Cumby (1987) lagoons that were partially aerated or circulated tended to cultivate nitrifying bacterial populations that helped reduce ammonia in the lagoon water by oxidizing ammonia to nitrite and nitrate. In order for this process to take place, the lagoon must be kept at a pH between 7 and 8 to maintain bacterial populations and minimize ammonia volatilization. Formation of a stratified lagoon requires more intensive management, and more research needs to be conducted to quantify the efficacy of lagoon stratification for abatement of gaseous nitrogen loss.

d. Lagoon Covers

The rate of volatilization from the surface of a lagoon relies on environmental factors such as ambient temperature, relative humidity, surface wind velocity, and precipitation. The addition of a lagoon cover can reduce uncontrollable variables and reduce unwanted emissions. A cover can be composed of floating plastic, a synthetic or natural cover of peat, straw, or polystyrene, or a natural cover formed by the presence of dry matter in the lagoon. When working properly, any of these covers can reduce nitrogen losses by 80-90% (Rotz, 2004), but any cracks in the cover will greatly reduce this efficiency. Misselbrook et al. (2005) found that the formation of a natural crust on the top of lagoons decreases ammonia emissions by up to 50%. Crust development occurs as a result of solids in the lagoon being carried to the surface by methane or carbon dioxide gas bubbles generated by microbial degradation of the organic matter in the lagoon. Evaporation at the surface of the lagoon promotes the drying of the solids and formation of the crust. The formation of a natural crust will occur when the lagoon has high solids content, the ambient air is dry, and there is little precipitation to break the crust, as in Colorado.

When considering the use of lagoon covers as a BMP to reduce ammonia volatilization, the economic impact and feasibility of retrofitting existing lagoons should be taken into account.

e. **Effluent Use**

Effluent from wastewater lagoons may be applied to fields or recycled for flushing alleys and pits in barns. When lagoon effluent is used as flush water for barns, the remaining nitrogen retained in the lagoon water is returned to the barns and usually volatilized as ammonia. Thus, with a recycling system, the nitrogen loss potential is near 100%. If the lagoon water is used for irrigation, this volatilization potential is less (about 50%) due to nitrogen application to fields (Rotz, 2004) and uptake by plants. While reducing the amount of lagoon effluent may reduce gaseous ammonia volatilization, it will increase the amount of fresh water use at animal feeding operations and increase nitrogen loads to surface waters. Again, caution should be taken when adopting BMPs to reduce nitrogen volatilization from lagoons to ensure that surface water quality is not detrimentally impacted.

f. Wastewater Runoff

An impoundment or wastewater runoff control structure located at open lot beef cattle operations should not be confused with wastewater treatment lagoons used at dairies and swine facilities. The runoff control structures are not designed for wastewater treatment and only serve to impound process wastewater until it can be land applied to agricultural land at agronomic rates. Runoff control structures tend to be much larger in size and experience greater fluctuations in levels than treatment lagoons. Little, if any, research has been done to characterize ammonia emissions from wastewater runoff control structures. Therefore, there is currently no baseline against which to measure the efficacy of any management practices intended to reduce emissions from these structures.

Application of management practices that have been tested for treatment lagoons to runoff control structures is largely infeasible. Open lot beef cattle feedyard runoff control structures do not develop a natural crust, and extreme variation in water levels and the surface area of such structures would make design and use of an effective cover difficult. Feedyard runoff control structures are circulated and aerated to some extent naturally with wind and wave action. Again, because emissions from these sources are thus far uncharacterized, there is no standard against which to measure the effectiveness of abatement measures. Therefore, research should be conducted to characterize emissions from runoff control structures.

5. **Manure Storage**

Retention time of manure scraped from animal feeding facilities, until it is disposed of, varies from facility to facility. Many facilities remove manure scraped from pens or barns immediately after scraping. Some, however, may store manure for periods of time or compost manure for land application at a later date. Of the total nitrogen entering manure storage as compost or manure piles, 20 to 50% is lost during ammonia volatilization[wbf2], and the remaining nitrogen is converted to products of nitrification/denitrification or immobilized. Few ideas have been proposed to reduce volatilization of ammonia from dry manure storage piles. Amendments such as alum have been proposed for reducing ammonia from poultry manure piles prior to incorporation or surface application. Kithome et al. (1999) found in laboratory experiments that calcium chloride applied at 20% by mass reduced the ammonia volatilization from composting poultry manure by 90%, whereas a 20% alum application by mass reduced ammonia volatilization by 28%. Unlike alum, the calcium chloride treatment works primarily due to microbial inhibition, rather than by reducing pH, thus having a greater impact on the entire manure pile. DeLaune et al. (2004) concluded that surface application of alum to litter piles, rather than incorporation into the pile was more effective at reducing ammonia volatilization from litter compost piles. Similar research is needed for manure storages piles for species of animals produced in Colorado. Furthermore, because a limited amount of data exists for these sources, more research is needed to determine the contribution of these sources to ammonia volatilization.

7. Land Application of Manure

Manure and/or effluent from animal feeding operations are most often disposed of by land application. Nutrient rich manures and effluents provide a valuable source of essential nutrients to cropping systems and over time can increase soil organic matter. However, significant gaseous nitrogen emissions can result from land application of manure, especially if application is not managed carefully.

As noted previously, the rate of ammonia volatilization is a function of temperature, relative humidity, and wind speed. The rate of ammonia loss increases exponentially with increasing temperature (Sommer, 2001), and increases with increasing wind speed up to about 2.5 meters per second. Therefore, application of manure during cool weather will decrease the amount of ammonia volatilized from the manure (Amon et al., 2006). Precipitation also decreases the rate of ammonia volatilization by binding ammonia in the aqueous phase and moving it into the soil (Rotz, 2004). However, in several studies elevated rates of ammonia release have been observed during the days after rain events during which time some of the aqueous ammonia is volatilized (Hutchinson et al, 1982; Sharpe and Harper, 2002). Furthermore, it is not always feasible to apply manure or effluent at times of optimal meteorological conditions. For example, beef cattle manure from cattle feedyards in Colorado is generally land applied two times per year. One window of manure application is after the winter small grains' harvest in the spring, and the second is after the summer crop harvest in the fall. The reason that manure is not land applied more consistently throughout the year is because it cannot be applied to a growing crop because it would physically damage the crop mechanically and through salt contact with plant tissue. Manure trucks have to drive through the field to spread the manure, and it is then usually plowed into the soil to reduce nutrient loss. Since manure is land applied in a very small window of time, it is not realistic to think that manure will be applied only when meteorological conditions are favorable for minimal ammonia loss.

Prior to land applying manure and/or process wastewater, manure from dairies and swine operations, is stockpiled or held in lagoons. Manure composition varies between animal species and manure type, which is also a function of the method of manure storage. Manure may be stored either in solid form (greater than 15% dry matter), slurry form (7-15% dry matter), or as a liquid (less than 7% dry matter). Solid manure storage is typical used at drylot operations or when bedding is used to absorb manure. Slurry is commonly used on dairies where feces, urine, and wash water are combined. Liquid storage in lagoons is common on large dairy, swine, and poultry production operations (Rotz, 2004). It is important to note that manure storage options that reduce ammonia emissions frequently lead to greater ammonia volatilization during disposal or land application (Amon et al., 2006).

Manure and soil should always be analyzed for nutrient content prior to application of manure or effluent to crop lands so that application rates can be properly matched to nutrient needs. Excess nitrogen in the soil may be lost via dentirification or volatilization. Denitrification inhibitors have been used to mitigate emissions with mixed success (Rotz, 2004), but application of appropriate amounts of nitrogen through soil and manure nutrient testing is a more long-term, proven solution. It should be noted that Colorado's Confined Animal Feeding Operations General Permit regulations already require soil sampling and nutrient budgeting to meet crop needs. They also require that manure and effluent be applied to agricultural land in such a fashion as to not generate runoff of manure or effluent or even create ponding or puddling.

Slurry pretreatment before application may reduce ammonia emissions after the slurry is applied, but to evaluate the net environmental benefit, the processes must be considered together. In a comparison of manure pretreatment on ammonia volatilization after application (40 m^3 ha^{-1}), Amon et al. (2006) found that the majority of ammonia emission occurred during application of slurry rather than storage. The amount of ammonia volatilized during field application was directly correlated to the amount of ammonia that was retained during storage. The less ammonia emitted during the storage period, the more ammonia that was emitted during field application. Of the storage methods, the liquid portion of separated manure (manure with solids mechanically removed) had the highest ammonia volatilization (81%) during storage, followed by aerated dairy slurry, which emitted 50% during storage. Consequently, separated manure slurry had the lowest ammonia volatilization during application (19%). The other manure treatments including anaerobic digestion, aerated, and untreated slurry had greater than 50% of the ammonia emissions volatilize after surface application through band spreading simulation. When both field and storage emissions were considered together, the untreated manure and anaerobically digested manure had the lowest total ammonia emissions (226.8 and 229.9 g NH_3 per m^3), while the emissions from separated and aerated treatments were nearly double that (402.9 and 422.0 g NH_3 per m^3). Authors noted that aeration can reduce the dry matter content of the slurry, thus reducing volatilization, but the total nitrogen lost in the aeration process counteracts the reduction in loss of applied nitrogen (Amon et al., 2006).

Reducing manure pH is another method for reducing ammonia volatilization (Sommer and Hutchings, 1995). By lowering the pH below 6.5 with sulfuric or nitric acid treatments, ammonia emissions were reduced up to 75%. Acidification can also be achieved by amendments of alum or ferrous sulfate (Rotz, 2004). Over application of acidified manure to soils, however, may decrease the soil pH. Initially, the soil will buffer the pH change causing little impact on plant growth, but eventually a pH change will occur and may decrease crop productivity. No economic feasibility studies were found to demonstrate the possibility of implementing this technology to reduce volatilization.

Ammonia volatilization from land-applied slurry is related to the slurry dry matter content and is dependent on the pre-treatment of the manure before application. Ammonia volatilization is generally proportional to the ammonia content of the manure, and generally increases with increasing dry matter content up to 12% (Rotz, 2004). The lower the dry matter content, the more quickly the slurry infiltrates into the soil (Rotz, 2004). Lowering the dry matter content by 50% (or diluting the manure), however, will double the amount of manure handled, since liquid addition will increase the volume of manure.

Generally, manure and/or effluent is applied to soils by overhead irrigation, broadcast spreading, band spreading, trail hose, or injection. The application method chosen depends on the method of storage (solid, slurry, or liquid) and on equipment availability. Because ammonia volatilization from liquid manure is dependent on the surface-air interface, reducing the size of slurry droplets when applying effluent via irrigation systems will increase ammonia volatilization during application by increasing the specific surface area of the droplets exposed to the air (Sommer and Hutchings, 2001). Practices aiming to reduce ammonia volatilization during liquid application of slurry should therefore reduce exposure time and increase slurry droplet size. Incorporation of manure and/or effluent soon after application to land where crops are not already established may also reduce interaction between applied wastes and the air, thus reducing ammonia volatilization.

Rotz (2004) reported that overhead irrigation (i.e. sprinklers) generally had the highest rate of ammonia volatilization compared to broadcast spreading, band spreading, and injection. With sprinkler irrigation, a portion of the total nitrogen is volatilized in the air as ammonia before the liquid manure reaches the soil surface. Broadcast application of slurry and cattle or swine manure also resulted in high ammonia losses (20 to 30% of total N). These loss rates, however, were highly variable with application to grassland versus heavy crop residues, which tended to increase ammonia loss by 30 to 50% due to increased urease activity in plant residues compared to soil.

Next to irrigation, broadcast spreading with a splash plate is the least expensive method of applying both slurry and liquid manures, while solid manures are applied with a broadcast spreader (Sommer and Hutchings, 2001). Band spreading is an alternate form of manure application and is primarily used on grasslands or on established crops. With well-formed bands, nitrogen loss can be reduced by 30 to 70% compared to broadcast spreading. Studies using wider bands that cover more surface area, however, have shown this method to be less effective than those with narrow bands (Rotz, 2004).

Due to the volatile nature of ammonia, incorporation of slurry into the soil immediately after application is an effective means to reduce ammonia emissions (Malgeryd, 1998; Sommer and Hutchings, 2001), and the deeper the incorporation, the less the emissions (Sommer and Hutchings, 2001). Slurry injection is effective for reducing nitrogen loss both during and after application (Rotz, 2004). Rotz (2004) found that slurry applied by shallow injection and deep injection (>10 cm depth) both demonstrated low ammonia losses (8 and 2%, respectively), but deep injection may cause root damage in grassland or established crops. Open slot injection leaves some slurry uncovered, which may increase ammonia volatilization compared to closed injection. Comparing injection techniques, Rodhe et al. (2006) found that injection in closed slots resulted in no detectable ammonia emissions. Due to increased nitrogen retention by the soil and low oxygen conditions at the injection site, injection may cause greater leaching and denitrification if application is not timed to match crop nitrogen needs or occurs prior to significant precipitation. Closed slot injection may be considered as a BMP for utilization of slurry waste in areas where groundwater quality will not be adversely affected by nitrate leaching.

Care must be taken when recommending BMPs for land application of manure and/or effluent because specific regulations are already in place guiding the land application of manure and effluent at both the state and national levels. Additional recommendations must mesh with those currently in place.

7. Pasture Management

The majority of ammonia losses on pasture are from urine (55 to 75%) (Van Horn et al., 1996), while emissions from feces are only about 5% of total fecal nitrogen (Rotz, 2004). Avoiding overgrazing with proper pasture management will help reduce the amount of ammonia emitted from urine spots by increasing plant cover and nitrogen uptake. Soil conditions will also influence ammonia volatilization with greater rates of emission occurring during dry, hot weather (Jarvis et al., 1989).

II. Domestic Area Sources of Ammonia Emissions

Any comprehensive strategy developed to address nitrogen deposition in RMNP should include consideration of all potential sources of ammonia emissions including nitrogen applications in urban environments such as lawn and turf applications to parks, golf courses, recreational fields and open spaces.

Any reasonable discussion of potential nitrogen volatilization sources should be contemplated in recognition of major trends impacting agriculture and urban users of nitrogen fertilizers. For example, over the period of the RMNP study, ammonia use for agricultural production has dramatically decreased, while urban development, corresponding water treatment volatilizations, and acres of turf requiring fertilization maintenance have dramatically increased.

Recent demographic trends show a decrease in the amount of lands dedicated for agricultural production, and at the same time show an increase in the developed landscape within our state. Between 1990 and 2000, the nine counties of the Denver metropolitan area added 555,700 people and 203,700 new households. During the 1990s, this nine county region, including Boulder, Gilpin, Clear Creek, Jefferson, Douglas, Arapahoe, Adams, Denver and Broomfield, alone, added 90 square miles of urban area, growing from 410 square miles in 1990 to 500 square miles by 2000. Of the more than 200,000 new households added to the region, 45 percent located in areas not previously urbanized. (DRCOG: www.drcog.org/drisin/urbangrowth.htm.) Further, Weld County, the state's highest grossing county, and the fifth highest grossing county nationally in agricultural sales, lost 271,491 acres of agricultural land between 1987 and 2002. (*Losing Ground: Colorado's Vanishing Agricultural Land,* Environment Colorado Research and Policy Center, March 2006)

As the state's population grows and pressures on agricultural resources such as land and water mount, these trends are anticipated to continue for the foreseeable future. It is predicted that by 2022 Colorado will lose another 3.1 million acres of agricultural land to urban sprawl. (*Losing Ground: Colorado's Vanishing Agricultural Land*, Environment Colorado Research and Policy Center, March 2006)

Associated with these shifts in landscapes are obvious differences in land use as well as environmental impacts. For example, loss of open space and increase in surface development leads to water quality degradation. Air quality can be impacted by increases in population and longer commute times. Additionally, land that was once managed on a cost-effective production basis is now managed primarily for aesthetics and "playability". It is estimated that one-quarter to one-third of urban areas are in turf as lawns, open spaces, parks, and golf courses. These areas are no longer managed for agricultural production, but rather as areas that beautify ones home or neighborhood or in the larger picture, the entire city. Lawns, parks, and golf courses consume large amounts of water as well as require significant amounts of fertilizer to help them stay a lush green. Volatilization of ammonia from urban nitrogen use fertilizer use and re-treatment of run-off wastewater should be included in any comprehensive approach to managing ammonia emissions and its subsequent deposition in sensitive areas such as RMNP.

It is worth noting that the primary nitrogen compound used in the commercial lawn care industry today is urea, one of the most volatile forms of nitrogen fertilizer. Urea is favored due to characteristics that minimize "burn" or grass leaf browning when applied. Application practices often do not consider nitrogen volatilization of urea into the atmosphere. For example, commercially applied urea is not necessarily applied in a manner that allows for timely water management to minimize volatilization, such as being applied on designated "watering days" or immediately before a watering.

It is also commonly recognized that application rates of fertilizer on urban landscapes may be significantly higher than the label recommendation or sound agronomic practices dictate. Homeowners and do-it-yourselfers are typically unlicensed, unregulated, and generally unaccounted for in estimates related to potential nitrogen volatilization.

At the same time the developed footprint in our state is increasing, the number of acres in agricultural production and subsequent fertilizer use, particularly the use of anhydrous ammonia, has been dramatically decreasing. Changes in agricultural application methods and increased efficiencies recognized by the agricultural industry have led to decreased amounts of fertilizer needed for production. Additionally, nitrogen fertilizer is a significant portion of an agricultural operator's production cost so producers must weigh their cost of production for profitability purposes, a factor of much less significance to the typical urban homeowner.

III. Point Sources of Ammonia Emissions

The 2006 Colorado point source ammonia emission inventory is estimated at 817 tons per year (<1% of anthropogenic sources) from 94 sources. Stationary sources are not obligated to report ammonia emissions, thus it <u>is likely that ammonia emissions are under-estimated</u>.

The top 10 sources emit 84% of the point source ammonia emissions statewide. Several of these sources emit ammonia as a consequence of controlling nitrogen oxide emissions from combustion turbine generators (CTG) with the use of selective catalytic reduction (SCR). Two of the top 10 sources are water treatment plants with ammonia emissions of 261 tons per year. Changing the water treatment process by retrofitting or installing covers may significantly reduce ammonia emissions from these sources by up to 90%. The cost of installing covers over water treatment facilities is difficult to determine since it is site specific. Also, the recent changes to Colorado's surface water quality standards may require treatment facilities on warm water segments to reduce ammonia concentrations in their discharge thus increasing gaseous ammonia emissions.