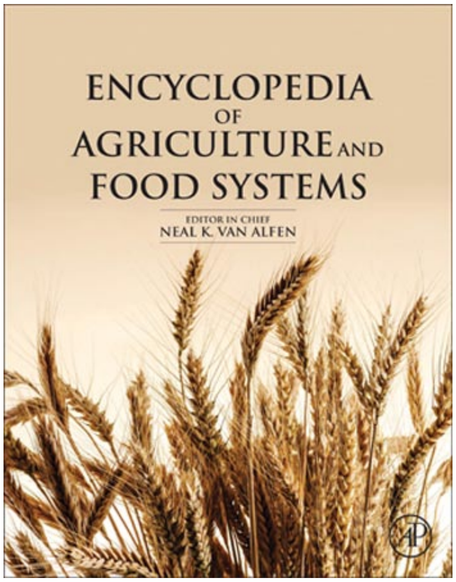

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Air: Confined Animal Facilities and Air Quality Issues

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Glossary

Air Pollutant Foreign and/or natural substances occurring in the atmosphere that may result in adverse effects to humans, animals, and/or the surrounding environment.
Ammonia (NH_3) A colorless gaseous compound of nitrogen and hydrogen that is highly soluble in water and has the ability to react with oxides of nitrogen to form ammonium nitrate, a particulate matter that contributes to air pollution and the resulting health implications.
Anaerobic digestion A biochemical process in which bacteria break down biodegradable organic material, such as manure, in an oxygen-free environment. The breakdown of organic materials results in the production of biogas, typically a mixture of methane and carbon dioxide.
Anthropogenic Originating from human activity.
Confined Animal Feeding Operation (CAFO) Agricultural operations where animals are kept and raised in confined areas, where animals feed, manure, and production operations are on a small land area. Usually, feed is brought to animals in CAFOs rather than the animals grazing. The US Environmental Protection Agency (EPA) separates CAFOs into three categories (large, medium, and small) based on the number of animals in a facility.
Criteria pollutant Six emissions identified and regulated by the EPA, including: sulfur dioxide, nitrogen dioxide, particulate matter, carbon monoxide, ozone, and lead.
Enteric fermentation The digestive process in ruminant animals, such as beef and dairy cattle, sheep, and goats, by which feed is broken down by microorganisms (bacteria, protozoa, and archaea) into simple molecules for absorption into the bloodstream. Byproducts of enteric fermentation include gaseous compounds (methane, carbon dioxide, etc.), which are expelled from animals via eructation.
Odors A substance giving off a smell, caused by one or more volatilized chemical compounds. In animal production, odorants are a major concern for the general public, as urban encroachment of agricultural land increases.
Particulate matter (PM) Any material that exists in the solid or liquid state in the atmosphere. The size of PM can vary from coarse, windblown dust particles to fine particles. Coarse particles (PM_{10}) range between 2.5 and 10 μm in diameter. Fine particles ($PM_{2.5}$) are less than 2.5 μm in diameter. Both PM_{10} and $PM_{2.5}$ can affect human and animal health and can contribute to smog and ozone formation.
Volatile organic compounds (VOCs) Carbon-containing compounds that evaporate into the air. These compounds contribute to the formation of smog and odor.

Introduction

The world population is expected to grow from today's 7 billion people to 9.3 billion people by 2050 (United Nations, 2009). Although the human population shows this dramatic growth, the amount of arable agricultural land needed to grow food to nourish these people is limited and can only increase moderately. Furthermore, increasing disposable income in developing and emerging countries leads to higher per capita consumption of animal protein, leading to an expected increase in global dairy and meat consumption of 74% and 58%, respectively (UNFAO, 2012). Thus, food production must become more efficient and intensification is one of the most viable solutions. In general, concentrated animal feeding operations (CAFOs) allow the production of relatively low cost food; however, there are externalities associated with CAFOs, such as air and water pollutants, and greenhouse gas (GHG) emissions.

Over the past decades, there has been a shift from traditional, rather low input, and extensive farms to CAFOs in the US and throughout much of the developed world. Owing to the increase in the number of CAFOs and the air quality issues surrounding them, the US Environmental Protection Agency (EPA) has created nationwide specifications for what constitutes a CAFO as well as what emissions from these operations must be monitored and mitigated.

For an animal operation to be considered a CAFO, it must first meet the definition of an animal feeding operation (AFO). An AFO is an 'operation where animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period and where vegetation is not sustained in the confinement area during the normal growing season' (USEPA, 2012b). 'Maintained' in this case means that the animals are confined in the same area where waste is generated or concentrated and can include areas where animals are fed, watered, cleaned, groomed, milked, or medicated (USEPA, 2012b). This definition also distinguishes AFOs from pasture- or grazing-based systems; therefore, animals raised on pasture are not considered to be produced in an AFO.

AFOs are defined as either medium- or large-sized CAFOs if a series of EPA specifications apply. Most significantly, an AFO is considered a CAFO if it is determined to be 'a significant contributor of pollutants to waters of the US' (USEPA, 2012b). Dairy and beef cattle, veal calves, swine, chickens, turkeys, ducks, horses, and sheep can all fall within the CAFO designation if specific threshold numbers are met. This article presents three types of CAFOs, namely those for large ruminants (beef and dairy cattle), swine, and poultry (broiler and layer).

Among the benefits of CAFOs are that they show decreases in animal mortality rates, improved feed efficiencies, and improved productivity (ASABE, 2006). However, CAFOs also have externalities including the production and emissions of nuisances, air pollutants, and GHGs. Emissions from CAFOs that contribute to poor air quality can vary in severity between the types of animals being produced (NRC, 2003); however, the key issues related to air quality remain the same across livestock production systems. Air emissions associated with CAFOs can include odorous, gaseous, and particulate compounds. This article will highlight the major air quality issues associated with CAFOs.

Air Pollutants

Air pollutants affect human and animal health as well as ecosystem health and visibility (Pope *et al.*, 2009; Cambra-Lopez *et al.*, 2010). Criteria pollutants that are regulated in the US and that have the greatest effects on air quality include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), particulate matter (PM) of less than 10 μm in diameter (PM_{10}), PM of less than 2.5 μm in diameter ($PM_{2.5}$), ground level ozone (O_3), and sulfur dioxide (USEPA, 2001). These criteria pollutants and some of their precursor compounds are regulated under the Clean Air Act and enforced by the USEPA, to address direct public health concerns (USEPA, 2012a). The National Research Council (NRC, 2003) provided a list of air emissions, which contribute most significantly to air quality concerns (**Tables 1** and **2**). In CAFOs, the primary air pollutants of concern are PM, ammonia (NH_3), hydrogen sulfide (H_2S), volatile organic compounds (VOC), and odors. Although NH_3, H_2S, VOCs, and odors are not directly regulated from most environmental agencies (with the exception of central and southern California), it is important to minimize these emissions because they can lead to the formation of criteria pollutants and often constitute nuisances. For example, ammonia can contribute to secondary PM formation (Pinder *et al.*, 2007), VOCs can contribute to O_3 formation (Shaw *et al.*, 2007; Sun *et al.*, 2008), and both NH_3 and VOCs contribute to odor production, a growing concern for policymakers as well as the general public. Additionally, there is an association between exposure to PM and adverse human and animal health effects in livestock CAFOs (Aneja *et al.*, 2009). Human exposures to $PM_{2.5}$ have been associated with pulmonary disease (Pope *et al.*, 2009) and those to PM_{10} with decreased lung function, cardiac arrhythmia, heart attacks, and premature death (Madden *et al.*, 2008). PM also contributes to impaired atmospheric visibility by scattering and absorbing light (Boylan *et al.*, 2006), issues which are discussed in other article.

The following section discusses air quality issues emitted across all CAFO types.

Ammonia

Livestock is estimated to be the single largest source of NH_3 emissions in the US, producing 71.3% of annual emissions (USEPA, 2000). Ammonia primarily results from manure degradation and forms when urease, an enzyme present in animal feces, catalyzes the hydrolysis of urea from urine (Sun *et al.*, 2008). The formation of ammonia occurs as follows:

$$(NH_2)\bullet 2CO + H_2O \rightarrow CO_2 + 2NH_3$$

Ammonia emissions are dependent on the amount of urea nitrogen (urea-N) and degree of mixing between urine and feces (Bussink and Oenema, 1998) and as a result, there are great variations in NH_3 emissions between farms (James *et al.*, 1999; VandeHaar and St-Pierre, 2006), manure land-application methods (Amon *et al.*, 2006), and time of year (Bussink and Oenema, 1998). The production rate of urea-N, and subsequently NH_3, is directly related to the concentration of nitrogen ingested by animals. Urea in ruminants is produced in the liver (detoxification of ammonia from blood circulation) and excreted in the urine. Overfeeding protein in the diet commonly leads to increased urea excretions, which affects NH_3 formation (Burgos *et al.*, 2010). The volatilization of NH_3 from any CAFO can be highly variable depending on the total NH_3 concentration in the solid or liquid phase, temperature, pH, and manure storage time. Emissions depend on how much of the N in solution reacts to form NH_3 versus ionized ammonium ($NH4^+$), which is nonvolatile (i.e., a nongaseous compound) (USEPA, 2001).

In general, NH_3 loss to the atmosphere can lead to PM formation, soil acidification, and eutrophication of surface waters (Fangmeier *et al.*, 1994; Krupa, 2003; CAST, 2011) and decreased livestock performance (Drummond *et al.*, 1980).

Table 1 Ranking of the importance of Animal Feed Operation (AFO) emissions at global and local scales

Emissions	*Global, national, and regional*	*Local, property line, and nearest dwelling*	*Primary effects of concern*
Methane (CH_4)	Significant[a]	Insignificant	Global climate change
Nitrous oxide (N_2O)	Significant	Insignificant	Global climate change
Ammonia (NH_3)	Major	Minor	Atmospheric deposition
Volatile organic compounds(VOCs)[b]	Insignificant	Minor	Quality of human life
Particulate matter	Insignificant	Significant	Health, haze
Odor	Insignificant	Major	Quality of life

[a]Ranking of the importance of each emissions based on NRC recommendations for the potential impact of emissions, both locally and nationally. Rank order from high to low is as follows: major, significant, minor, and insignificant.

[b]According to the NRC, 2003, compared with other sources, VOC emissions from AFOs are considered to be insignificant; however, recent research may warrant changes in this classification.

Source: Adapted from National Research Council (NRC), 2003. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs. Washington, DC: National Academies Press.

Table 2 Classification of air emissions from Animal Feed Operations (AFOs)

Emissions	*Criteria pollutant*	*Hazardous air pollutant*	*Greenhouse gas*	*Regulated air pollutant*
CH_4	–	–	X	–
N_2O	–	–	X	–
NH_3	–	–	–	X
Volatile organic compounds	Precursor of ozone	X	X	X
Particulate matter	X	–	–	–
Odor	–	–	–	X

Source: Adapted from National Research Council (NRC), 2003. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs. Washington, DC: National Academies Press.

Hydrogen Sulfide

Hydrogen sulfide (H_2S) and other reduced sulfur compounds are produced as manure decomposes anaerobically, resulting in the breakdown of organic matter. Hydrogen sulfide can arise from storage, handling, and decomposition of animal waste. There are two primary sources of sulfur in animal manures: (1) the sulfur amino acids present in animal feed and (2) inorganic sulfur compounds, such as copper sulfate and zinc sulfate, which are used as feed additives to supply animals with trace minerals and serve as growth stimulants for animals (USEPA, 2001; NRC, 2003). Although sulfates are used as trace mineral carriers in all sectors of animal agriculture, their use is more extensive in the poultry and swine industries. A possible third source of sulfur in some locations is trace minerals in drinking water (USEPA, 2001; NRC, 2003). Under anaerobic conditions, any excreted sulfur that is not in the form of H_2S will be reduced microbially to H_2S. Therefore, manure managed in liquid form or slurries are potential sources of H_2S emissions. The magnitude of H_2S emissions is a function of liquid phase concentration, temperature, and pH. Temperature and pH affect the solubility of H_2S in water. The solubility of H_2S in water increases at pH values above 7. Therefore, as pH shifts from alkaline to acidic, the potential for H_2S emissions increases (Snoeyink and Jenkins, 1980; USEPA, 2001). Under anaerobic conditions, livestock and poultry manures are acidic, with pH values below 5.5 (USEPA, 2001). In addition, H_2S causes respiratory problems (Donham *et al.*, 1986) and may lead to adverse effects on workers' health (Mitloehner and Calvo, 2008). Hydrogen sulfide is toxic and can be highly dangerous especially when it is suddenly released in high concentrations from stored manure in a confined area and has caused human and animal mortalities (Ni *et al.*, 2012).

Volatile Organic Compounds

VOCs vary in their reactivity and contribution to O_3 formation (Carter, 1994), and many of the VOCs emitted from fermented animal feeds have low ozone-formation potentials relative to other anthropogenic sources (Howard *et al.*, 2010a,b); however, the quantity of VOC emissions produced from CAFO feed (dairy facilities in particular) generates a valid air quality concern. VOCs are formed as intermediate metabolites in the degradation of organic matter in feed and manure (USEPA, 2001). Under aerobic conditions, any VOC formed is rapidly oxidized to carbon dioxide and water. Under anaerobic conditions, complex organic compounds are degraded microbially to volatile organic acids and other VOCs, which in turn are converted into methane and carbon dioxide by methanogenic bacteria (USEPA, 2001). When the activity of the methanogenic bacteria is optimal, virtually all of the VOCs are metabolized to simpler compounds, such as CH_4, and the potential for VOC emissions is minimal (USEPA, 2001). Other effects of VOC emissions include odor production, PM formation, O_3 formation, and ecosystem degradation (Cambra-Lopez *et al.*, 2010; Pinder *et al.*, 2007). Additionally, VOC emissions can lead to adverse health effects, such as ear, nose, and throat damage (Mitloehner and Calvo, 2008). VOCs encompass a wide range of compounds.

Odors

Odors from CAFOs are a major nuisance and have the potential to negatively impact the quality of life for the nearby residents (Fournel *et al.*, 2012). Gaseous compounds associated with odor vary greatly in molecular weight and odorant strength making it challenging to quantify and compare odors. As a result, the concept of an 'odor unit' (OU) was developed as a way to normalize the specific odor-related effect of an odor or mixture of odors. There are six major groups of odorous compounds, as identified by Mackie *et al.* (1998), which includes the previously discussed air pollutants, NH_3 and VOCs, and several sulfur-containing compounds.

Large Ruminant Facilities

Large ruminant facilities include both dairy and beef cattle operations. In 2009, US dairy and beef industries produced 85.9 billion kilogram of milk and 11.8 billion kilogram of beef, respectively (USDA, 2010). Both the industries span the continental US and range from small- to large-scale operations. Although there are still extensive, pasture-based dairy and beef operations in the US and around the world, this article focuses on intensive dairy and beef CAFOs. Typically, dairy CAFOs are integrated, freestall operations, whereas beef CAFOs are feedlots. This section provides a brief description of both dairy and beef CAFOs and the air quality issues surrounding these facilities.

Most freestall dairies are integrated, which means that they house calves, growing heifers, and dry and lactating cows on the same farm. Animals in dairy CAFOs are typically housed and fed in confinement and manure is removed from housing areas daily. Most feedstuffs are piled up on the farm premises and mixed to assemble a total mixed ration (TMR) for the cows. On dairy CAFOs, calves are typically fed milk or milk replacer, and diets are supplemented with grain. Calves are housed individually in calf hutches for approximately 2 months, until animals are weaned. Heifers are group housed and fed a forage-based TMR, and are managed to calve at approximately 2 years of age. Dry cows are fed a high-forage TMR for a 60-day period between lactations in order to recover before the next lactation. Finally, lactating cows are fed a high-nutrient, well-balanced TMR to optimize milk production.

The most intensive sector in beef cattle production is the finishing phase. This is the final phase of beef production and involves housing cattle in dirt-floored drylot corrals known as feedlots. The time an individual steer or heifer spends in a feedlot depends on its entering weight, rate of gain, and desired weight at slaughter. Cattle typically enter feedlots at 350–400 kg, with the exception of male dairy calves, which enter at 150 kg (Stackhouse *et al*., 2011). On average, cattle are housed for a total of 4–6 months until a slaughter weight of approximately 550 kg is reached (Stackhouse *et al*., 2011). Feedlot cattle are fed a high-concentrate diet containing 75–90% corn, soybean meal, dried distiller's grains, etc. and 10–25% roughage.

Manure management in large ruminant CAFOs is critical due to the sheer size of these animals and associated amounts of excreta. An adult bovine excretes 41–60 kg of feces and urine daily (Davis *et al*., 2002; CAST, 2011). Typical manure management in dairy CAFOs involves scraping excreta from dirt-floored corrals and piling it into dry storage piles. Manure from concrete floored freestall barns in which mainly lactating cows are housed can occur by either scraping or flushing. Most modern dairies prefer the latter and manure is flushed into liquid storage structures, which are often referred to as lagoons. If managed inappropriately (e.g., by overloading with nutrients), lagoons can be major sources of NH_3, H_2S, and odor emissions. In addition, manure lagoons are large contributors of GHG emissions in dairy CAFOs. Although land-application practices of dairy manure can vary, most large dairies use flood irrigation of liquid manure from the lagoons to fertilize crops on the surrounding fields. In beef CAFOs, manure from a corral is typically removed every 4–6 months, namely after a cattle group is leaving to be slaughtered. During the time cattle reside in the corrals a manure pack is formed, which can be a source of odor and PM emissions. Scraped manure from cattle corrals are mostly land applied to crops as fertilizer. Management of manure in dairy CAFOs can affect the chemical and physical properties of manure, including chemical composition, microbial populations, oxygen content, pH, biodegradability, and moisture content (MC). Manure storage allows for conservation of nutrients present in manure, which can then be utilized for application onto cropland, biodigesters, or composting.

In addition to manure management, there are several other air emission sources that result from beef and dairy CAFOs. Both dairy and beef CAFOs contribute to air pollution through emissions from animals (also known as enteric fermentation), manure, cropping systems, and feed management. This section covers the major air pollutants contributing to air pollution from dairy and beef CAFOs, namely NH_3, H_2S, VOCs, and odors.

Ammonia

The main sources of NH_3 emissions from dairies are fresh manure, long-term manure storage, and land application of manure (Bussink and Oenema, 1998). Similarly, primary emissions from beef CAFOs are from corrals, manure storage, and field-applied manure (Stackhouse-Lawson *et al*., 2012). Both dairy and beef cattle have the unique ability, being ruminants, to recycle N back to rumen bacteria that would otherwise be excreted as urinary urea-N. Although this physiological process reduces N losses, an excess of dietary crude protein (CP) beyond the animal's nutritional needs leads to an increase in urinary urea-N content (Marini and Van Amburgh, 2005). As mentioned in the Section Air Pollutants, NH_3 emissions can be very variable depending on the climate, time of year, etc. For example, NH_3 emissions from dairies were found to be two to three times greater during the summer compared with winter (Todd *et al*., 2008; Bluteau *et al*., 2009). Emissions of NH_3–N from feedlots has been estimated to be as low as 9% and as high as 56% of N fed to animals (Faulkner and Shaw, 2008; Todd *et al*., 2008; CAST, 2011). Total NH_3 losses at dairy CAFOs can range from 17 to 40 kg N per year per cow (Bussink and Oenema, 1998) or between 20 and 40 g NH_3–per day per AU (animal unit) in freestall areas (Groot Koerkamp *et al*., 1998; Snell *et al*., 2003). Diet can be altered to reduce the amount of NH_3 emissions from manure (James *et al*., 1999; VandeHaar and St-Pierre, 2006). Through optimization of N content of a diet, N excretion per unit of product, and the related NH_3 emissions, can be reduced (de Boer *et al*., 2011). The use of precision feeding that closely matches the nutritional needs of an animal can help to minimize the emissions from manure (Tylutki *et al*., 2008). Through precision feeding, producers can avoid the expenses associated with overfeeding animals and minimize nutrient excretion that can lead to emissions. This is especially beneficial when monitoring CP content of the diet because it avoids excess N being converted to urea-N, thus avoiding extra emissions of NH_3 to the environment, as mentioned above.

Manure management in dairy and beef CAFOs can also result in variability of NH_3 emissions. For example, ammonia emissions from scraped or dirt-floored corrals have been found to be three times greater than those from flushed systems (Kroodsma *et al*., 1993). Additionally, with short-term manure storage, solid manure has been found to have significantly higher NH_3 emission rates than liquid manure; however, long-term storage of manure has a reverse effect (Dewes, 1999). In the case of lagoons, a cover provided by either crust or tarp reduces NH_3 compared with uncovered manure storage structures (Sommer *et al*., 1993). One method to control emissions from manure is through the use of additives. Manure additives include commercially available products that are intended to reduce ammonia volatilization from manure. The additives are typically mixed with water and poured evenly into the manure slurry but effectiveness is variable (USEPA, 2001).

Hydrogen Sulfide

The most significant source of H_2S in dairy and beef CAFOs is from stored manure. When manure is stored in anaerobic lagoons (as is the case in many dairies) and undergoes microbial degradation, both NH_3 and H_2S are produced (Xue and Chen, 1999). Hydrogen sulfide is the result of anaerobic decomposition of sulfur-containing amino acids within these lagoons. Hydrogen sulfide emissions also contribute to the formation of odorous pollutants, which is further discussed in the Odor Section below.

Volatile Organic Compounds

Among large ruminant CAFOs, dairies are believed to be one of the largest sources of VOC emissions (Malkina *et al.*, 2011). Emissions of VOCs in dairy CAFOs originate predominantly not only from fermented feedstuff before it is ingested (Howard *et al.*, 2010a), but also by manure and from dairy cattle directly via enteric fermentation (Filipy *et al.*, 2006; Shaw *et al.*, 2007; Alanis *et al.*, 2010). Fluxes of VOCs from cows and waste include methanol, acetone, propanal, dimethylsulfide, and acetic acid (Shaw *et al.*, 2007). Additionally, when assessing manure alone from dairies, the most abundant VOC fluxes were found to be methanol and acetic acid (Hobbs *et al.*, 2004; Shaw *et al.*, 2007). Fermented feeds, such as silage, are major sources of VOC and they require large amounts of fossil fuel inputs for production (de Boer, 2003; Schils *et al.*, 2007).

Silage production has recently been identified as a major source of VOCs from dairies (Alanis *et al.*, 2008) and might show to be the leading agricultural source in locations like Central California (Howard *et al.*, 2010a). In a recent study, Chung *et al.* (2010) identified 48 VOCs from dairy sources, which included sources from silage and TMRs, whereas Malkina *et al.* (2011) identified 24 VOCs from silage and TMR emissions.

Odor

According to the National Research Council (2003) the main sources of odors emitted from dairy CAFOs result from silage mounds, barns, waste storage facilities, or land-applied manure. The greatest contributors of odors in livestock CAFOs are several groups of VOCs, including sulfur-containing compounds (hydrogen sulfide), volatile fatty acids (VFAs), phenols, and indoles (Shabtay *et al.*, 2009). Odor emissions from beef cattle fattening operations are affected by life stage and manure management (Shabtay *et al.*, 2009). In dairies, VOCs have the greatest impact on odors. Additionally, land application of manure, storage of manure, and dairy housing have been found to produce odor emissions of 1.5–90, 5.1–32, and 1.3–3.0 OU s^{-1} m^{-2}, respectively (Pain *et al.*, 1991; ASABE, 2006). Techniques to minimize odor from manure storage include covering lagoons, either with a natural crust or an artificial membrane, aerating storage basins (Westerman *et al.*, 2000), or utilizing anaerobic digestion of manure (Powers *et al.*, 1997).

Swine Facilities

To optimize production efficiency, the majority of swine facilities use enclosed and ventilated barns for housing. The hog production cycle has three main phases consisting of farrowing, nursing, and growing/finishing. Swine CAFOs can consist of one or two of these phases per barn but most commonly encompass all three in a farrow-finish production program (USEPA, 2001). In swine CAFOs, emissions are primarily generated from anaerobic microbial decomposition of organic matter in manure and spoiled feedstuff occurring either in barns, manure storage structures, or during manure land application (CAST, 2011). As with other livestock species, swine diet composition has a significant impact on the concentration and type of emissions coming from animal manure. There are various management methods utilized in swine production settings. In the US, swine are mainly intensively managed indoors on bedded or slatted floors. Bedding, such as straw, cornstalks, or sawdust, is used to collect solid manure and this bedding along with the manure is applied to cropland as fertilizer. There are four principal types of waste management systems used with confinement housing in the swine industry: deep-pit, pull-plug pit, pit recharge, and flush systems (**Table 3**). These differ depending on the state of manure collection and frequency of cleaning and draining. All of these systems use slatted floors (USEPA, 2001). The pit system allows the animal waste to fall through the slats directly into a pit and is collected in liquid form (Hamon *et al.*, 2012). Manure storage is in either an anaerobic lagoon or an external storage facility. In the pit systems, the space may be cleaned from daily to annual intervals, depending on the type utilized. In flush systems, manure is removed several times a day (USEPA, 2001). The pull-plug system removes manure from the pit after being stored for about a week and is then moved to outside storage facilities. This keeps emissions lower within the swine facilities but not necessarily with the later storage of removed manure (Cole *et al.*, 2000). These storage practices result in the decomposition of manure and formation of biogas. Ammonia, hydrogen sulfide, and VOC emissions may be higher in flush systems than from pit recharge and pull-plug pit systems due to turbulence during flushing.

Ammonia

The major air quality concern from swine CAFOs is NH_3 emissions from manure (Cole *et al.*, 2000). Ammonia

Table 3 Summary of emissions from Swine Model Farms (tons per year per 500 animal unit farm)

Type of manure	*Ammonia (NH_3)*	*Hydrogen sulfide (H_2S)*	*Volatile organic compounds*
Flush	15	2.6	0.6
Pit recharge	15	0.9	0.6
Pull-plug with lagoon	15	0.9	0.6
Pull-plug with storage tank	11	NA	NA
Deep pit	12	0.3	NA

Source: Adapted from US Environmental Protection Agency (USEPA), 2001. Emissions from Animal Feeding Operations. EPA 68-D6-0011. Research Triangle Park, NC: USEPA.

concentrations inside confined swine facilities varies widely, from 1.9 ppm to as high as 25.9 ppm and is dependent on the cleanliness of the facility (Duchaine *et al.*, 2000) as well as the time of year and barn ventilation rate (Heber *et al.*, 2000, 2004, 2005). Ammonia emission rates can be affected by housing type, animal size and stage of production, manure management, storage and treatment, feed nitrogen content, and climatic variables (Leneman *et al.*, 1998; Arogo *et al.*, 2003). Ammonia emissions have been found to vary by stage of production. For example, farrowing rooms and nurseries have lower NH_3 emissions than gestation or grow-finish facilities (Zhu *et al.*, 2000; Jacobson *et al.*, 2006). This is due to the higher protein requirement for growing/finishing animals. Zahn *et al.* (2001) studied the ammonia emission rates from 29 swine manure storage systems. These studies showed that deep-pit and pull-plug systems emitted NH_3 at a rate of 57 g NH_3 per square meter per day. On average, lagoons released 85 g NH_3 per square meter per day. Earthen, concrete-lined steel tanks emitted NH_3 at a rate of 144 g NH_3 per square meter per day. These external storage tanks release a significant amount more than the other two systems. The USEPA (2001) confirmed this large NH_3 formation in external manure storage facilities. In general, one of the greatest issues around ammonia in swine production are its effects on the respiratory system leading to irritation of the eyes, skin, mucous membranes, and upper respiratory system.

Hydrogen Sulfide

Hydrogen sulfide forms in deep-pit, pull-plug pit, and in external manure storage management systems (USEPA, 2001). According to Zahn *et al.* (2001), on average, lagoons emitted 0.25 g H_2S per square meter per day; deep-pit and pull-plug systems emitted 0.32 g H_2S per square meter per day; and the eternal tanks emitted 0.95 g H_2S per square meter per day. Once again, the external tanks emitted a significant amount more than the lagoons, and deep-pit and pull-plug systems. In addition to being a health hazard and air pollutant in swine facilities, H_2S contributes to odors, as outlined in the following Odors Section.

Volatile Organic Compounds

In addition to NH_3 and H_2S, Zahn *et al.* (2001) investigated VOC emission rates in 29 manure storage systems. The lagoons systems averaged 63.8 g per VOC syterm per hour; the deep-pit and pull-plug systems emitted 89.9 g per VOC system per hour; and the steel tanks emitted 394 g per VOC system per hour. Other studies have also been performed to quantify VOC emissions from swine facilities. Bicudo *et al.*, 2002 measured the mean VOC emissions at three different swine facilities and found that an 8000-head nursery emitted 204 $\mu g\, s^{-1}\, m^{-2}$, a 2000-head finishing facility emitted 291 $\mu g\, s^{-1}\, m^{-2}$, and a 3000-head finishing facility emitted 258 $\mu g\, s^{-1}\, m^{-2}$. Compared with all manure storage systems, anaerobic lagoons emit the least VOCs and noxious odors (USEPA, 2001).

Odor

Odors from swine CAFOs are primarily comprised of NH_3 and H_2S emissions (Cole *et al.*, 2000; Hamon *et al.*, 2012). Emissions of odors are dependent on seasonal and climatic parameters, as is the case with other CAFOs. Anaerobic processes can also release VFAs that can be considerably more offensive than ammonia or hydrogen sulfide. In terms of manure management, odors increase as the animal manure decomposes (Cole *et al.*, 2000). H_2S creates a very pungent and noticeable sulfur odor. In addition to odor contributions from NH_3 and H_2S emissions, feed composition also plays a direct role in the quantity and intensity of the odors produced (Gralapp *et al.*, 2002). Although NH_3 and H_2S are abundant odors in terms of concentrations in swine CAFOs, approximately 400 different odorous compounds have been identified (Hamon *et al.*, 2012).

Poultry Facilities

Poultry CAFOs include both broiler (chickens used for meat production) and layer (chickens used for egg production) facilities. Broilers are typically produced in littered floor systems, where birds are kept in a closed structure (termed a house) with space to move and access to feed and water systems. Bedding for broiler housing varies by geographical location, but material can include rice hulls, wheat or rye hulls, sawdust or wood shavings, peanut shells, sand, chopped straw, or corn stalks. The bedding used in broiler houses is referred to as litter when it is mixed with feces (USEPA, 2001). Most of the litter is reused (also known as built-up litter) over multiple flocks of production (CAST, 2011). Alternatively, caked litter (i.e., litter that has a wet and hardened surface layer, usually found along the feed and water lines where much of the manure is deposited) is removed between each flock (CAST, 2011; USEPA, 2001). Layer chickens are primarily raised in cage systems, where the birds are housed in cages with a relatively limited amount of space. These can either be in high-rise (HR) (65–70% of cage systems), or manure-belt (MB), (25–30% of cage systems) housing systems (CAST, 2011; Xin *et al.*, 2010) but alternative cage-free housing systems do exist and are increasingly popular. Manure in HR facilities is typically stored in the lower level of the house for 1 year and removed as solid manure in the fall for cropland application. Manure in MB houses is removed daily to weekly, via the MB, and can be stored either on-site, in separate storage, or a composting facility (Xin *et al.*, 2010).

As with other livestock facilities, emissions vary depending on housing and manure management systems. Although a substantial amount of research has been performed to determine air quality emissions associated with on-site production and storage of manure, there is limited data on emissions associated with land-applied poultry manure (a common practice for poultry facilities). Air quality in poultry CAFOs is an area of concern; however, most research is on NH_3, whereas data on other air pollutants, such as PM and VOCs is limited.

Mitigation techniques in poultry facilities are utilized mainly by manure management. Dietary manipulation (Roberts *et al.*, 2007), topical application of chemical or mineral additives to poultry manure (Li *et al.*, 2008), treatment of exhaust air via a biofilter or wet scrubber (Melse and Ogink, 2005; Manuzon *et al.*, 2007; Shah *et al.*, 2008), and faster application of land-applied manure have been investigated as possible mitigation techniques to minimizing emissions associated with manure from poultry CAFOs. Through direct incorporation, or injection, of manure into soil with immediate tillage there is the potential to minimize emissions from land-applied manure (CAST, 2011). Injection of manure during land application can minimize odors, NH_3, and VOC emissions. In layer facilities specifically the use of MB systems should be used for manure management because they significantly reduce odors and NH_3 emissions (Fournel *et al.*, 2012).

Ammonia

Among both layer and broiler CAFOs, NH_3 is the major noxious gas produced. The primary source of NH_3 from poultry is from manure, both in-house and off-site. Manure excreted from poultry has a high MC and as the moisture evaporates, NH_3 is emitted (USEPA, 2001). The generation and concentration of indoor NH_3 is influenced by housing and manure management practices, as with other livestock CAFOs. Broiler manure storage is in-house, so continuous airflow from ventilation systems is used to help minimize the amount of NH_3 exposure for animals, as NH_3 is emitted year round (USEPA, 2001). However, this does not minimize NH_3 emissions; rather it likely leads to elevated emissions of NH_3 to the atmosphere (CAST, 2011). Manure management in layer housing systems that utilize manure belts allows manure to dry to between 30% and 60% MC, making it easier to transport and creating less NH_3 emissions (Xin *et al.*, 2010). Ammonia concentrations in MB housing are generally lower than in other housing systems (Green *et al.*, 2009) due to the higher frequency of manure removal (Green *et al.*, 2009). Long-term broiler manure storage with high MC can further mineralize organic nitrogen to NH_3 (USEPA, 2001). Though only a small amount of research has been performed in regard to land-applied poultry manure, NH_3–N losses from land-applied poultry manure (expressed as a percentage of manure nitrogen content) have been estimated at 7% for dry laying-hen manure (Lockyer and Pain, 1989), 41.5% for wet laying-hen manure (Lockyer and Pain, 1989), and 25.1% for broiler litter (Cabera *et al.*, 1994). Prolonged exposure to elevated NH_3 concentrations adversely affects bird health, such as the respiratory system and productivity (e.g., feed intake, bodyweight gain, egg production, and feed conversion) (CAST, 2011). For poultry housing, the recommended indoor NH_3 concentration is less than 25 ppm (MidWest Plan Service, 1990; United Egg Producers, 2010).

Hydrogen Sulfide

With dry manure collection from poultry and the associated manure storage facilities, any sulfur excreted should be oxidized to nonvolatile sulfate, thus making H_2S production negligible (USEPA, 2001). Hydrogen sulfide emissions are varied because of MC, the time manure stays in the facility, the ventilation rate, and incidence and duration of storage (USEPA, 2001). In broiler facilities, daily mean H_2S concentrations have an inverse relationship to house ventilation rates and molting of birds causes these H_2S concentrations to decrease (Ni *et al.*, 2012). There is little information about H_2S emissions from layers but averages of 19.7 ppb H_2S have been reported for commercial layer houses, 26.4 ± 17.6 and 24.9 ± 19.0 ppb for HR houses, and 40.0 ± 21.1 and 41.2 ± 31.5 ppb MB houses (Lim *et al.*, 2003; Ni *et al.*, 2012, respectively). Higher concentrations of H_2S have been reported to be approximately 40–100 ppb in some broiler facilities (Zhu *et al.*, 2000). Poultry H_2S emissions are much lower than those from other livestock, such as swine (Zhu *et al.*, 2000). If there is residual H_2S in poultry manure at the time of land application, it is oxidized to sulfate but with transient saturated soil conditions sulfate can be reduced back to H_2S and be aerosolized (USEPA, 2001).

Volatile Organic Compounds

Poultry manure is also a contributor to VOCs which, as mentioned in the Section Air Pollutants, can contribute to ozone and odor formation. The high MC of poultry manure leads to the production of VOCs (USEPA, 2001). Poultry manure forms different dienes, ketones, aldehydes, and aromatics, with an overall contribution of 36.43 ± 26.57 ug m^{-3} of total VOC from animal sources (Howard *et al.*, 2010b). The overall contribution from poultry has been found to be significantly less than contributions from cattle or swine (Howard *et al.*, 2010b). Poultry litter composting also contributes to VOC emissions. Composting of poultry litter has been found to emit high amounts of alkanes and alkylated benzenes, with much lower emissions of aldehydes, terpenes, and ketones (Turan *et al.*, 2007). The greatest production of VOC emissions occur early during the composting process and declines rapidly thereafter with the maximum production of VOCs obtained within the first 5 days (Turan *et al.*, 2007).

Odor

Odor associated with poultry is often a result of manure and the most noxious odor has been identified as ammonia (CAST, 2011). Although there is odor associated with poultry CAFOs, its incidence is much less than that of swine facilities and is produced at constant concentrations throughout the day (Zhu *et al.*, 2000). In layer facilities the use of MB systems, both forced air drying and natural drying, reduces odor emissions, respectively, by 37% and 42% compared with odor emissions from a deep-pit technique (Fournel *et al.*, 2012). MB systems also produce less odor than deep-pit systems due to their frequent manure removal (Fournel *et al.*, 2012). Odor incidence in poultry increases as a result of higher temperatures during summer months, and odor varies depending on the age of birds and the season (Fournel *et al.*, 2012; Hayes *et al.*, 2006). Odor from broiler facilities is associated with litter and worsens when the litter is damp (Hayes *et al.*, 2006). Broiler house odors of the same concentration are perceived as more intense than odors emitted from pig slurry and there is a greater correlation between poultry manure odor intensity and concentration than in swine (Misselbrook *et al.*, 1993). Composting of litter also produces odor as organic compounds can be volatilized during composting (Turan *et al.*, 2007).

Conclusion

As the global human population rises and the degree of affluence in developing nations grows, people demand more food and in particular more high quality animal protein. This demand for protein requires intensification of animal facilities in order to maximize production on limited land. CAFOs have become the main mode for efficient animal production in the US. However, the high stocking density of CAFOs leads to greater amounts of air pollutants and a rise in associated concerns. Additionally, manure and feed storage and management have been a recurring contributor to air quality issues in all three CAFOs. Dairy, beef, swine, and poultry CAFOs all emit NH_3, H_2S, VOCs, and odors, and these air pollutants can impact human and animal health. Numerous approaches to mitigate emissions are currently being studied and include improvements of animal production efficiency, herd health, nutrition, and feed production, as well as manure management strategies.

See also: Air: Greenhouse Gases from Agriculture. Beef Cattle. Climate Change: Animal Systems. Dairy Animals. Dust Pollution from Agriculture. Poultry and Avian Diseases. Swine Diseases and Disorders

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