Published July 14, 2014

Journal of Environmental Quality SPECIAL SECTION

LIVESTOCK GRACEnet

Livestock GRACEnet: A Workgroup Dedicated to Evaluating and Mitigating Emissions from Livestock Production

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Abstract

Ammonia, greenhouse gases, and particulate emissions from livestock operations can potentially affect air quality at local, regional, and even global scales. These pollutants, many of which are generated through various anthropogenic activities, are being increasingly scrutinized by regulatory authorities. Regulation of emissions from livestock production systems will ultimately increase on farm costs, which will then be passed onto consumers. Therefore, it is essential that scientifically based emission factors are developed for on-farm emissions of air quality constituents to improve inventories and assign appropriate reduction targets. To generate a larger database of on-farm emissions, the USDA–ARS created the workgroup Livestock GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement Network). This introduction for the special section of papers highlights some of the research presently being conducted by members of Livestock GRACEnet with the intent of drawing attention to critical information gaps, such as (i) improving emissions measurements; (ii) developing emissions factors; (iii) developing and validating tools for estimating emissions; and (iv) mitigating emissions. We also provide a synthesis of the literature with respect to key research areas related to livestock emissions, including feeding strategies, animal housing, manure management, and manure land application, and discuss future research priorities and directions.

Ammonia (NH_3), greenhouse gases (GHGs), and other emissions (e.g., particulate matter [PM], volatile organic compounds [VOCs], and hydrogen sulfide [H_2S]) from livestock production systems are being increasingly scrutinized by state and federal regulatory agencies. These pollutants, which are also generated by energy, industrial, and transportation sectors, can adversely affect air quality on local, regional, and even global scales. When evaluating the impact of emissions from livestock production on air quality in the United States, NH_3 emissions are by far the greatest concern. According to the USEPA 2011 Emissions Inventory (USEPA, 2013), an estimated 82% of total NH_3 emissions is directly related to agriculture, with the majority associated with livestock production (livestock waste, 54%; fertilizer, 27%). Beef and poultry production are each estimated to generate approximately 28% of the livestock NH_3 emissions, followed by swine (21%) and dairy (18%) (Fig. 1a).

Ammonia is generated during the decomposition of urea and other organic nitrogen (N) compounds in excreted urine and feces and is quickly volatilized to the atmosphere from livestock housing and manure management systems, and during the land application of livestock manures. Estimated percentage losses of NH_3 from total ammonium-N excreted from animals in housing, manure storage, and land application is presented in Fig. 2. Atmospheric NH_3 contributes to the formation of fine PM (<2.5 μm PM; $PM_{2.5}$) that is linked to human respiratory problems (Kampa and Castanas, 2008), and its deposition in the environment can lead to the degradation of terrestrial and aquatic ecosystems (Kirchmann et al., 1998). Presently, NH_3 emissions are regulated by the USEPA under the Emergency Planning and Community Right-To-Know Act, requiring that NH_3 releases that exceed 45 kg d^{-1} must be reported (USEPA, 2014a); this threshold level is often exceeded at large livestock operations. The regulation of NH_3 as a precursor for $PM_{2.5}$ under the Clean Air Act (CAA) is currently being evaluated by the USEPA, which could have a large impact on agriculture.

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Abbreviations: bLS, backward Lagrangian stochastic; CAA, Clean Air Act; CBSM, corn–soybean meal; CO_2e, CO_2 equivalents; CP, crude protein; DDGS, dried distillers grains with solubles; GHG, greenhouse gas; GRACEnet, Greenhouse gas Reduction through Agricultural Carbon Enhancement Network; IFSM, Integrated Farm System Model; MUN, milk urea nitrogen; NAEMS, National Air Emissions Monitoring Study; PM, particulate matter; SS, enhanced solid–liquid separation; SS + NDN, solid–liquid separation plus biological N treatment using nitrification–denitrification; TDL, open-path tunable diode laser absorption spectrometer; TRS, total reduced sulfides; UUN, urine urea nitrogen; VOC, volatile organic compound; WDGS, wet distillers grains with solubles.

J. Environ. Qual. 43:1101–1110 (2014)
doi:10.2134/jeq2014.06.0264
Received 18 June 2014.
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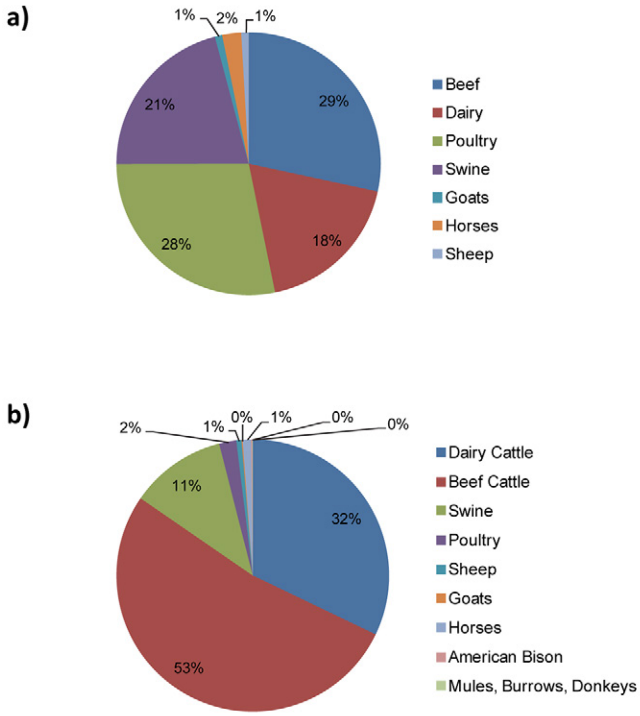

Fig. 1. The percentage of total livestock emissions of (a) ammonia and (b) greenhouse gas associated with each livestock species. Data source: USEPA (2013, 2014b).

While occurring naturally in the atmosphere, the most important GHGs directly emitted during anthropogenic activities are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In the United States, livestock production accounts for approximately 4.6% of total GHG emissions when weighted by their relative contribution to global warming (USEPA, 2014b). Enteric CH_4 emissions account for 41% of total GHG emissions from agriculture, followed by CH_4 (13%) and N_2O (4%) emissions from manure management. A breakdown of GHG emissions by livestock species is provided in Fig. 1b. Beef, dairy, and swine production systems are responsible for the majority of these emissions at 53, 32, and 11%, respectively. Under the CAA, a rule has been filed requiring reporting of GHG emissions from manure management systems that produce >25,000 t of CO_2 equivalents (CO_2e) per year (USEPA, 2009). However, implementation of this rule has not yet taken effect because funding has not been provided by the U.S. Congress.

The generation of dust or PM from livestock housing has generally been regarded as an indoor pollutant, but emissions from outdoor housing units have also been linked to ambient air quality issues (Cambra-López et al., 2010). Livestock houses are important sources of fine (<2.5 μm) and coarse (2.5–10 μm) PM (Takai et al., 1998), with fine fractions causing respiratory and cardiovascular disease and, in some cases, mortality (Pope et al., 2002). Agriculture is estimated to contribute 33% of total anthropogenic fine PM emissions, with livestock operations at about 1.1% of total (Pouliot et al., 2010). Other emissions, such as VOCs and H_2S from manure storage or decomposition of land-applied manures, are known to cause irritation in humans and can be a public nuisance from an odor standpoint (Schiffman et al., 2006).

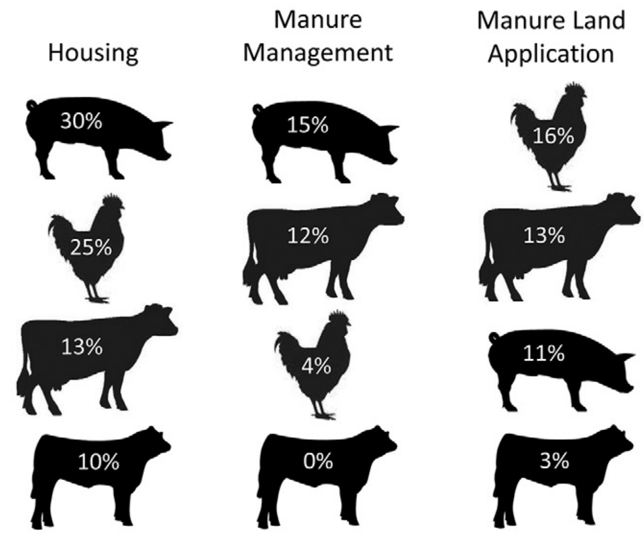

Fig. 2. Estimated losses of ammonia as a percentage of ammonium-nitrogen excreted by species from housing, manure storage, and land application of manure. Data source: USEPA (2004).

Livestock GRACEnet

To generate a larger database of on-farm emissions that can be utilized to develop emission factors, develop and validate process-based models, and evaluate the effectiveness of mitigation strategies, collaboration at the national level is necessary. To facilitate this collaboration, the workgroup Livestock GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement Network) was recently created by the USDA (2014). Livestock GRACEnet is currently composed of scientists who are located at 13 USDA–ARS locations (Fig. 3). Based on current needs of livestock producers and policymakers, the objectives of Livestock GRACEnet are (i) to develop emission factors for CH_4, N_2O, NH_3, PM, and VOCs that can reliably be used to estimate emissions from livestock housing and manure storage areas based on species, on-farm management practices, and climactic conditions; (ii) to develop or improve on current process-based models to accurately quantify emissions; and (iii) to identify and develop new management practices to decrease emissions from livestock production systems. This special section highlights some of the research presently being conducted by members of Livestock GRACEnet, with the intent of drawing attention to these critical research areas.

Key Research Areas and Needs

Livestock operations are highly complex, having multiple emission sources such as housing, manure management, and land application of manures. Each species of livestock also have unique production systems, which in some cases may vary across geographical regions. In addition to having differing production systems with multiple sources that are challenging to monitor, the complex environmental variables affecting emissions also need to be quantified. Three approaches are commonly used to measure on-farm emissions from livestock systems: mass balance, chambers, and noninterference methods (which attempt to model emission rates using techniques such as flux gradient, integrated horizontal flux, and inverse dispersion modeling). Hu et al. (2014) recently published a review of these different methods within the context of measuring emissions from livestock production. Continued validation of these techniques is needed for determining accuracy of these methods for on-farm emissions estimates, while economically feasible options for either continuous on-farm monitoring or mobile applications is essential for enforcement and evaluation of mitigation strategies.

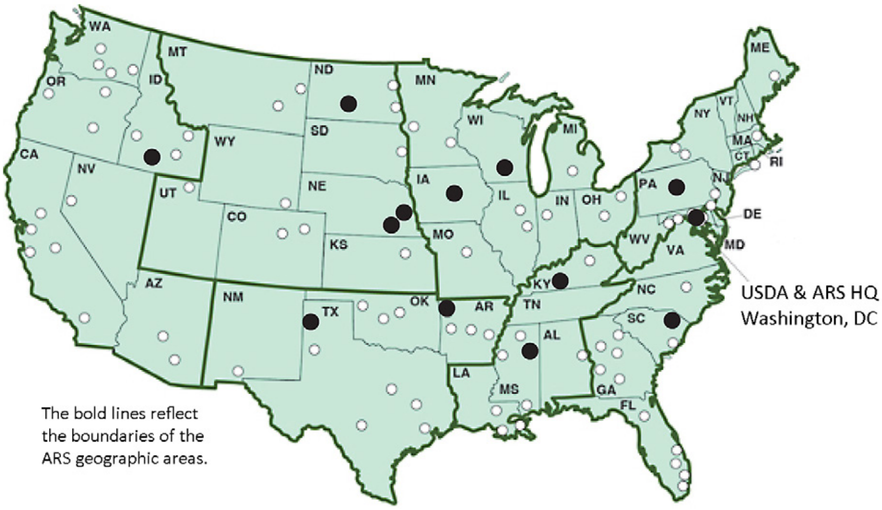

Fig. 3. Location of USDA–ARS research units that are part of the Livestock GRACEnet workgroup (marked with black circles). To date, the group is composed of 24 scientists at 13 locations. The white circles on the map represent all other ARS locations that are not part of the current workgroup.

Increasing environmental regulation of livestock production will increase on-farm costs, which will ultimately be passed onto consumers. Therefore, it is essential that scientifically based emission factors are developed for on-farm emissions of air quality constituents to improve emissions inventories and assign appropriate emissions reduction targets. In 2005, the National Air Emissions Monitoring Study (NAEMS) was funded by the poultry, swine, and dairy industry to quantify emissions (PM, NH_3, H_2S, and VOCs) from livestock housing and lagoons (USEPA, 2014c). Over a 2-yr period, 25 sites in nine states were monitored, including broiler houses (2), egg layer houses (4), dairy barns (5), dairy corral (1), swine barns (5), swine lagoons (6), and dairy lagoons (2). This was the most comprehensive study of emissions from livestock agriculture at the time; however, it did not include emissions of GHGs. Since then, additional peer-reviewed studies have investigated emissions from livestock production in the United States, including beef (Todd et al., 2011, 2014), dairy (Cassel et al., 2005; Rumburg et al., 2008; Bjorneberg et al., 2009; Flesch et al., 2009; Leytem et al., 2011, 2013; Moore et al., 2014), swine (James et al., 2012; Rahman and Newman, 2012), and poultry (Miles et al., 2006; Moore et al., 2011; Hayes et al., 2013). Even with the completion of the NAEMS study, the USEPA Science Advisory Board (2013) recommended that more data are required before the USEPA develops emission methodologies for these livestock sectors, suggesting that quantification of on-farm emissions is still a key area of future research. In particular, there is a lack of on-farm GHG emissions data covering the range of species and climatic regions necessary to accurately estimate these emissions. Demand for these data is large as there are currently methodologies being developed for trading C credits based on mitigation of GHG emissions from livestock production systems, with the basis for many of these methodologies relying on limited datasets.

To assess current livestock emissions and quantify reductions of future emissions, we need tools that can easily and accurately determine on-farm emissions, as it is cost prohibitive and impractical to monitor emissions at every farm. These tools will need to either (i) model the processes that control emissions and allow calculation of on-farm emissions by describing the livestock population, housing, and manure management system; or (ii) provide indices that can enable producers and regulators to make simple on-farm measurements to assess their emissions potential. Process-based models have the potential to estimate emissions from livestock production systems by simulating emissions based on species, livestock populations, diet, housing system, manure storage, and climate. Two process-based models available in the United States for estimating emissions from whole farm systems (including the cropping system for feed production) are the Integrated Farm System Model (Rotz and Oenema, 2006; Chianese et al., 2009a,b) and the Manure Denitrification–Decomposition model (Manure-DNDC; Li et al., 2012). In addition to being able to model a given farm based on farm configuration, other advantages of process modeling include the ability to assess both short- and long-term emissions and allow modeling of multimedia (soil, air, and water) and testing of site-specific mitigation strategies to determine the whole system response to changes in practices. While process-based models have great promise for use as a tool for estimating emissions, validation of these models using on-farm data is essential for determining their accuracy and reliability.

In lieu of modeling whole farm systems, there may be simple indices that could be developed to estimate some on-farm emissions. One example of this is the use of milk urea nitrogen (MUN) to estimate NH_3 emissions from dairy cattle (Burgos et al., 2010; Powell et al., 2011). Milk urea nitrogen has been measured extensively on commercial dairy farms and been used to predict urinary N excretion, which is the main source of NH_3 emissions on dairy farms. By tracking MUN, producers will have an indication of whether they are overfeeding protein to their cows and therefore increasing NH_3 emissions on their farms. Tools such as these, which incorporate the use of data already being collected by producers, could be valuable in assisting in on-farm emission assessments and tracking potential changes in emissions over time. The development of new tools and indices to predict on-farm emissions is a potential research area of great interest.

Ultimately, the goal of measuring and modeling emissions from livestock production is to develop baseline values and then assess a variety of mitigation strategies to reduce on-farm emissions. Strategies for reducing on-farm emissions will depend on the air quality concern (e.g., NH_3, CH_4, PM), as well as the livestock species and production system. For instance, strategies to reduce NH_3 and CH_4 emissions could include dietary changes and changes in housing or manure management, whereas reductions in PM would need to focus on livestock housing and in some cases manure management.

Feeding Strategies

Modifying feeding practices and using alternative feed ingredients can, in some cases, help to mitigate gaseous emissions. One research area of interest for reducing NH_3 emissions has been making dietary changes that enhance N use efficiency in the animals, reducing excreted N, and thereby reducing potential NH_3 and in some instances N_2O emissions. For example, the use of amino acids to balance rations in swine and poultry (Panetta et al., 2006; Liu et al., 2011a,b), phase feeding in cattle to match dietary protein to animal needs (Cole et al., 2006), and reducing crude protein (CP) to meet N needs of the animal (Agle et al., 2010) have all been shown to reduce excreted N and related N emissions. Improving diet digestibility and addition of fats has been shown to reduce enteric CH_4 production in cattle (Beauchemin et al., 2008). On the other hand, increasing the use of low-cost rations, such as dried or wet distillers grains with solubles (DDGS or WDGS) in the diet of feedlot cattle, has been found to contribute to the production of malodorous VOCs (e.g., volatile fatty acids, phenol) and NH_3 emission from increased N in urine (Hao et al., 2009; Spiehs and Varel, 2009). As feed management can have both positive and negative effects on emissions, it will be important to gain more knowledge related to the interactions of animal genetics, management, and feeding on emissions and to develop practices to maximize nutrient utilization and reduce losses.

Housing

Livestock housing can be a large source of emissions. Therefore, development of housing systems with a focus on reducing emissions may be possible, or management of animals and manure within the housing system may reduce emissions. For example, frequent manure removal from housing systems can reduce NH_3 and H_2S emissions (Lim et al., 2004), although in some cases this just transfers the losses to another sector, such as manure storage or land application. The use of additives to control pH or inhibit conversion of urea to NH_4 can reduce NH_3 losses from housing (Moore et al., 2000; Parker et al., 2005). Moisture management in barns, pens, and nonpaved roads can also help to reduce PM emissions (Ellen et al., 2000; Pedersen et al., 2000; Miller and Berry, 2005). As we move toward more environmentally friendly livestock production, perhaps new housing systems can be designed that can manage animals and manure in ways that reduce emissions losses from this sector. The conversion of high rise layer housing to belt houses is just one example of a success in housing design that has reduced NH_3 emissions by 67% (Liang et al., 2005).

Manure Management

Often one of the most challenging aspects of livestock production is the management of the manure generated on farm. Manure handling and storage areas can be sources of NH_3, CH_4, N_2O, VOCs, H_2S, and in some cases PM emissions. Typically, the greatest complaints of nearby residents of livestock facilities is the odor produced (and flies), which are usually associated with the manure handling and storage system. To address some of these challenges, a variety of manure treatment technologies have been developed for on-farm use. Burton and Turner (2003) provide an excellent detailed discussion of many of these practices; some brief examples follow.

Handling solid manure on farm has often involved some form of composting to reduce the moisture content and therefore the volume of material that needs to be transported off farm. One large drawback to composting is the valuable loss of N as NH_3, which can range from 3 to 60% of total initial N (Bernal et al., 2009), reducing its value as a fertilizer for crop production. Additives such as zeolite and biochar have been shown to reduce N losses by up to 52% (Steiner et al., 2010; Luo et al., 2011). Fukumoto et al. (2011) demonstrated that the use of struvite precipitation and nitration promotion in the composting process of swine manure reduced total N losses by 60%.

Liquid manure storage systems undergo losses of NH_3 as well as generation of CH_4, H_2S, and VOCs due to the development of anaerobic conditions. The use of enhanced solid separation, typically with addition of flocculating agents, can reduce the load of N and solids that enter the storage systems, thus reducing potential emissions from storage. For example, solid separation using screens with a flocculant agent can remove >90% of total and volatile solids, >70% of chemical oxygen demand and total N, and >50% of total phosphorus (García et al., 2009; Pérez-Sangrador et al., 2012). The use of covers on liquid storage systems can also reduce NH_3, CH_4, and VOC emissions. Guarino et al. (2006) tested several permeable covering systems (maize stalks, wood chips, vegetable oil, expanded clay, wheat straw) to reduce emissions from livestock slurry tanks and lagoons. They reported reductions of NH_3 emissions from swine and dairy slurry in the range of 60 to 100% with 140-mm solid covers or 9-mm liquid covers. Miner et al. (2003) reported that a permeable polyethylene foam lagoon cover reduced NH_3 emissions by approximately 80% on an anaerobic swine lagoon. Floating an impermeable cover over the surface of a lagoon or pond can also capture up to 80% of CH_4 and reduce odors. The trapped gas can be flared or used to produce heat or electricity. Craggs et al. (2008) reported that placing a floating polypropylene cover on anaerobic swine and dairy ponds yielded biogas recoveries of 0.84 and 0.032 $m^3\ m^{-2}\ d^{-1}$, respectively. Respective estimates for energy production were 1650 and 135 kWh d^{-1} from fully coved anaerobic ponds. Anaerobic digestion has become increasingly popular with the goal of reducing CH_4 emissions, generating electricity and perhaps even generating C credits for producers. Zaks et al. (2011) estimated that construction of anaerobic digesters on livestock facilities have the potential to generate 5.5% of U.S. electricity and mitigate 151 million t of CO_2e, mostly from CH_4 abatement.

Future research will need to focus on finding ways to generate more value from the manure stream on farm, capture nutrients for reuse, capture C, and reduce emissions. Some high-tech options available for producers are being used on a few demonstration farms, but they may not be economically feasible for the average producer. Finding ways to make these technologies more affordable or generate income that can make them self-sustaining should be a priority.

Land Application

The application of manure (both liquid and solid) to field crops and pastures is the most common use of manure generated at livestock operations. However, land application of manure generates emissions of NH_3, N_2O, VOCs, and PM. While the generation of PM from agriculture is substantial (33%), the majority of this is associated with tillage (Pouliot et al., 2010), not the application of manure itself. The emissions of NH_3, N_2O, and VOCs originate from the manure that is field-applied, and finding methods to reduce these emissions is important for controlling odor, improving air quality, and reducing agriculture's impact on climate change. Ammonia volatilization from land-applied manures tends to be very rapid, and therefore, incorporating manures into the soil as quickly as possible is one of the best ways to reduce losses. Brunke et al. (1988) reported that NH_3 flux from surface-applied manure declined rapidly over the period of 10 h after application and that incorporation of manure led to an 85 to 90% decrease in NH_3 losses. Sullivan et al. (2003) showed that NH_3 losses following swine effluent application to Bermuda grass pasture decreased steadily over 5 d, with 60% of the total NH_3 volatilization taking place within 4 d of application. Morken and Sakshaug (1998) reported a 62% decrease in NH_3 losses when manure slurry was direct injected into the ground compared with surface broadcast application, and that the majority of losses occurred over the first 24-h period. The rapid incorporation of manures can also help to reduce odors and flies, which generate nuisance complaints from nearby residents.

While the incorporation of manure conserves N due to lowering NH_3 volatilization, there has been concern over the potential to enhance N_2O losses. Webb et al. (2014) investigated the effects of incorporation of cattle, pig, layer, and broiler manure on both NH_3 and N_2O emissions. They found that immediate incorporation of manure by plowing is the most effective means of reducing NH_3 emissions (90% reduction) and that incorporation of the manure did not necessarily increase emissions of N_2O, but that N_2O emissions could be affected by soil type, with a greater possibility of increased emissions on coarse sandy soils. Webb et al. (2010) provided a review of the literature regarding the impacts of manure application methods on emissions of NH_3 and N_2O, and crop response. Their overall findings were that incorporation of manure was very effective at reducing losses of NH_3 and while there were circumstances where N_2O emissions may be enhanced, the increases are not inevitable, and concern over the emissions tradeoffs should not overrule the benefit of reduced NH_3 emissions.

As we move toward more conservation tillage and reduced tillage systems to reduce PM emissions and erosion, techniques will need to be developed for incorporating manure in these systems. While injection systems exist for liquid manure, the injection of dry manures into fields and pastures is more problematic. A USDA–ARS prototype known as the Subsurfer has been show to effectively inject dry poultry litter into soils, reducing NH_3 volatilization by an average of 88% (Pote and Meisinger, 2014). Perhaps other methods for subsurface injection of manure can be developed that will help reduce emissions of NH_3 and VOCs while also reducing PM emissions from tillage. In addition, there may also be other manure treatment technologies that could be developed to stabilize N in manures, allowing them to be surface applied without the large losses of NH_3 experienced from untreated manures.

While mitigation strategies have been developed for reduction of on-farm emissions, the adoption rates of these technologies in some instances have been low. The reasons for nonadoption of technologies are associated with the high cost of some practices and the complexity of managing the mitigation strategy on farm, as well as the beliefs and biases of producers. Not only do technologies need to be cost effective and easy to manage, but in some instances they need to be demonstrated on-farm in a variety of situations to convince producers that the technology can work for them. There is still a great need for new and innovative technologies that can be used to capture and reuse nutrients on farm and reduce emissions, while being economically feasible for producers in a wide variety of settings.

Contents of the Special Section Papers

While the focus of the special section papers is on gaseous and particulate emissions from livestock operations, they represent a wide cross-section of topics. To facilitate comprehension of the special section papers, a summary of the main research topics is provided here.

Improving On-Farm Emissions Measurements

The backward Lagrangian stochastic (bLS) inverse-dispersion technique is a micrometeorological method that is widely used to estimate gas emission rates at livestock housing (Flesch et al., 2007; Leytem et al., 2013). In brief, the emission rate is calculated from gas concentrations downwind of the emissions source. While the bLS technique is accurate when flat terrain exists, applying this technique to a lagoon environment is challenging because it technically violates the bLS's underlying assumption of idealized wind flow over flat and homogenous terrain. Livestock waste lagoons are generally surrounded by a berm and, in some cases, vegetative barriers (e.g., trees), which can complicate wind flow patterns. One strategy to minimize the effect of wind complexities is to move wind and concentration sensors far downwind where the wind has approached more idealized flow conditions; however, this is not always an option. Ro et al. (2014) used a pipe network as a controlled release source of CH_4 from a lagoon landscape to evaluate optimal senor locations (i.e., three-dimensional sonic anemometer and open-path tunable diode laser absorption spectrometer [TDL]) for the bLS technique. The TDL location had a significant impact on the accuracy of the bLS technique, with the worst results (<69% accuracy) occurring when the laser was aligned across the middle of the pond near the surface of the water. When the TDL was positioned on the downwind berm, regardless of three-dimensional anemometer location, the accuracy of the bLS technique was highest (79–108%). The emission calculations from the downwind berm measurements were determined to be similar to those of a flat grass field. Considering the numerous complexities associated with equipment placement at livestock waste lagoons, the authors recommend that wind and concentration sensors be positioned on the downwind berm.

Developing Emission Factors

Emissions factors for GHGs, NH_3, VOCs, and PM are needed to fully understand the contribution from livestock production, especially if regulations are to be implemented and mitigation strategies are required. To date, there is large uncertainty in the national emissions inventories, thus prompting a flurry of research to quantify emissions from the various components of livestock operations. Miles et al. (2014) measured N_2O and NH_3 concentrations in a tunnel-ventilated commercial broiler house in Mississippi during five flock cycles to investigate the long-term reuse of pine shaving litter. Average NH_3 emissions were determined to be 14.8 kg d^{-1} or 0.54 g $bird^{-1}$ d^{-1}, and average N_2O emissions were 2.3 kg d^{-1} or 0.085 g $bird^{-1}$ d^{-1}. Emission rates were found to increase with time over the 43-d flock cycle. With respect to the NH_3 emission rate, it was about four times lower than the value of 2.32 g $bird^{-1}$ yr^{-1} used by the USEPA (2004) for broiler emissions. Extended reuse of litter, greater than 2 yr, did not contribute to increased emissions of N_2O and NH_3 beyond that reported by others where litter had been reused for 1 yr or less. The results from this study suggest that extended litter reuse could be used as a cost-savings measure without the consequence of increasing emissions.

Beef and dairy cattle are the most significant source of enteric CH_4 emissions. Increasing our understanding of CH_4 emissions from beef cattle feedlots is necessary to build more accurate emission inventories and improve predictive models to meet future regulatory requirements. Todd et al. (2014) conducted a study to quantify CH_4 emissions during winter and summer at a beef cattle feedlot on the southern High Plains in Texas. Over 32 d in the winter and 44 d in the summer, feedlot emissions rates were determined using TDLs and the bLS technique. Respective CH_4 emission rates ranged from 0.07 to 0.12 kg $animal^{-1}$ d^{-1} and 0.07 to 0.13 kg $animal^{-1}$ d^{-1}, with a calculated emissions factor of 30.9 kg CH_4 animal yr^{-1}. The CH_4 emissions from this study were within the range found at feedlots in other studies. The fraction of gross energy intake lost as CH_4 (Y_m) averaged 2.8% in the winter, 3.2% in the summer, and 3.0% overall. These values support use of the current Y_m of 3.0% recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006) for Tier 2 estimates of enteric CH_4 emissions from feedlot fed cattle.

Dust emissions from livestock operations represent a potential health hazard to individuals in the downwind environment. Bonifacio et al. (2014) used a flux-gradient technique to determine emissions of PM with an aerodynamic diameter ≤10 μm (PM_{10}) from a commercial beef cattle feedlot in Kansas. The highest hourly PM_{10} flux was 272 mg m^{-2} h^{-1}, with an overall median flux of 36 mg m^{-2} h^{-1}. The PM_{10} emissions were found to vary diurnally and seasonally; under warm conditions (21 ± 10°C), the highest hourly fluxes (116–146 mg m^{-2} h^{-1}) occurred in the early evening, while under cold conditions (−2 ± 10°C) the highest hourly fluxes (14–27 mg m^{-2} h^{-1}) occurred in the afternoon. Results from this study also demonstrate that changes in PM_{10} fluxes coincided with changes in friction velocity, air temperature, sensible heat flux, and surface roughness. Aside from meteorological conditions, the water content of the pen surface (a mixture of soil and manure) was an important parameter that affected emissions. The PM_{10} emissions were significantly lower when the water content was >20%, indicating that overall emissions could be reduced by up to 60%.

Tools for Estimating On-Farm Emissions

There is a great need for a comprehensive farm-scale model that represents all of the major sources of NH_3 emission and their interaction with other farm processes. Rotz et al. (2014) describe the development and evaluation of a process-based model, known as the Integrated Farm System Model (IFSM), that was expanded to include NH_3 formation, speciation, aqueous-gas partitioning, and mass transfer. Depending on the dairy configuration, sources of NH_3 at the dairy farms included manure on the floor of the housing, manure storage, field-applied manure, and pasture-deposited manure. The performance of the emission component was evaluated through a comparison of simulated emissions to measured and published emission data. Simulated daily, seasonal, and annual NH_3 emissions compared well with measured and published data from differing barn designs, manure storage, field-applied manure, and pastures. The expanded IFSM provides a tool for evaluating management effects on NH_3 emissions from dairy and beef cattle production systems, as well as the interacting effects of nitrate leaching, GHG emissions, nutrient runoff losses, and farm profitability.

Waldrip et al. (2014) utilized a modified version of IFSM to allow for simulated NH_3 emissions from commercial open-lot beef feedlots, with the objective of evaluating the model to predict daily, seasonal, and annual NH_3 emissions. Simulated emissions were compared with data from two feedlots in the Texas High Plains. Overall, the process-based model responded well to changes in feedlot NH_3 production and was sensitive to changes in air temperature and dietary CP. The IFSM mean daily NH_3 emission rates had 71 and 81% agreement with the observed data from the two feedlots, while annual feedlot emissions were within 11 and 24% of observations. In addition, the authors compared total annual IFSM-predicted per capita emissions with a constant emission factor used by the USEPA (i.e., 13 kg $head^{-1}$ yr^{-1}) to estimate feedlot NH_3 emissions. They determined that the constant emission factor underestimated feedlot emissions by as much as 79%. This study demonstrates that IFSM, with the feedlot module, is a useful tool for estimating average NH_3 emissions and evaluating the effects of management and climate on the potential environmental impacts of beef production.

Urea N from urine is the principal N source for emissions of NH_3 and N_2O from livestock manures. Powell et al. (2014) investigated the integrative nature of dietary N management, secretion of urea in milk, excretion of urea in urine, and emissions of N from dairy production systems. Using Wisconsin dairy farms as an example, the main objectives of their study were (i) to evaluate how changes in dietary CP, MUN, and urine urea N (UUN) may affect N emissions from commercial dairy farms; (ii) to determine how reductions in MUN and UUN may lead to statewide reductions in N emissions from dairy manure; and (iii) to discuss challenges and opportunities to expand use of MUN to enhance dietary CP use and decrease UUN excretion and N emissions from dairies. Based on analysis of MUN records from 197 herds (about 38,000 cows) in Wisconsin, approximately one-half of cows were likely consuming CP in excess of that required. The IFSM was used to estimate NH_3 and N_2O emissions from five typical dairy production systems in Wisconsin as a function of dietary CP and UUN excretion. Using the statewide average MUN of 12.5 mg dL^{-1}, the authors estimated that 48 to 87% of UUN was emitted as NH_3, with the lowest loss from a pasture-based system. The greatest loss of NH_3 emissions was associated with farms that used tie-stall barns with daily hauling of manure. Farms with free-stall barns were predicted to lose 64 to 74% of UUN as NH_3, mostly during land application and from the barns. On a daily basis, each 1 mg dL^{-1} decrease of MUN (within the range of 10–16 mg dL^{-1}) provided an associated decrease in UUN of 16.6 g cow^{-1}, which then decreased N emissions from manure by 7 to 12%. While additional data on herd MUN–UUN relationships is required, the results from this study suggest that MUN monitoring could be used to enhance dietary CP use and reduce N emissions from dairy farms.

Mitigation Strategies

To offset costs associated with standard corn (*Zea mays* L.)–soybean [*Glycine max* (Merr.) L.] meal (CBSM) diets, swine producers are supplementing diets with DDGS (Stein and Shurson, 2009). To date, most research on DDGS in swine diets has focused mainly on animal performance and carcass composition (Duttlinger et al., 2012; McClelland et al., 2012), with little attention given to environmental impacts. Trabue and Kerr (2014) fed 24 finishing pigs a standard CSBM diet or CSBM diet containing 35% DDGS for 42 d. The manure was collected twice daily and stored under simulated conditions typical of those at swine facilities. Compared with the CBSM diet, the manure from the DDGS-supplemented diet had reduced pH, increased dry matter content and surface crusting, and increased C, N, and S. However, respective manure emissions of NH_3 and H_2S were found to be 1.7- and 2.1-fold higher from the CBSM diet, while no dietary treatment effect was found for CH_4 and N_2O emissions. The results from this study indicate that swine diets containing DDGS can affect manure composition and potentially lower NH_3 and H_2S emissions during manure storage when crusting occurs.

Beef confinement operations are becoming increasingly more abundant in midwestern states such as Iowa, Minnesota, South Dakota, and Nebraska. At these facilities, cattle are sometimes raised on concrete flooring, with bedding material added on a weekly basis. Many producers maintain a bedded pack of manure and bedding through one or more groups of cattle. Bedding generally consists of locally available by-products from cereal grain production, with corn stover being the most commonly used material (Doran et al., 2010). Spiehs et al. (2014a,b) investigated the effect of using corn stover or three alternative wood-based bedding materials (kiln-dried pine wood chips, dry cedar chips, and green cedar chips) on airborne concentrations of NH_3, total reduced sulfides (TRS), CO_2, CH_4, and N_2O above laboratory-simulated bedded manure packs (Spiehs et al., 2014a). In addition, the concentration of odorous VOCs and *Escherichia coli* inside the bedded pack material was determined (Spiehs et al., 2014b). The use of dry or green cedar wood products as bedding was found to decrease airborne NH_3 and CO_2 concentrations by about 20% relative to corn stover, without affecting N_2O and TRS concentrations for at least 28 d. As the bedded pack aged, the use of green cedar was found to increase the airborne CH_4 concentration by as much as 194% after 28 d, while use of dry and green cedar also increased TRS concentrations. The use of pine chips resulted in similar gas concentrations to corn stover, with the exception of the CO_2 concentration, which was 20% higher. Green cedar bedding also had the highest concentration of odorous VOCs and pine chips the lowest. Calculated odor activity values for the packed bedding were highest for green cedar, followed by dry cedar, corn stover, and pine chips. Overall, the concentration of odorous VOCs increased as the bedded packs aged, particularly in packs containing dry or green cedar chips. Total *E. coli* concentrations in the bedded packs initially increased up to 21 d; however, by the end of the study, concentrations decreased and were statistically similar among the bedding treatments. On the basis of this information, producers who use long-term bedded pack management at their facility may benefit from using pine chips as a result of lower odor potential. Those who frequently remove bedding and manure might benefit from using cedar-based bedding materials.

Uncomposted cattle manures are often land-applied because they are a valuable source of nutrients for crop production. Volatile organic compounds emitted from the manure can be a nuisance to nearby populations, especially if the manure is not incorporated into the soil after application. In a study conducted by Brandt et al. (2008), odor concentrations were about 60% lower for injected dairy slurry when compared to surface application, with similar results reported for swine manure applications (Hanna et al., 2000; Feilberg et al., 2011). Woodbury et al. (2014) evaluated the effect of land application method (surface vs. disking), diet, soil moisture, and time since manure application on VOC emissions. Manure was obtained from feedlot pens where beef cattle were fed corn-based diets containing 0, 10, and 30% WDGS. The manure was applied at rates to meet the N requirement of corn, and VOC emissions were then measured using a wind tunnel chamber (Parker et al., 2013). In general, the emission rate of volatile fatty acids and aromatics was highest in the no-tillage treatment under dry soil conditions during the first several hours after manure application. Gas fluxes were reduced after an irrigation event but were higher in the case of sulfides (dimethyl disulfide, dimethyl trisulfide), especially in plots treated with manure from the 30% WDGS diet. Irrigation combined with manure incorporation produced the greatest reductions in odor compounds; however, manure must be immediately incorporated after application to achieve maximum benefit.

In the southeastern United States, anaerobic lagoons are used to store and treat wastewater from swine operations. Organic N compounds in the wastewater are mineralized, resulting in the formation and volatilization of NH_3, which is known to contribute to the pollution of atmospheric, terrestrial, and aquatic environments (Kirchmann et al., 1998; Hristov et al., 2011). As a result, there is much interest in technologies to reduce NH_3 from confined swine operations (Aneja et al., 2008). Szogi and Vanotti (2014) conducted a 15-mo mesoscale column study to evaluate the effect of manure pretreatment on water quality, reduction of N losses, and sludge accumulation in swine lagoons. Each of the columns initially received 14.2 L of sludge and 22.6 L of liquid from an adjacent anaerobic lagoon. Three types of liquid were applied to the columns on a weekly basis: (i) raw liquid manure from a pit recharge system (control);

(ii) liquid from a flocculant-enhanced solid–liquid separation module (SS); and (iii) liquid from a biological N module that uses nitrification–denitrification after solid–liquid separation (SS+NDN). At the end of the study, total Kjeldahl N and total ammoniacal N concentrations were both about 36% and 98% lower in the SS and SS+NDN columns, respectively, when compared to the control. Based on a N mass flow analysis, the SS and SS+NDN pretreatment reduced total N inflow by 30% and 82%, respectively. It was estimated that SS was ineffective at reducing NH_3 emissions compared with the control, whereas SS+NDN reduced total NH_3 losses by 50%. As a result, it is possible that SS+NDN effluents could be used for crop irrigation without the risk of increasing NH_3 losses during land application.

Future Directions

The ability of livestock producers to continue to provide consumers with desired products at a reasonable cost will depend on innovative ways to reduce the environmental impact of livestock production. Although the impact of livestock production on air quality is just one piece of this puzzle, it is an area that has gained much attention over the past decade. Some of the issues that will need to be addressed include (i) development of better emission factors for all air quality constituents of concern; (ii) development and/or improvement of techniques for quickly estimating on-farm emissions; and (iii) development of strategies to reduce these emissions. In addition to these issues, there is a need to start thinking on a larger scale, as airsheds cover expansive geographical areas and transport of gases over long distances is possible. Development of large-scale atmospheric models that accurately predict the generation of and quantify movement of air quality constituents will be essential, particularly when it comes to regulating these pollutants. Another area that deserves greater attention is the potential health impacts of air quality constituents (e.g., bioaerosols, PM, VOCs) from livestock production. Because there is no reliable pool of clinical data that evaluates which constituents may be the most important in terms of controlling to protect the health of nearby residents, funding such research should be a future priority.

Acknowledgments

This special section would not be possible without the dedicated and outstanding efforts by the contributing authors, reviewers, and associate editors. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. The USDA is an equal opportunity provider and employer.

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