Ammonia Emissions from Cattle-Feeding Operations Part 1 of 2: Issues and Emissions

AIR QUALITY EDUCATION IN ANIMAL AGRICULTURE

Issues: Ammonia
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This publication discusses how ammonia emissions from cattle-feeding operations impact animal and human health, and the environment.

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Ammonia (NH_3) is a lighter-than-air, colorless gas with a recognizable pungent smell. It is a source of the essential nutrient nitrogen for plants and animals, but also is classified as a hazardous substance by the U.S. Environmental Protection Agency (EPA). Ammonia occurs naturally and is normally found in trace amounts in the atmosphere where it is the dominant base, combining readily with acidic compounds. It is produced by the decomposition or fermentation of animal and plant matter containing nitrogen, including livestock manure. There is concern about ammonia because of its potential to negatively affect air and water quality, and human and animal health.

Sources and Emissions

Concentrated animal feeding operations (CAFOs) import feed ingredients that contain large quantities of nutrients such as nitrogen. Cattle retain a proportion of the nitrogen they consume, but approximately 70-90 percent is excreted in feces and urine (Cole et al., 2008a). Ammonia is produced by breaking down nitrogenous molecules in manure, such as urea and protein. Urea in urine is rapidly converted to ammonia and is a major ammonia source in manure, while more complex nitrogen-containing compounds, such as proteins, are decomposed more slowly by microbes.

Historically, ammonia was considered a problem only within livestock buildings with inadequate ventilation or poor management. High ammonia levels negatively affect animal health and production, and threaten the health of humans working inside. Correcting ventilation problems and periodically removing animal waste reduces ammonia levels within the building, but these measures do not address the problem of ammonia emissions into the atmosphere. Ammonia emissions to the atmosphere from open-lot CAFOs now also must also be addressed.

Ammonia begins to volatilize (convert to a gas and be lost to the atmosphere) almost immediately after urea is excreted. The loss can continue as manure is handled, stored, or land-applied as fertilizer. As an essential plant nutrient, nitrogen is a primary component of fertilizer; nitrogen lost to the atmosphere from manure by ammonia volatilization is a loss of fertilizer value.

Ammonia in the atmosphere eventually returns to the Earth. Ammonia deposition occurs when ammonia in the atmosphere is deposited as gas, particulates, or in precipitation onto surfaces such as soil or water. Ammonia deposition on nutrient-starved farmlands may be beneficial to crops; however, deposition in sensitive areas may be undesirable.

The complexity of biological and chemical processes, coupled with management decisions, complicates the understanding of ammonia emissions from livestock operations. Differences in livestock digestive systems, diets fed, feed and manure management systems, facility design, location, and weather are just a few of the factors that affect ammonia sources and emissions.

Ammonia in the atmosphere eventually returns to earth. Ammonia deposition in sensitive areas may be undesirable.

Environmental Concerns

Undesirable ammonia deposition may occur locally as dry deposition when ammonia is transferred to sensitive land and water surfaces by air currents or at longer distances as wet deposition. Ammonia deposition can harm sensitive ecosystems when excessive nitrogen stimulates excessive growth of algae in surface waters or weeds in fields or pastures. When algae growth dies, its decomposition consumes oxygen, resulting in hypoxia (low oxygen) in aquatic environments.

For example, the hypoxic "dead zone" near the mouth of the Mississippi River is caused by excess nitrogen and phosphorus carried by the river into shallow coastal waters. This process of eutrophication is characterized by significant reductions in water quality, a disruption of natural processes, imbalances in plant, fish, and animal populations, and a decline of biodiversity.

Sensitive terrestrial ecosystems may experience excessive weedy plant growth, which outcompetes more desirable native species (Todd et al., 2004). Ammonia deposited in soil can undergo nitrification, which converts ammonia to nitrate, which is mobile in water. This chemical reaction lowers (acidifies) the pH of soil (Myrold, 2005). Forests in the humid eastern United States are especially susceptible to soil acidification, which can cause winter injury, loss of tree vigor, and decline of desirable species.

The National Atmospheric Deposition Program (NADP, 2007) and the Clean Air Status and Trends Network (CASTNET) are excellent sources of long-term deposition data. Multiple monitoring stations are located in strategic areas across the United States to monitor and document wet and dry deposition of ammonium, nitrates, and other pollutants. Data from NADP and CASTNET are available online at *http://nadp.sws.uiuc.edu/* and *http://www.epa.gov/castnet/*, respectively.

Human Health Concerns

Ammonia can significantly contribute to reduced air quality when it reacts with sulfur dioxide or nitrogen dioxide in the atmosphere to form aerosols. Aerosols, also known as particulate matter (PM), are atmospheric particles that are classified by the EPA according to their aerodynamic diameter.

Figure 1. Ammonia emissions to the atmosphere from open-lot CAFOs have the potential to negatively affect environmental quality and animal health.

Respirable aerosols are particles that can be deeply inhaled into the lungs and have a mean aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$). $PM_{2.5}$ poses a threat to human health because it is associated with respiratory symptoms and diseases that lead to decreased lung function and, in severe cases, to premature death (EPA, 2009). Aerosols also reduce visibility in air, diminish irradiance, affect cloud formation, and alter the ozone layer (Romanou et al., 2007; Chin et al., 2009).

Ammonia deposition can contaminate drinking water by increasing the nitrate concentration. This may occur by direct deposition onto water bodies, or indirectly by leaching of nitrogen from soils or erosion of nitrogen-laden soil particles into surface water.

Odor implications of ammonia are localized to regions in the vicinity of the CAFO. Ammonia is easily recognized by its smell, but is seldom associated with nuisance odor complaints near CAFOs any more than other manure constituents such as sulfides, cresols, or volatile fatty acids. Ammonia readily disperses from open lot feedyards and dairies, which helps to reduce its odor intensity to below human detection thresholds. Ammonia odors tend to be more noticeable inside animal barns than in open lots and are greater on or near CAFOs than at more distant off-site locations.

Measuring Ammonia

Two categories of air quality measurements are commonly applied to ammonia at or near CAFOs: ambient concentrations and emission rates. Ambient concentrations are measurements of the ratio of ammonia to air in the atmosphere, usually measured in parts per million by volume (ppmv), parts per billion by volume (ppbv), or micrograms per cubic meter ($\mu g/m^3$). Accurate measurement of the atmospheric concentration in a large mass of dynamic, open air is difficult and requires special instrumentation and/or significant labor inputs.

Emission rates quantify ammonia flux from surfaces to the atmosphere and are reported in units of mass per unit area per unit time as in kilograms per square meter per day ($kg/m^2/day$), and also in units of mass per unit animal per unit time such as kilograms per thousand head per year (kg/1000 hd/yr).

Measurement of ammonia emissions from nonpoint sources such as CAFOs is also difficult because once produced, ammonia quickly volatilizes and is dissipated by air currents. Quantifying ammonia flux from the feedyard surface to the atmosphere relies on direct measurement using fast-response instrumentation, or on a flux model, which attempts to accurately predict the dispersion of gases and particulates through turbulent air. Further, emissions will vary depending on the type of surface (pens, lagoons, buildings) and the nature of processes at individual facilities.

Two categories of air quality measurements are commonly applied to ammonia at or near cattle feedyards: ambient concentrations and emission rates.

Regulatory Issues

Federal reporting requirements (EPCRA)

Ammonia emission is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-To-Know Act (EPCRA). In December 2008, the EPA published a final rule that exempted CAFOs from reporting ammonia emissions under CERCLA. However, under EPCRA [40 CFR §355 App A], CAFOs are required to report ammonia emissions in excess of 45 kilograms (100 pounds) per day. Despite the challenges in accurately measuring ammonia emissions from CAFOs, an estimate of the lower and upper bounds can be calculated based upon animal headcounts and research-based figures for average emission rates per head. Noncompliance with the EPCRA ammonia emission reporting requirements could result in fines of $37,500 per day, criminal charges, and up to five years imprisonment.

Ammonia emissions may be indirectly addressed by federal and state regulations aimed at $PM_{2.5}$ concentrations such as those in the National Ambient Air Quality Standards (NAAQS). Because ammonia is a precursor to $PM_{2.5}$, it may be necessary to

Few state regulations currently are directed at ammonia emissions from animal agriculture.

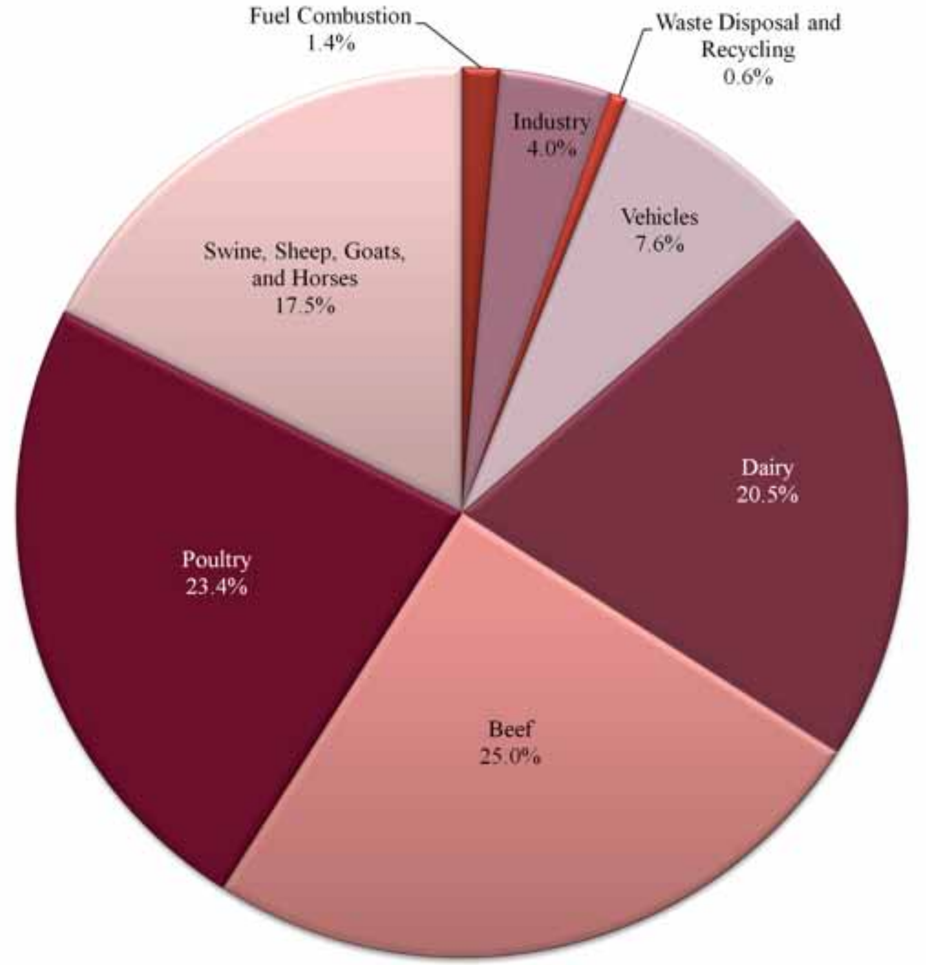

Figure 2. Estimated contributions of various U.S. ammonia sources based on the National Emissions Inventory (EPA, 2008).

reduce ammonia emissions to obtain a reduction in $PM_{2.5}$ concentrations.

Few state regulations currently are directed at ammonia emissions from animal agriculture. In 2003, California's Senate Bill 700 removed the reporting exemption from agricultural sources, and in 2006, Idaho put into force its "Permit By Rule" program requiring dairy farms with the capacity to produce more than 100 tons of ammonia annually to comply.

Except for Idaho and California, existing agricultural state regulations of ammonia are aimed primarily at the distribution, storage, and land application of anhydrous ammonia fertilizer. However, states can directly address ammonia emissions in $PM_{2.5}$ non-attainment areas in any case in which ammonia has been shown to be a significant contributor to $PM_{2.5}$ concentrations. In some states, general air quality regulations are based on atmospheric concentrations, and in other states they are based on actual emissions similar to those stipulated by EPCRA. However, atmospheric concentrations and ambient emissions of pollutants like ammonia are not well correlated. How these existing air quality regulations will be applied to livestock ammonia sources in the future is unknown.

Ambient Concentrations at Cattle Feedyards

The determination of atmospheric concentrations of ammonia requires highly sophisticated and expensive equipment, considerable labor, and much time. Measurements must be taken over large areas and extended periods, including all annual seasons, to represent the large spatial and temporal variability.

Other factors that must be reported include a detailed description of the facility, the animals, management practices, on-site weather, and sampling height. Data collected on atmospheric ammonia concentrations at CAFOs vary considerably, but tend to exhibit a 24-hour pattern, with daytime concentrations greater than those observed at night. Ammonia concentrations at cattle feedyards have rarely been observed over 3 ppm.

A variety of methods are available to measure atmospheric concentrations of ammonia, each with a unique set of advantages and disadvantages.

Gas washing, denuders, and passive samplers provide average ammonia concentrations over relatively long periods of 1 to 4 hours. Gas washing is useful for calibration and standardization, but is labor intensive. Fourier-transformed infrared (FTIR) spectroscopy, laser spectrometry, ultraviolet differential optical absorbance spectroscopy (UVDOAS), and chemiluminescence allow collection of nearly real-time measurements and relatively short periods of 5 seconds. Open-path lasers, UVDOAS, and FTIR have the added advantage of integrating measurements over distances from 50 to 500 meters. Dust concentration in the vicinity of feedyards tends to be high, so special measures must be taken when sampling for atmospheric ammonia to avoid errors. Examples of these special measures include installing Teflon® filters preceding detectors, or shortening measurement path lengths.

Emission Rates from Cattle Feedyards

An estimated 64-86 percent of total global anthropogenic ammonia emissions come from CAFOs (Baum and Ham, 2009; EPA, 2008; Becker and Graves, 2004; Battye et al., 1994). Of the CAFO emissions, roughly 43-48 percent come from cattle operations (EPA, 2008; NRC, 2003; Battye et al., 1994). *Figure 2* presents a graphic illustration of the relative contributions to ammonia emissions by various U.S. sources, based on the National Emissions Inventory (EPA, 2008). This inventory considered ammonia emissions based on ammonia emission factors and county-level populations of livestock intentionally reared for the production of food, fiber, or other goods, or for the use of their labor. The livestock included beef cattle, dairy cattle, ducks, geese, horses, poultry, sheep, and swine.

There is extensive literature regarding ammonia emissions from swine and poultry facilities, but relatively little comprehensive research on large, open-lot beef cattle feedyards (Todd et al., 2008). Methods for estimating ammonia emissions from area sources such as feedyards include mass balance, micrometeorology, flux chambers, wind tunnels, and dispersion models (Hristov et al., 2011). The accuracy and applicability of these estimation methods vary greatly. For example, flux chambers and wind tunnels are appropriate for comparing treatments or assessing relative emission rates, but not for quantifying actual emissions (Cole et al., 2007a; Paris et al., 2009; Parker et al., 2010). Dispersion models all rely on specific assumptions that are often challenged by the feedyard environment and can induce error in emission estimates (Flesch et al., 2005, 2007). Mass balance restraints are necessary to set an upper bound on emission estimates.

Calculating a total nitrogen balance for a facility, which involves determining the amount of nitrogen imported and exported from a feedyard and assuming that unaccounted nitrogen is mostly ammonia, can provide reasonable estimates of ammonia emissions (Bierman et al., 1999; Farran et al., 2006; Cole and Todd, 2009). This is because the majority of gaseous nitrogen loss to the atmosphere is in the form of ammonia, as opposed to nitrous oxide, nitrogen gas, or nitrogen oxides (Todd et al., 2005).

Comparing estimates obtained by multiple methods with calculations from a complete nutrient balance, and local atmospheric concentration data can minimize errors. However, this approach is site-specific and impractical for the purpose of regulatory monitoring at every livestock operation.

Micrometeorological methods such as eddy covariance (EC) and relaxed eddy accumulation (REA) are ideal for feedlots because they provide measurements of

Because so many variable and interactive system components must be considered, using a single emission factor is inadequate to predict ammonia rates.

ammonia flux for large areas without disturbing the emitting surface. EC involves high frequency measurements using a fast-response analyzer, accounting for vertical air movements and the mixing ratio of ammonia in the air. REA is an adaptation of EC in which samples from air moving vertically are accumulated over time and analyzed with slower-response analyzers.

The most common method currently used by regulatory agencies to estimate ammonia emissions from CAFOs is to multiply a research-based emission factor by the number of animals on location. However, a single emission factor is not appropriate because ammonia emissions are affected by multiple, complex, and dynamic environmental variables. Therefore, the National Research Council (NRC, 2003) has recommended a process-based modeling approach over the use of emission factors. Process-based models are based on the physical, chemical, and biological processes that contribute to emissions, and take into account dynamic variables such as weather conditions, management practices, and technologies. Thus, they are applicable to a wide range of feedyard situations.

Research Needs

Statistical, empirical, and process-based models are available to estimate ammonia emissions from CAFOs. Statistical models are usually based on data collected from a particular location and provide estimates that may not be appropriate for a different site. Empirical models are commonly built from data collected under controlled conditions and predict well only when those particular conditions exist. Process-based (also known as mechanistic) models apply chemical and physical principles to a theoretical model of a real system, such as a CAFO. Their ability to predict ammonia emissions depends on how well the model represents real processes and the accuracy of important process factors used as inputs in the process-based model.

Many cross-disciplinary factors are considered in the construction of a process-based model, such as animal nutrition, feedyard management strategies, environmental aspects, and meteorological factors (*Figure 3*). Process-based models of emissions from CAFOs often begin by describing the effects of diet and facility management on nutrient excretion by the animals. In the case of nitrogen, the various chemical forms, routes, and processes the nitrogenous molecules undergo as a feed constituent consumed and excreted by animals is described. Next, the nitrogenous manure

Figure 3. Developing a process-based model requires research inputs from multiple disciplines to estimate ammonia emissions.

constituents are accounted for and partitioned into several pools. Depending on the facility, these pools may include feces, urine, pen surfaces, manure stockpiles, effluent lagoons, and so forth. Finally, the chemical and physical transformations, transfer, and equilibria that occur during manure storage, handling, treatment, and export in each of the several cases are modeled. The model may then be used to predict ammonia emissions.

Models must consider atmospheric ammonia phases, which include gaseous ammonia (NH_3), fine particulate ammonia ($(NH_4)_2SO_4$ and NH_4NO_3), and liquid ammonia (NH_4OH) as clouds or fog. The transition between these three phases depends on other inconstant atmospheric constituents. Therefore, the proportion of the phases relative to one another is also continually changing. Ammonia readily forms strong hydrogen bonds with water and will attach to many surfaces. Therefore, most materials exposed to air containing ammonia will absorb or adsorb ammonia compounds. In a CAFO environment, gaseous ammonia is prevalent and attaches to the airborne particulate matter emitted from the facility.

The dynamic nature of the atmosphere and its constituents results in significant variations in ammonia concentrations with respect to time, location, and height above the ground. Increasing the distance from the emission source can result in decreasing ammonia concentrations, with the rate of decrease depending on other factors such as air temperature, relative humidity, or wind speed. Dry deposition rates proximate to the CAFO also can decrease with respect to distance, and range widely, depending on atmospheric conditions and emission rates.

Measuring Emissions

It is difficult to measure ammonia emission rates from open-lot CAFOs. Ammonia tends to collect inside sampling instruments, adversely affecting measurement. Open-lot CAFOs have lower ammonia concentrations than those typical of facilities with livestock housing, so more sensitive instrumentation is required. There is relatively little data on ammonia emission rates, flux rates, or emission factors from open-lot beef cattle facilities.

Despite sampling challenges, changeability of ammonia concentrations, and scarcity of data, the average daily ammonia concentrations observed at several facilities by different researchers are consistent. *Table 1* presents ammonia concentrations observed at several commercial feedyards in different studies conducted at different times of the year.

Table 1. Ammonia concentrations (ug/m^3) measured at commercial open-lot beef cattle feedyards. Adapted from Hristov et al., 2011.

Study	***Time***	***Location***	***Mean or Range***
Hutchinson et al., 1982	April-July	Colorado	290 - 1,200
McGinn et al., 2003	May	Canada	66 - 503
	July		155 - 1,488
Todd et al., 2005	Summer	Texas	90 - 890
	Winter		10 - 250
Baek et al., 2006	Summer	Texas	908
	Winter		107
McGinn et al., 2007	June-October	Canada	46 - 1,730

When estimating ammonia emissions from open-lot beef cattle facilities, several components of the CAFO system must be considered. Emission factors fail to account for effects of particular components included in process-based models, such as animal diet and age, air and surface temperatures, time of year, geographic location, and many others. So many variable and interactive system components must be considered that using a single emission factor is inadequate to predict ammonia emission rates (Hristov et al., 2011).

Processed-based models, which describe physical processes mathematically as opposed to statistically, are better suited to this task than emission factors. A single ammonia emission factor based primarily on European data proposed by the EPA (2005) is 13 kg/hd annually for feedlot cattle or 23 percent of the total amount of imported nitrogen. This EPA report also estimates the following nitrogen losses as ammonia: 1) stockpiles — 20 percent of nitrogen entering, 2) storage ponds — 43 percent, and 3) land application — 17-20 percent. Because European beef systems vary greatly from U.S. systems, these values may not apply to U.S. feedlot systems.

Studies conducted at North American feedyards using a variety of measurement methods observed a wide range of emission and flux (quantity per unit area per unit time) rates. Reported emission factors ranged between 18 and 104 kg/hd annually, and flux rates ranged from 3.6 to 88 $\mu g/m^2/s$. Most studies also noted seasonal or 24-hour patterns in ammonia flux rates (Hristov et al., 2011). Reported losses from runoff holding ponds ranged from 3-70 percent of the N entering the pond. Other sources of ammonia loss on beef cattle feedyards include compost piles, which have been estimated to lose 10-45 percent of the N entering the compost (Hristov et al., 2011).

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AIR QUALITY

Ammonia Emissions from Cattle-Feeding Operations Part 2 of 2: Abatement

Air Quality Education in Animal Agriculture

Mitigation: Ammonia Abatement
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This publication discusses ammonia abatement measures and when they can be implemented in livestock production.

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Air Quality in Animal Agriculture
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Abatement Measures

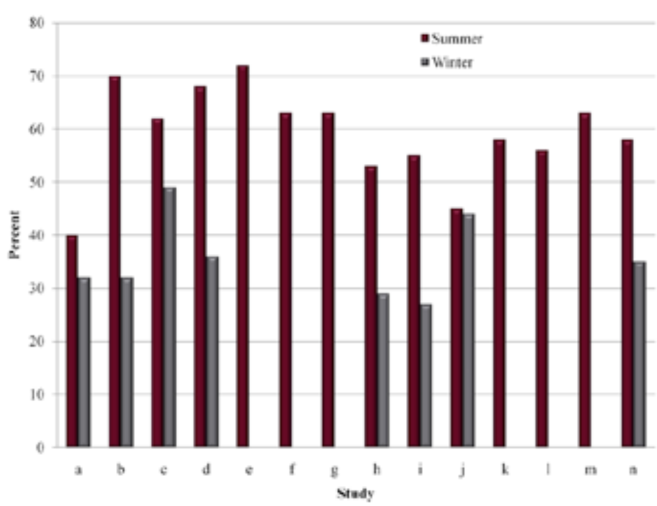
Ammonia abatement measures can be implemented at two different stages of livestock production. First-stage measures are applied in the pre-excretion stage. These include nutrition-based strategies to reduce the amount of nitrogen excreted in livestock manure. In the second or post-excretion stage, management strategies are implemented to reduce the amount of ammonia transferred to the environment from the manure by agricultural operations.

Nutritional Ammonia Abatement Methods

One means of reducing ammonia emissions from concentrated animal feeding operations (CAFOs) is to reduce the amount of nitrogen excreted by the animals, especially the quantity excreted as urea in urine. Urinary pH also can affect ammonia emissions (Cole et al., 2008a). In some cases, it is possible to manipulate nutritional intake to reduce total nitrogen and urinary nitrogen excretion while continuing to meet the nutritional requirements and performance expectations of the animals. Based upon consistent observations among researchers over the past decade, annual ammonia losses from beef cattle feedyards tend to be approximately half of the nitrogen consumed by cattle, and summer emission rates are about twice those in winter (Todd et al., 2009).

Table 1 presents ammonia-nitrogen loss as a percentage of fed nitrogen for beef cattle feedyards in the Great Plains. Ration composition can be modified in a variety

Table 1. Ammonia-nitrogen loss as a percentage of fed nitrogen from Great Plains beef cattle feedyards. Studies: (a) Todd and Cole, unpublished data, (b) Todd and Cole, unpublished data, (c) Todd et al., 2011, (d) Todd et al., 2008, (e) van Haarlem et al., 2008, (f) McGinn et al., 2007, (g) Flesch et al., 2007, (h) Harper et al., 2007, (i) Todd et al., 2005, (j) Todd et al., 2005, (k) Cole et al., 2006, (l) Erickson and Klopfenstein, 2004, (m) Erickson et al., 2000, (n) Bierman et al., 1999.



Reducing the amount of nitrogen excreted by livestock is one way to reduce ammonia emissions.

of ways to effectively reduce ammonia emissions by 20-50 percent with only small effects on animal performance (Cole et al., 2005, 2006a; Todd et al., 2006). Some of the nutritional factors that can be manipulated include crude protein and/or degradable intake protein concentrations (including phase feeding), fat concentration, fiber source and concentration, cation-anion balance (CAB), as well as some growth-promoting feed additives and implants. However, the large size of many CAFOs presents economic and logistic challenges when modifying diets or feeding practices. Modifications to equipment, diets, or management practices may impose increased cost, labor, and time, for example (*Figure 1*).

Crude Protein

The concentration of protein in feed, as well as its ability to be degraded in the rumen, may affect the quantity and route of nitrogen excretion by beef cattle (Cole et al., 2005). Beef cattle consume dietary crude protein in two forms. The first is degradable intake protein (DIP), which is processed by microbes in the rumen and either absorbed from the rumen (normally as ammonia) or converted to microbial protein and nucleic acids. The second is undegradable intake protein (UIP), which escapes digestion in the rumen and passes to the intestine where it is digested and absorbed as amino acids (approximately 80 percent) or excreted (approximately 20 percent). In general,

Figure 1. Rations can be modified in a variety of ways to effectively reduce ammonia emissions with only small effects on animal performance, but some modifications may pose economic and logistic challenges to large CAFOs.

as nitrogen consumption increases, urinary nitrogen excretion also increases. Further, as the ratio of DIP to UIP increases, urinary nitrogen excretion also increases. Dietary changes must be made carefully and with consideration to unintended consequences. If, for example, in an attempt to lower ammonia emissions the dietary protein intake is reduced below the nutritional needs of the animal, the growth rate may be slowed, the animal will require more days on feed to reach market weight, and the cumulative ammonia emissions from a feedlot may actually increase. In addition, making changes to decrease ammonia emissions may potentially result in the increase of other undesirable emissions such as nitrous oxide.

In closed chamber laboratory (Cole et al., 2005) and artificial pen surface (Todd et al., 2006) experiments, decreasing the crude protein concentration of beef cattle finishing diets based upon steam-flaked corn from 13-11.5 percent decreased ammonia emissions by 30-44 percent. Ammonia fluxes from an artificial feedyard surface were reduced by 30 percent in summer, 52 percent in autumn, 29 percent in spring, and 0 percent in winter (Todd et al., 2006). The research team concluded that despite requirements to maintain cattle performance, reducing crude protein in beef cattle diets may be the most practical and cost-effective way to reduce ammonia emissions from feedyards. Another study by Todd et al. (2009) determined that feeding high concentrations (> 20 percent) of wet distiller's grains, which are becoming increasingly available as a ration component, increased crude protein intake in beef cattle and resulted in increased ammonia emissions.

Phase Feeding

As beef cattle mature, they require less dietary protein. Phase feeding involves adjusting nutrient intake over time to match the changing needs of the animal. If protein is not progressively diminished through the feeding period in balance with the animals' nutritional requirements, potentially more nitrogen is excreted and more ammonia may be emitted from the facility (Cole et al., 2006a; Vasconcelso et al., 2009). Studies on cattle fed high-concentrate, steam-flaked corn-based diets have suggested that a moderate reduction (~1.5 percent) in dietary crude protein (CP) in the final 28 to 56 days of the feeding period may decrease ammonia emissions by as much as 25 percent, with little adverse effect on animal performance (Cole et al., 2006a). Based on seven cooperative studies to determine the effect of crude protein on ammonia emissions and animal performance (Cole, 2006b), a reduction of dietary crude protein from 13 percent, which is optimal for growth, to 11.5 percent resulted in a 3.5 percent decrease in average daily gain and an approximate 30 percent reduction in ammonia emissions. Therefore, in certain economic conditions, it may be practical to accomplish a significant reduction in ammonia emissions with a minimal effect on animal performance.

Distiller's Grains

Distiller's grains have recently been introduced into beef cattle rations and may affect CAFO ammonia emissions. Research by Cole et al. (2008b) reported that a 10 percent increase in distiller's grains in rations based upon steam-flaked corn increased manure production by approximately 10 percent. In rations based upon dry-rolled corn, the same increase in distiller's grains resulted in a 0-7 percent increase in manure production. In both cases, the concentration of nitrogen in the manure was not affected. The combination of increased manure volume and steady nitrogen concentrations may result in potentially greater ammonia emissions. In a comparison of ammonia emissions at two feedyards, Todd et al. (2009) found that one feedyard feeding distiller's grains averaged 149 g NH_3-N head^{-1} d^{-1} over nine months, compared with 82 g NH_3-N head^{-1} d^{-1} at another feedyard feeding lower protein, steam-flaked corn-based diets.

Fiber

Manipulation of dietary fiber also may affect ammonia emissions from feedyards. In a study by Erickson et al. (2000), dietary fiber in the form of corn bran was increased in cattle finishing diets. During the winter-spring study period, nitrogen volatilization rates were decreased, but animal performance was adversely affected.

As beef cattle mature, they require less dietary protein. Phase feeding involves adjusting nutrient intake over time to match the animal's changing needs.

In another study by Bierman et al. (1999), beef cattle were fed different diets containing wet corn gluten feed (WCGF), corn silage, and alfalfa hay. The researchers concluded that dietary fiber and carbohydrate source affected the way feed was digested and excreted by cattle, resulting in changes to the amount of nitrogen excreted. Nitrogen excretion was highest for cattle fed a ration based on WCGF, but these cattle also had the highest performance.

Farran et al. (2006) manipulated alfalfa hay and WCGF in beef cattle diets and made similar observations. Increasing alfalfa hay or WCGF intake resulted in an increase in nitrogen intake, nitrogen excretion, nitrogen volatilization, and cattle performance. They further concluded that recovery of nitrogen in the manure and finished compost was also increased, especially in the case of WCGF, as a result of increased organic matter content in the manure.

Cation-Anion Balance

Ammonia emissions are inhibited in low-pH environments, and lowering dietary cation-anion balance (DCAB) can potentially lower the pH of cattle urine. Thus, notwithstanding other factors, lowering the pH of cattle urine may potentially reduce CAFO ammonia emissions. However, Erickson and Klopfenstein (2010) noted no effect of DCAB on nitrogen volatilization losses. Lowering urine pH may have little effect on ammonia emissions because the pen surface of feedyard pens may have significant buffering properties that strongly resist pH changes, tending to maintain a pH of approximately 8 or higher (Cole et al., 2009). Furthermore, cattle performance may be reduced by low-DCAB diets (Cole and Greene, 2004).

Post-Excretion Ammonia Abatement Methods

Post-excretion ammonia abatement strategies, such as improving manure management, can reduce the rate of nitrogen volatilization and ammonia emissions. Animal health considerations in post-excretion methods are not as great a concern when compared to nutritional methods. However, some manure management strategies, such as pen scraping, can be beneficial for animal health. Manure contains nitrogen and phosphorus, both of which contribute to the value of manure as a fertilizer. Nitrogen volatilization can reduce the nitrogen:phosphorus ratio to below most plant requirements, thereby reducing the fertilizer value of the manure and requiring a greater land application area to avoid excessive phosphorus applications. Reducing ammonia emission rates from manure will enhance the fertilizer value of manure and lower ammonia emissions. Besides manure management, manipulating other factors such as the pH and moisture content of soil and/or manure also can affect ammonia emissions (Cole et al., 2008a).

Urease Inhibitors, Zeolites, Fats, and Other Pen Surface Amendments

Based upon laboratory studies, a number of compounds can potentially be applied to feedlot pen surfaces to reduce ammonia emissions from feedyard surfaces (Varel, 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Substances such as zeolites (a microporous, aluminosilicate mineral), fats, and urease inhibitors such as N-(n-butyl) thiophsphoric triamide, cyclohexylphosphoric triamide, and phenyl phospohorodiamidate may change manure properties such as pH, ammonia adsorption potential, or hydrolysis potential, which in turn affects ammonia emission rates.

Urease inhibitors work by slowing down or blocking the hydrolysis of urea (found in urine) by the enzyme urease (found in feces). However, urease inhibitors must continually be applied to manure because they rapidly degrade (Powers, 2002; Parker et al., 2005). Application of some compounds such as fats may be accomplished indirectly via dietary supplementation. Zeolites and urease inhibitors have been shown to decrease ammonia emissions when applied as a surface amendment, but not when used as a dietary amendment (Varel, 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Both dietary and surface amendments of fat appeared to decrease ammonia emissions (Cole et al., 2007). The dietary fat effect is likely because a proportion of fed fat is voided onto the feedyard surface after being excreted in undigested form by feedyard cattle. No significant effects on animal performance were observed.

Lowering pH

One of the most important factors involved in ammonia emissions from surfaces is the pH of the emitting medium. In general, ammonia volatilization rates increase with pH. Therefore, lowering the pH of soil or manure can reduce ammonia emissions. With acidic conditions, given a constant temperature, more nitrogen will remain in the form of ammonium (NH_4^+), thereby decreasing the amount of ammonia available to volatilize. A significant reduction in ammonia emissions has been observed with acidifying amendments such as aluminum sulfate (alum), ferrous sulfate, phosphoric acid, or calcium salts.

Maintaining the low pH can be challenging, however, because manure may have a strong buffering capacity, which results in the pH eventually returning to a more basic level and a resumption of ammonia emission. Strong acids are more cost-effective than weak acids or acidifying salts, but they are more hazardous and, therefore, are not suitable for use in agricultural environments (Ndegwa et al., 2008).

Manure Harvesting, Storage, and Application

Frequent pen cleaning may help to capture nitrogen in the manure by decreasing loss to the atmosphere. Research in Nebraska (Erickson and Klopfenstein, 2010) revealed that cleaning pens once per month, as opposed to once after every 166-day feeding period, reduced apparent ammonia nitrogen losses by 24 percent. The effectiveness of the monthly cleaning strategy varied seasonally, being less in winter. This may be due to the accumulation of nitrogen that occurs in the pen surface manure pack during the winter, apparently the result of decreased ammonia losses during the colder months (Cole et al., 2009). In addition, the amount of nitrogen collected in the manure was 50 percent greater from pens cleaned monthly.

Covering manure to reduce its exposure to elements such as sun, wind, and rain is very effective at reducing ammonia emissions from storage areas. When manure is land-applied, immediate incorporation or injection into the soil has been shown to significantly reduce ammonia losses when compared to broadcasting alone (Ndegwa et al., 2008).

Post-excretion ammonia abatement strategies can reduce the rate of nitrogen volatilization and ammonia emissions.

Frequent pen cleaning may help capture nitrogen in the manure by decreasing loss to the atmosphere.

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