Environmental impacts and sustainability of egg production systems[1]

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ABSTRACT As part of a systemic assessment toward social sustainability of egg production, we have reviewed current knowledge about the environmental impacts of egg production systems and identified topics requiring further research. Currently, we know that 1) high-rise cage houses generally have poorer air quality and emit more ammonia than manure belt (MB) cage houses; 2) manure removal frequency in MB houses greatly affects ammonia emissions; 3) emissions from manure storage are largely affected by storage conditions, including ventilation rate, manure moisture content, air temperature, and stacking profile; 4) more baseline data on air emissions from high-rise and MB houses are being collected in the United States to complement earlier measurements; 5) noncage houses generally have poorer air quality (ammonia and dust levels) than cage houses; 6) noncage houses tend to be colder during cold weather due to a lower stocking density than caged houses, leading to greater feed and fuel energy use; 7) hens in noncage houses are less efficient in resource (feed, energy, and land) utilization, leading to a greater carbon footprint; 8) excessive application of hen manure to cropland can lead to nutrient runoff to water bodies; 9) hen manure on open (free) range may be subject to runoff during rainfall, although quantitative data are lacking; 10) mitigation technologies exist to reduce generation and emission of noxious gases and dust; however, work is needed to evaluate their economic feasibility and optimize design; and 11) dietary modification shows promise for mitigating emissions. Further research is needed on 1) indoor air quality, barn emissions, thermal conditions, and energy use in alternative hen housing systems (1-story floor, aviary, and enriched cage systems), along with conventional housing systems under different production conditions; 2) environmental footprint for different US egg production systems through life cycle assessment; 3) practical means to mitigate air emissions from different production systems; 4) process-based models for predicting air emissions and their fate; and 5) the interactions between air quality, housing system, worker health, and animal health and welfare.

Key words: hen-housing system, environmental footprint, emissions mitigation

STATEMENT OF THE ISSUE

Animals, feed, manure, and housing accessories, such as bedding materials and heating devices, constitute the potential sources of environmental footprint (carbon, nitrogen, phosphorus, airborne particulates, and microorganisms) of an animal feeding operation. The impact on the ecological systems may result from direct release of airborne constituents into the atmosphere, direct runoff to water bodies, leaching to groundwater, or indirect deposition of the airborne constituents

into water bodies. An emerging means of quantifying the environmental impact is to characterize the system in terms of its environmental footprint, which may entail carbon and nitrogen cycles and the underlying energy resources needed for operation. Current and emerging commercial egg production facilities involve varieties of housing and manure handling practices, which can produce different magnitudes of environmental footprint. Different production or housing systems also have variable abilities to provide the appropriate thermal and nonthermal microenvironments to the hens, thereby affecting hen comfort, health, or both and resource utilization efficiency. However, research information concerning the environmental footprint for various egg production systems and the system's ability to maintain the microenvironment that is conducive to enhancing bird welfare and health, conservation of natural resources, and production efficiency is meager in the literature.

The objectives of this white paper were 2-fold:

1. To review the state of science on the environmental impacts of different egg production systems and summarize available literature information; and

2. To identify knowledge gaps and hence future research needs that will lead to improved understanding of environmental impacts by various egg production systems, especially the emerging alternative egg production systems.

STATE OF THE SCIENCE

Characteristics of Manure Handling Systems

Manure characteristics and handling practices have profound impacts on the production of aerial constituents and their fate after aerial transport from an animal feeding operation. Different manure handling practices or systems exist in egg production facilities because of specific production systems used (e.g., littered floor vs. cage housing) or different management schemes [e.g., manure removal frequency or drying method (air duct vs. natural evaporation) in manure belt (**MB**) housing systems]. Although hen manure is a valuable nutrient resource for crops and feedstock for renewable energy, its handling or presence can pose significant environmental burdens for both air and water quality and energy for processing. In cage layer systems, the houses will take either the high-rise (**HR**) style or MB style (Figure 1). The approximate partitioning of the total cage layer houses in the United States is 70% HR and 30% MB, although the new houses mostly use the MB style. Noncage housing systems commonly incorporate a combination of manure management schemes. A major difference between cage and noncage systems is that the noncage housing uses some type of bedding material (e.g., sawdust, wood shavings, rice hulls, and rye hulls) in at least part of the house, which will alter the physical and nutrient properties of the manure and litter (mixture of manure and bedding).

MB Housing Systems. In the MB cage housing system, fresh manure [approximately 75% moisture content (**MC**)] drops onto a belt beneath each row of cages. Manure on the belt is either dried "naturally" by the ventilation air or a forced-air stream directed, through an air duct under the cages, over the manure surface. At a given interval, ranging from daily to weekly, the manure is conveyed via the belt to one end of the house and removed to an on-farm or off-farm storage or composting facility or land application. Depending on natural or forced drying on the belt and the seasonal climate, manure leaving MB houses will have a MC of less than 30 to 60%. Lower MC manure is easier to transport and emits less ammonia. On a per-hen basis, MB cage systems are generally 50% higher in capital costs than their HR counterparts; however, MB systems offer considerable benefits. Manure removal from MB houses is less labor-intensive than the other methods, but maintenance of the belt conveyor is critical. Belt manufacturers continue to improve the quality of manure belts over the years, and today's manure belts generally have a lifespan of 10 yr or longer. Indoor air quality, especially ammonia and dust levels, of MB houses is generally much better than that with other manure management practices (i.e., HR or littered floor rearing systems; Green et al., 2009). The frequent manure removal also results in significantly lower ammonia emissions from MB houses as compared with HR houses (Liang et al., 2005). It should be noted that manure storage for MB houses also contributes to atmospheric emissions. However, because of the much-reduced manure surface area and generally lower storage temperature, emissions per hen from manure storage are considerably lower than those in house, as revealed from environment-controlled, laboratory-scale studies (Li, 2006; Li and Xin, 2010). Moreover, aerial emissions from separate manure storage for MB houses can be more readily controlled through physical, chemical, or biological means (Li et al., 2008c). This is because a) the manure area to be treated in a storage shed is much smaller and thus requires less treatment agent and b) it is away from housing components (e.g., ventilation fans and hens) and hence eliminates potential corrosive effects of chemicals. Additional research is needed to further quantify aerial emissions from manure storage associated with MB operations under commercial production conditions.

HR Housing Systems. In the HR cage housing system, manure either directly drops into a storage area

Figure 1. A schematic representation of a high-rise layer house (left) and photos of a manure belt layer house (middle) and manure storage shed (right). Color version available in the online PDF.

beneath the cages or first falls onto dropping boards, followed by periodic (4 to 6 times daily) scraping into the manure store. In the cases with dropping boards, manure will lose some of its moisture from evaporation on the dropping board. In either case, most of the drying is done via ventilation air during the storage. The ventilation systems and the cage arrangements in HR houses are engineered such that the warmed ventilation air, after passing through the hen area, is directed to flow over the manure surface, providing a degree of manure drying. Compared with direct manure dropping into storage, the board-scraper systems have narrower floor gaps (typically 15 cm, or 6 in.) between the cages and the manure store, which causes higher air velocity over the manure piles and thus an enhanced drying effect. While on the dropping boards, manure has a greater surface area exposed to air, and consequently manure in the board-scraper houses generally has a lower MC than that in the direct-drop (HR) houses [e.g., 32 vs. 50% as reported by Lorimor and Xin (1999)]. The ventilation system also prevents most of the ammonia in the manure storage area from migrating to the bird level by a pressure differential between the levels, hence improving bird-level air quality. Manure is typically removed from the store once a year (in the fall), although some operations opt to remove manure more frequently, even on a weekly basis. Removal of manure is more labor-intensive but occurs less frequently, and as such, maintenance of manure-handling equipment is less demanding and time-critical. The inherent characteristics of manure pile formation throughout the manure collection and storage level and the warmer in-house environment make ammonia emissions from HR houses much higher than those from MB counterparts (Liang et al., 2005). Research and demonstration are ongoing to reduce ammonia generation of the manure through dietary manipulation, and the results have been promising (Roberts et al., 2007; H. Xin, unpublished data).

Littered-Floor Housing Systems. In noncage housing systems with pullets or hens reared on a littered floor or partially littered floor, manure collects on the litter floor and beneath the slatted floor and is typically removed between flocks. Management of the littered floor has a significant effect on the ammonia and particulate matter (**PM**) concentrations within the barns. Regular additions or replenishing of fresh bedding (e.g., sawdust or wood shavings) and appropriate ventilation can reduce the litter MC and thus ammonia released into the air. Because of the lower stocking density (fewer birds per unit of barn space), ventilation rates are generally much lower in these types of houses to conserve building heat. Consequently, ammonia levels in such barns are much higher and air temperature is much lower during cold weather, as compared with cage systems (Green et al., 2009). The presence of litter also causes dust concentrations and emissions to be much higher for the noncage littered floor barns than

for cage barns (Martensson and Pehrson, 1997; Wathes et al., 1997; Takai et al., 1998).

Free-Range Operations. For free-range operations, some manure is excreted on pasture and thus does not have to be collected and stored. However, this makes pasture management a critical issue for free-range systems and results in a greater environmental footprint (Williams et al., 2006). As in other pasture systems, intensive management of rotational grazing systems is critical for both forage quality and nutrient management. In certain soils, a build-up of phosphorus from poultry manure application is a key issue because grazing cattle return to the pasture over 80% of phosphorus consumed in the forage (Wilkinson and Stuedemann, 1991).

Land Application. For systems with manure or litter storage, manure or litter is periodically land-applied. The manure or litter serves as a rich and increasingly valuable source of crop nutrients. Because of bedding materials in the litter, its manure nutrient levels are less than pure manure; however, litters are generally much drier than pure manure. Relatively long-term research has demonstrated that proper application of laying hen manure to crops (corn and soybean) improves water quality and crop yields, as compared with use of commercial fertilizers (Nichols et al., 1994; Chinkuyu et al., 2002; DeLaune et al., 2004; R. Kanwar, Iowa State University, personal communication). Application of manure to croplands based on nutrient profiles of both soils and manure (i.e., following a comprehensive nutrient management plan) is the norm in modern use of livestock and poultry manure for crop production. State and national training programs are available and routinely conducted to continually update knowledge for animal producers and technical service providers.

Alternative Uses of Manure Nutrients. Besides land application, laying hen manure or litter may be composted, pelletized, or used as a renewable energy feedstock. Compost and pelletized manure is a valuable fertilizer or soil amendment. Uses as a renewable energy feedstock include thermochemical conversion processes such as direct burning, gasification, pyrolysis, and anaerobic digestion for biogas generation. A comparative analysis of various manure nutrient uses with regard to the environmental footprint and economic viability would be beneficial.

Air Emissions from Laying Hen Facilities

Ammonia is the major noxious gas associated with poultry operations. Bird feces contain uric acid that can be rapidly converted to ammonia in the presence of appropriate microbes. Elevated concentrations of atmospheric ammonia in poultry houses will reduce feed intake and impede bird growth rate (Charles and Payne, 1966a; Carlile, 1984; Deaton et al., 1984), decrease egg production (Charles and Payne, 1966b), damage the respiratory tract (Nagaraja et al., 1983), increase sus-

ceptibility to Newcastle disease virus (Anderson et al., 1964), increase the incidence of air sacculitis (Oyetunde et al., 1978) and keratoconjunctivitis (blind eye; Faddoul and Ringrose, 1950), and increase the prevalence of *Mycoplasma gallisepticum* (Sato et al., 1973). Egg quality may also be adversely affected by high levels of atmospheric ammonia as measured by reduced albumen height, elevated albumen pH, and albumen liquefaction (Cotterill and Nordsog, 1954). Furthermore, hens prefer fresh air to ammoniated atmospheres, although the aversion is not apparent until about 30 to 40 min after initial exposure (Kristensen et al., 2000). The commonly recommended ammonia level for US poultry housing has been 14.7 mg/kg (25 ppm; UEP, 2008), which is the same as the 8-h daily time-weighted average exposure limits for humans set by the National Institute of Occupational Safety and Health (CDC, 2005) and in the United Kingdom. Indoor ammonia levels are greatly affected by housing and management factors, such as housing type, bird age and density, manure or litter conditions and handling schemes, and building ventilation rate. Ammonia emissions are an environmental concern because atmospheric ammonia can significantly alter oxidation rates in clouds and enhance acidic particle species deposition (acid rain). Ammonia is also a component of odor and can be a precursor of secondary fine PM. Thus, it is of national interest to determine sources of ammonia and their relative contributions to a national inventory.

A US Environmental Protection Agency (**EPA**)-funded ammonia inventory study (Battye et al., 1994) has been widely referenced in estimating agricultural contributions to US ammonia emissions inventory. The report suggests that 80.9% of total US ammonia emissions were from animal husbandry activities (cattle 43.4%, poultry 26.7%, swine 10.1%, and sheep 0.7%). The report primarily used European literature (British, Dutch, and Scandinavian countries) for their results. The latest EPA estimations of ammonia emissions from animal husbandry operations can be found at http://www.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf (accessed March 2009). Since the release of the National Academy of Sciences Report (NRC, 2003) that called for the collection of baseline air emissions data for US animal feeding operations, a few multistate research projects have been completed that quantify air (especially ammonia) emissions from US poultry production operations (Liang et al., 2005; Wheeler et al., 2006; Burns et al., 2007; Li et al., 2008b; Li and Xin, 2010). A study is currently in progress that monitors 3 laying hen farms (a total of 8 barns, including 6 HR barns and 2 MB barns and a manure storage shed) in 3 states (California, Indiana, North Carolina) under the EPA's Air Consent Agreement with the egg industry. Furthermore, increasing attention has been devoted to investigating practical means to reduce air emissions from animal production facilities. For instance, a multistate project is ongoing that involves field demonstrations of using dietary manipulation to mitigate ammonia emissions from layer houses without adversely affecting bird nutrition and production performance (H. Xin, personal communication). Other mitigation methods under investigation include topical applications of various treatments to manure, including acidifiers, adsorbent minerals (zeolite), and urease inhibitors (Li et al., 2008c; Singh et al., 2009).

Particulate matters in laying hen facilities can originate from the hens themselves (feathers and skin dander), feed particles, litters (in the case of noncage, littered floor systems), and feces. Particulate matter is generally classified according to the size of the particles, such as total suspended particulate (**TSP**), PM with an aerodynamic diameter of 10 μm or less (**PM_{10}**), and PM with an aerodynamic diameter of 2.5 μm or less (**$PM_{2.5}$**). Particulate matter with an aerodynamic diameter of 10 μm or less is also referred to as inhalable particulate, whereas $PM_{2.5}$ is referred to as respirable. The smaller the PM, the more harmful they can be to animals and humans because they can penetrate deeper into the animal's or human's respiratory system (lungs). In addition to the PM sources mentioned above, another $PM_{2.5}$ source is the secondary particle formation process that takes place when ammonia combines with oxides of nitrogen or sulfur. In the United States, the 8-h daily time-weighted average exposure limits for humans are 15 mg/m^3 for total dust and 5 mg/m^3 for respirable dust (OSHA, 2006). The PM levels in animal housing are greatly influenced by the levels of animal activities, feeding events, litter MC, and environmental conditions (especially humidity levels). More activities will stir up more dust, especially with the presence of litter, and drier air and litters will lead to more dust generation (Li et al., 2008a).

Poultry operations can also be a source of greenhouse gases (**GHG**), although their contributions are far less than those of ruminant animals. These gases include H_2O, CO_2, CH_4, and N_2O. Greenhouse gases absorb energy (heat) in specific wavelength bands in the thermal infrared. Global warming potential (**GWP**) of GHG is an index that is usually used in a relative sense to compare a specific gas to a reference gas in terms of its ability to trap outgoing thermal infrared radiation. The atmospheric lifetime of both molecules is taken into account in the GWP calculation, and CO_2 is usually chosen as the reference molecule. Thus, both high absorbance and long atmospheric lifetime can elevate GWP. In GHG inventories, the GWP of a gas or gas mixture may be expressed as CO_2 equivalents over a certain time horizon. The 100-yr horizon values (i.e., presence of the GHG in the atmosphere for 100 yr) for CH_4 and N_2O have GWP of 23 and 296 times of that for CO_2, respectively, and are therefore important in discussion of climate change even though they are present in the atmosphere at concentrations less than 1/100 of that of CO_2 (IPPC, 2007).

The production of N_2O from poultry manure depends on feces composition, microbes and enzymes involved, and the conditions after excretion. Mostly, N_2O can

Table 1. Summary of NH_3 emission rates (ER, g of $NH_3 \cdot AU^{-1} \cdot d^{-1}$)[1] of laying hen houses with different housing and management schemes in different countries (Liang et al., 2005)

Country	House type (season)	Manure removal	NH_3 ER	Reference (year)
England	Deep pit (winter)	Information not available	192	Wathes et al. (1997)
England	Deep pit (summer)	Information not available	290	Wathes et al. (1997)
England	Deep pit (NA[2])	Information not available	239	Nicholsen et al. (2004)
United States (Ohio)	High-rise (March)	Annual	523	Keener et al. (2002)
United States (Ohio)	High-rise (July)	Annual	417	Keener et al. (2002)
United States (Iowa)	High-rise (all year)	Annual	299	Yang et al. (2002)
United States (Iowa and Pennsylvania)	High-rise (all year)— standard diet	Annual	298	Liang et al. (2005)
United States (Iowa)	High-rise (all year)—1% lower CP diet	Annual	268	Liang et al. (2005)
The Netherlands	Manure belt (NA)	Twice a week with no manure drying	31	Kroodsma et al. (1988)
The Netherlands	Manure belt (NA)	Once a week with manure drying	28	Kroodsma et al. (1988)
Denmark	Manure belt (all year)	Information not available	52	Groot Koerkamp et al. (1998)
Germany	Manure belt (all year)	Information not available	14	Groot Koerkamp et al. (1998)
The Netherlands	Manure belt (all year)	Information not available	39	Groot Koerkamp et al. (1998)
England	Manure belt (all year)	Weekly	96	Nicholsen et al. (2004)
England	Manure belt (all year)	Daily	38	Nicholsen et al. (2004)
United States (Iowa)	Manure belt (all year)	Daily with no manure drying	17.5	Liang et al. (2005)
United States (Pennsylvania)	Manure belt (all year)	Twice a week with manure drying	30.8	Liang et al. (2005)

[1]AU = animal units; 1 AU = 500 kg of live weight.

[2]NA = not available.

be emitted as an intermediate product during nitrification and denitrification reactions and nitrate reduction can occur in some litter systems. In a series of environmentally controlled laboratory studies that quantify gaseous emissions from laying hen manure storage, Li (2006) reported undetectable N_2O concentration by the infrared photoacoustic measurement instrument.

The production and emission of gases and PM in poultry or any livestock facilities involve complex biological, physical, and chemical processes. The rate of emission is influenced by many factors, such as diet composition and conversion efficiencies, manure handling practices, and environmental conditions. The composition of bird diet and the efficiency of its conversion to eggs affect the quantity and physical and chemical properties of the bird manure. Manure handling practices and environmental conditions also affect chemical and physical properties of the manure, such as chemical composition, biodegradability, microbial populations, oxygen content, MC, and pH. For instance, drying feces reduces the water activity and thereby the microbiological production of ammonia.

Available Emissions Data

Before the National Academy of Sciences Report (NRC, 2003), most of the air emissions data for animal feeding operations had been collected from European production facilities (Table 1). It can be seen that there exist considerable variations in the magnitude of emissions. Houses with manure belts, and thus frequent manure removal, have reduced emissions as compared with houses with in-barn manure storage. Since then, an increasing amount of information has been collected from US production facilities managed under US conditions.

Specifically, a multistate (Iowa, Kentucky, and Pennsylvania), multidisciplinary project funded by the USDA-Initiative for Future Agricultural and Food Systems Program was completed that quantified ammonia emissions from representative US broiler and layer houses over an extended (1-yr) period of time. The ammonia emission rates from layer houses with different housing styles, manure management practices, and dietary schemes in Iowa and Pennsylvania have been published (Liang et al., 2005; Table 1), as well as those of broiler houses in Kentucky and Pennsylvania (Wheeler et al., 2006). Information on PM emissions for poultry houses has been rather limited due to the inherent difficulty associated with real-time and continuous measurement of PM concentrations in animal feeding operations. Tables 2 and 3 summarize the PM data for laying hen facilities, primarily from European studies. The ongoing EPA Air Consent Agreement studies involving 3 cage layer farms in California, Indiana, and North Carolina are expected to provide additional baseline emissions data for HR and MB layer facilities. The motivation for collecting US-based emissions data is to account for differences in production conditions, such as housing and ventilation styles, hen stocking density, genetics, feed compositions, and climate, as well as advances in husbandry and genetics.

Emissions Mitigation

Baseline air emissions data are essential for establishing a sound national emissions inventory and assessing the contribution of different production systems to the emissions inventory (Gates et al., 2008). However, developing practical strategies to reduce air emission, thus the environmental impact of animal production,

Table 2. Experimental conditions of studies on particulate matter (PM) emissions from and concentrations in laying hen houses[1] (Li et al., 2009)

Study no.	Reference	Location of study	Production system	Bird age and weight range	Ventilation mode	Manure removal frequency	PM measurement	Ventilation measurement	Measurement duration	Measurement frequency
1	Takai et al. (1998)[2]	North Europe	Perchery	—	—	—	GF	Tracer gas	2 d	Intermittent[3]
2	Takai et al. (1998)[2]	North Europe	Caged	—	—	—	GF	Tracer gas	2 d	Intermittent[4]
3	Wathes et al. (1997)[2]	United Kingdom	Perchery	29 to 69 wk, 1.82 to 2.3 kg	MV	—	GF	Tracer gas	2 d	Intermittent[5]
4	Wathes et al. (1997)[2]	United Kingdom	Caged	18 to 69 wk, 1.94 to 2.18 kg	MV	—	GF	Tracer gas	2 d	Intermittent[5]
5	Lim et al. (2003)	Indiana, United States	Caged	1.6 kg	MV	1 yr	TEOM	Fan status	6 d	Continuous
6	Fabbri et al. (2007)	Italy	Caged	—	MV	2 yr	GF and optical	Fan status/RPM sensor	1 yr	Continuous
7	Fabbri et al. (2007)	Italy	Caged	—	MV	3 to 4 d	GF and optical	Fan status/RPM sensor	1 yr	Continuous
8	Qi et al. (1992)[2]	Pennsylvania, United States	Caged	217 to 413 d	MV	—	—	—	10 mo (Jun. to Mar.)	Intermittent[6]
9	Lim et al. (2007)	Ohio, United States	Caged	1.65 kg	MV	1 yr	TEOM	Fan status	10 mo (Apr. to Jan.)	Continuous
10	Martensson and Pehrson (1997)	Sweden	Caged	3 to 16 wk	MV	3 d	GF	—	~4 mo (Aug. to Sep. and Dec. to Mar.)	Intermittent[7]
11	Martensson and Pehrson (1999)	Sweden	Perchery	3 to 16 wk	MV	3 d	GF	—	~4 mo (Aug. to Sep. and Dec. to Mar.)	Intermittent[7]
12	Guarino et al. (1999)[2]	Italy	Caged	34 to 42 wk	MV	—	GF	—	3 mo (Apr. to Jun.)	Intermittent[8]
13	Heber et al. (2005)	Indiana, United States	Caged	—	MV	24 to 30 mo	TOEM	Fan status	15 mo	Continuous
14	Davis and Morishita (2005)	Ohio, United States	Caged	—	MV	—	Optical	—	9 wk	Intermittent[9]
15	Vucemilo et al. (2007)	Croatia, Europe	Caged	—	—	—	GF	—	Winter	Intermittent[10]

[1]GF = gravimetric filtration; TEOM = tampered element oscillating microbalance; MV = mechanical ventilation; RPM = revolutions per minute.

[2]Inhalable and respirable fractions of PM were measured and reported.

[3]Twenty-two buildings surveyed, each measured over a summer day and winter day.

[4]Twenty-six buildings surveyed, each measured over a summer day and winter day.

[5]Four buildings surveyed, each measured over a summer day and a winter day.

[6]One day per week.

[7]Three to four times a day.

[8]Three times a day, 5 d each week, a week for each month.

[9]Once a week.

[10]Fifteen times a day.

is the ultimate goal for all involved. To this end, since 2004, the United Egg Producers has commissioned an Environmental Scientific Panel (**ESP**) to assist the egg industry with air quality issues. The missions of the ESP are a) to serve as a clearinghouse for the US egg industry on air quality research and findings pertaining to the egg industry and b) to identify current and emerging areas in air quality that warrant long-term or short-term research, with the focus on exploring practical solutions to mitigate air emissions from egg operations. The ESP consists of representatives from egg production and allied industries, US government agencies, and land-grant universities. Since 2004, the ESP has developed a list of research priorities in the areas of source (i.e., preexcretion) reduction; manure, exhaust, or both air (i.e., postexcretion) treatment; and alternative measurement techniques.

Dietary or Nutritional Manipulation. Dietary manipulation can be an effective means to lower ammonia emissions by reducing excessive nitrogen excretion or manure pH. In a 1-yr field study involving 4 commercial HR houses in Iowa, Liang et al. (2005) showed that a nutritionally balanced diet with 1% lower than standard CP content led to about a 10% decrease in annual ammonia emission while maintaining hen production performance. Roberts et al. (2007a,b) showed that inclusion of high-fiber ingredients (e.g., corn distillers dried grains with solubles, wheat middlings, or soybean hulls) in laying hen diets lowered ammonia emission from the manure with no adverse effect on egg production. Increased bacterial fermentation of the dietary fiber in the large intestine is thought to produce short-chain fatty acids (e.g., acetate, butyrate, and propionate) that lower the pH of the manure (Roberts et al., 2006). The lower pH shifts the equilibrium ($NH_3 + H^+ \leftrightharpoons NH_4^+$) toward the more water-soluble, thereby less volatile, ammonium ion (NH_4^+). To further demonstrate the efficacy and viability of the distillers dried grains with solubles diet and other dietary strategies on ammonia reduction, hen production performance, and production economics, field demonstration studies in Iowa and Pennsylvania are ongoing (Xin, 2009, Iowa State University, personal communication). Results thus far have been positive. Dietary manipulation to lower ammonia emissions should be applicable to all production systems.

Manure Handling and Treatment. How manure is stacked during storage will affect the ammonia emissions per pound of manure or per hen. Figure 2 illustrates the impact of hen manure stack configuration on ammonia emission (Li, 2006; Li and Xin, 2010). It can be noted that for a given amount of manure, spreading the manure into thin layers would give rise to higher emissions than stacking it into thicker piles. The impacts of manure MC and storage temperature on ammonia emissions from the manure are illustrated in Figures 3 and 4. Higher MC is associated with higher emissions, as is warmer environmental temperature. The implications of these results are that a) spreading of manure over a

Table 3. Particulate matter (PM) emissions and concentrations in laying hen houses reported in literature[1] (Li et al., 2009)

Study no.	Emission TSP, inhalable, g/AU per d	Emission TSP, inhalable, g/bird per d	Emission PM10, respirable, g/AU per d	Emission PM10, respirable, g/bird per d	Emission PM2.5, g/AU per d	Emission PM2.5, mg/bird per d	Concentration TSP, inhalable, mg/m³	Concentration PM10, respirable, mg/m³	Concentration PM2.5, mg/m³
1[2]	74	0.300	14.30	0.057[3]	—	—	2.19 to 8.78	0.35 to 1.26	—
2	15	0.060	1.90	0.008[3]	—	—	0.75 to 1.64	0.03 to 0.23	—
3[2]	42	0.168	5.40	0.022	—	—	2.80	0.40	—
4	20	0.080	3.50	0.014	—	—	1.70	0.27	—
5	63	0.200	16.00	0.050	1.10	3.52	1.89	0.518	0.039
6	—	—	16.00	0.048	4.73	14.20	—	—	—
7	—	—	4.44	0.019	1.45	6.20	—	—	—
8	11[3]	0.044	8.00[3]	0.032	—	—	—	—	—
9	44.5	0.147	9.20	0.030	—	—	2.37	0.565	—
10	—	—	—	—	—	—	2.5 (1.0 to 3.6)	1.0 (0.3 to 1.3)	—
11[2]	—	—	—	—	—	—	5.3 (2.8 to 8.1)	1.1 (0.5 to 2.2)	—
12	—	—	—	—	—	—	1.58	0.28	—
13	—	—	3,202	—	—	—	1.44	0.553	0.033
14	—	—	—	—	—	—	—	<2.00	—
15	—	—	—	—	—	—	1.6 to 2.8	—	—

[1]TSP = total suspended particulate; PM10 = PM with aerodynamic diameter of 10 μm or less; PM2.5 = PM with aerodynamic diameter of 2.5 μm or less; AU = animal units.

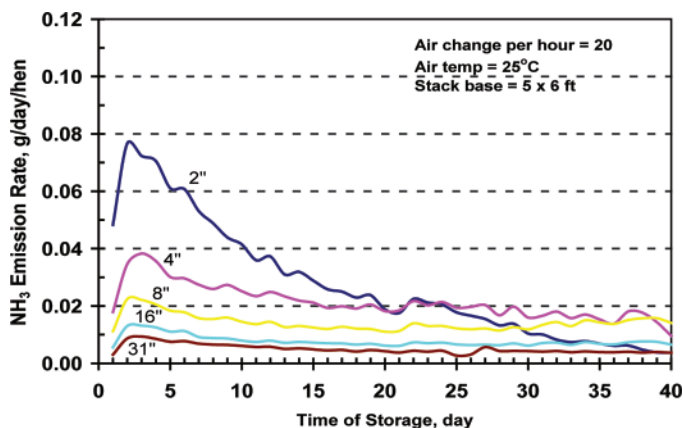[2]Perchery systems.

[3]Bird weight assumed as 2 kg.

Figure 2. Ammonia emission from hen manure storage as affected by stacking configuration (1 ft = 0.3048 m, 1 in. = 2.54 cm). All stacks had the same base area of 2.8 m^2 (30 ft^2). Air temperature (temp) was held at 25°C (77°F; Li and Xin, 2010). Color version available in the online PDF.

large area will lead to greater emissions and b) manure with higher MC (e.g., rained on pasture) will generate a greater environmental footprint.

In addition to physical treatment of hen manure, such as proper stacking, ammonia emission from manure storage may be controlled through chemical means, biological means, or both. In a series of laboratory-scale studies (Li et al., 2008c), 5 treatment agents, including zeolite, liquid Al$^+$Clear (aluminum sulfate, General Chemical, Parsippany, NJ), granular Al$^+$Clear (aluminum sulfate), granular Ferix-3 (ferric sulfate, Kemira Water Solutions Inc., Bartow, FL), and Poultry Litter Treatment (sodium bisulfate, Jones-Hamilton Co., Walbridge, OH) were topically applied to stored laying hen manure removed from a MB house. In all cases, topical application of the treatment agents showed appreciable reduction (33 to 94%) in ammonia emissions over a 7-d manure storage period for the 3 dosages. Likewise, Wilson (2004) reported that liquid alum reduced ammonia fluxes by 32% from laying hen manure in an HR house
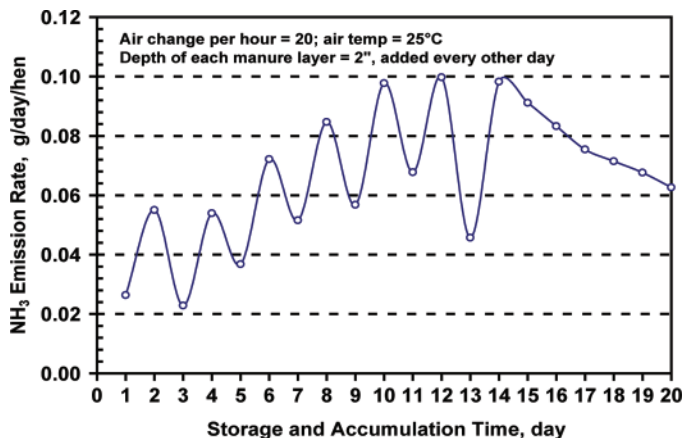
when applied using an automatic liquid alum delivery system. Further investigation is needed to effectively apply the agents under field conditions, including a life-cycle analysis. The economics of applying the manure additives also needs to be evaluated under production situations. As previously stated, treatment of manure in a central area, (e.g., a manure storage shed for MB housing systems) may be more readily accomplished. Conversely, controlling emissions from manure spread over a large area would be more challenging.

Treatment of Exhaust Air. In houses with fans grouped in a central location (e.g., at the ends of the house for tunnel-ventilated houses), treatment of the exhaust air may be possible. The treatment may use some type of impact curtains or biomass stack-wall, with the idea to take out part of the gas- or odor-laden particulates or deflecting the exhaust air stream to enhance its dispersion. Vegetative environmental buffers (i.e., trees planted in the downstream of the exhaust air) have also been used by egg producers in an attempt to reduce environmental impact of the exhaust air. More recently, wet scrubbers are being investigated that aim to precipitate dust, ammonia, and odor from the exhaust air. However, for poultry housing, the biggest challenge is the obstruction of the filtration system by feathers. The system is also rather energy-intensive because extra energy is used to overcome the resistance to the air flow.

Environment Control

Maintaining a high-quality microenvironment for the birds and their caretakers is critical to ensuring good welfare and productivity of the birds and the caretakers. Environmental control, and thus bird comfort, in modern laying hen production facilities is achieved by a) providing ample amount and uniform distribution of fresh air through properly engineered ventilation systems; b) cooling incoming air during warm weather, through use of evaporative cooling pads, high-pressure
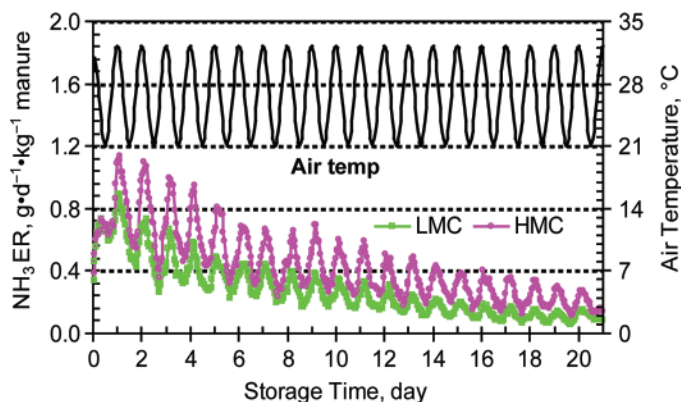

Figure 3. Ammonia emission from hen manure storage, with new manure (5-cm or 2-in. depth) added on top every other day. Air temperature (temp) was 25°C (77°F; Li and Xin, 2010). Color version available in the online PDF.

Figure 4. Ammonia emission rate from hen manure storage as affected by air temperature (temp) and moisture content of the manure (LMC = low moisture content, 50%; HMC = high moisture content, 77%; Li and Xin, 2010). Color version available in the online PDF.
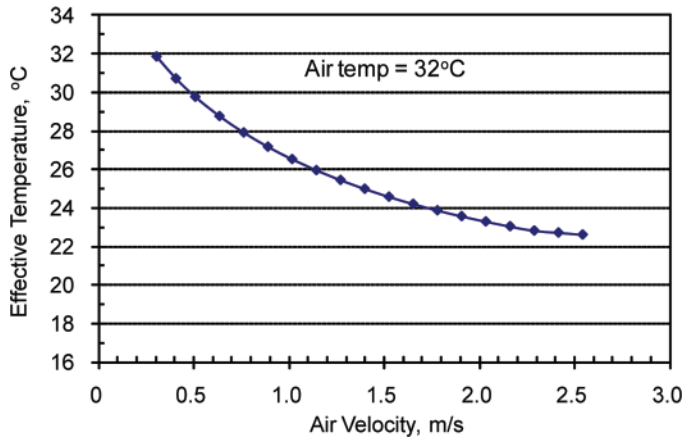
Figure 5. Effective environmental temperature vs. air velocity for poultry. temp = temperature. Color version available in the online PDF.

fogging, or direct surface wetting that may be coupled with tunnel ventilation; c) automatic adjustment of ventilation rate to attain the desired indoor air temperature and humidity during cold weather; and d) supplying adequate lighting to the birds. Over the years, as genetics, nutrition, and housing equipment advance, researchers have been trying to update the fundamental data relevant to heat and moisture production of the modern birds and housing systems used to design and operate building ventilation and environmental control systems (Chepete and Xin, 2002, 2004a,b; Chepete et al., 2004; Green and Xin, 2009). Heat stress, one consequence of inadequate ventilation in hot weather, significantly reduces the performance of the birds. In addition, heat stress also inhibits immune function, reduces feed consumption, and negatively impacts production performance (Mashaly et al., 2004). The effect of sufficient air velocity over the birds to help alleviate heat stress for adult poultry is illustrated by the effective environmental temperature vs. air velocity relationship shown in Figure 5. This is the reason for the use of tunnel ventilation for poultry and other animal production during warm climates. Figure 6 shows an example regarding the effect of evaporative cooling to reduce thermal stress in modern poultry production houses. Alternative cooling methods for laying hens (e.g., surface sprinkling or high-pressure fogging) have also been studied and used in commercial production (Chepete and Xin, 2000; Ikeguchi and Xin, 2001; Yanagi et al., 2002; Xin, 2009).

As previously indicated, most of the modern laying hen houses in the United States use either a HR or MB housing style. In either case, the birds are separated from their feces, hence providing a greatly improved hygienic environment for the birds. A recent field observational study in Iowa compared the indoor air quality of noncage (litter floor) laying hen houses vs. HR or MB houses during winter and summer (Green, 2008; Green et al., 2009). The results revealed that ammonia levels in the noncage houses (as high as 41 mg/kg or 70 ppm) were 3 to 6 times those in the HR or MB houses in winter (Figure 7). The same study revealed considerably lower indoor air temperature in the noncage houses (Figure 8), due to the smaller number of hens in the building. Lower environmental temperatures translate to more feed energy going toward maintaining constant body temperature of the birds and, accordingly, less feed energy toward egg production. The end result is less egg production per kilogram or pound of feed consumed. Appleby et al. (1988a) reported a comparative study involving conversion of a deep-pit cage house to a deep-litter noncage system with a slatted floor over the pit. The authors reported that total egg production was lower for birds on litter and that dust and ammonia levels were high for the floor-raised system. Ammonia levels were also high for the deep-pit manure storage. Comparative studies conducted by other European researchers also have shown considerably higher dust levels in noncage systems as compared with cage
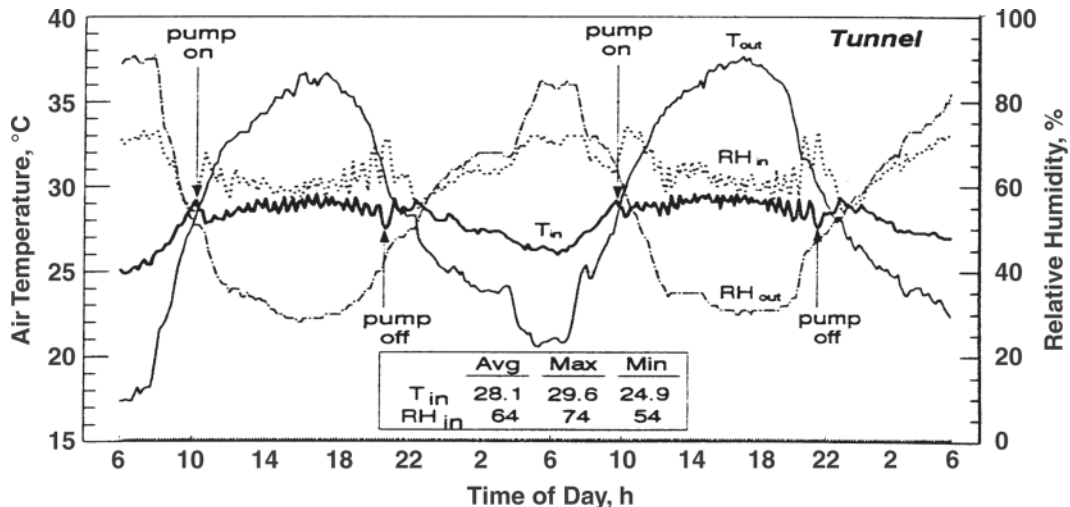

Figure 6. Air temperature reduction by an evaporative cooling pad-fan system in a tunnel-ventilated poultry house (Xin et al., 1994). T_{in}, T_{out} = inside and outside air temperature, respectively; RH_{in}, RH_{out} = inside and outside RH, respectively.
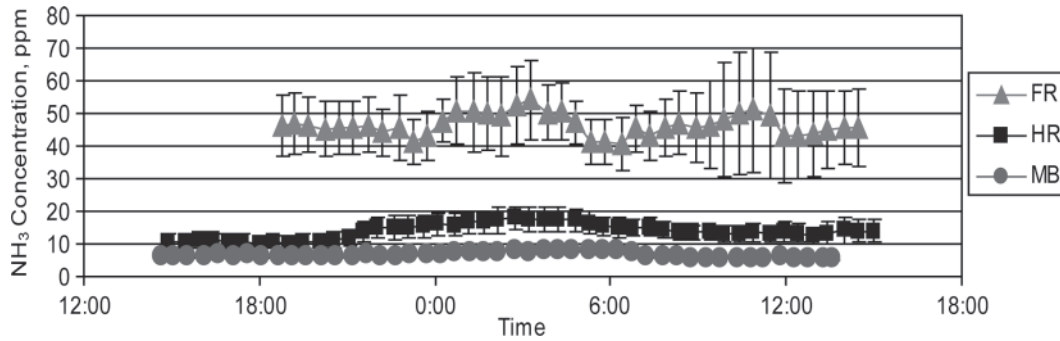
Figure 7. Ammonia concentration (mean $\pm$ SE) in floor-raised (FR), high-rise (HR), and manure belt (MB) laying hen houses during winter conditions in the Midwest (Green et al., 2009). 1 ppm of NH_3 = 0.59 mg of NH_3/kg of air.

systems (Martensson and Pehrson, 1997; Wathes et al., 1997; Takai et al., 1998). Higher dust levels pose greater heath risks to both birds and caretakers in the facilities and higher dust emissions add greater environmental (air quality) burdens to the atmosphere, as described earlier.

Wathes et al. (1983) highlighted the problem of ventilation solely for temperature comfort, which may result in an environment with poor air quality and can result in another set of problems. Wathes (1998) suggested that interactions between exposure to aerial pollutants and respiratory effects should be further explored in poultry. A summary of relevant literature at the time showed that ammonia concentrations varied for the reporting countries from 1.6 to 11.9 ppm for caged layers and 8.3 to 29.6 ppm for noncage houses (Wathes, 1998).

Resource Utilization Efficiency

Modern cage houses efficiently use space, housing a large number of birds in a smaller area. The most land demanding system is the free-range system. To compare the land utilization efficiency, cage systems would house 37 to 52 hens/m^2 of land area, whereas noncage houses without access to outdoor run would house 6 to 9 hens/m^2 of land area. Hence, the noncage systems can accommodate less than 25% of the hens housed in cage systems. In other words, to raise the same number of hens, noncage (without access to out-

door runs) systems would need 4 times the land area as required by cage housing systems. Taking advantage of the metabolic body heat (energy resources) naturally produced by the birds, along with carefully engineered buildings with appropriate insulation and ventilation control, cage houses are able to maintain the desired thermal comfort for the birds without needing supplemental heating energy, even under cold conditions. In comparison, the lower number of birds and thus insufficient amount of sensible heat generation by the birds in noncage systems necessitate that supplemental heat be supplied during cold weather. One major problem for free-range producers is the space requirement for ranging outdoor birds and the potential environmental destruction for large numbers of birds on pasture for an extended time.

De Boer and Cornelissen (2002) developed a method for assessing sustainability of housing systems. Based on equal importance of all sustainability indicators, the traditional cage system was most sustainable, followed by the aviary system, and then floor-raised systems. Improvements to economic performance of noncage systems or alterations to the weighting of indices may change the result. Simulations of environmental footprint of each system yielded similar results, with traditional cages having the smallest impact and the free-range system the greatest (Williams et al., 2006). Specifically, the authors reported that organic or free-range (nonorganic) egg production each increase energy use by 15% as compared with all housed production.
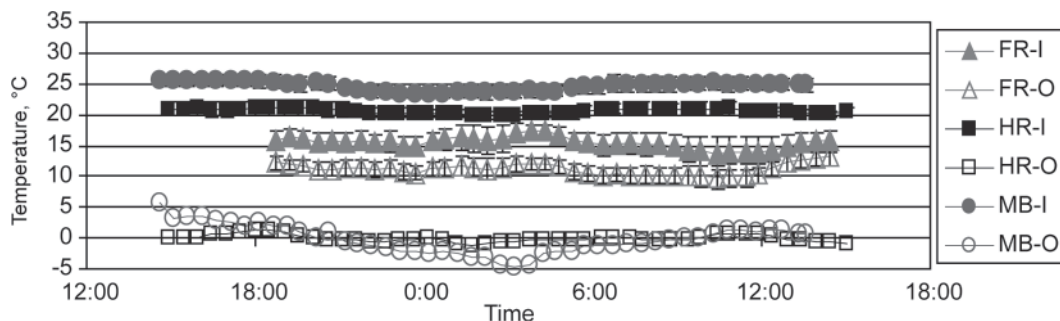

Figure 8. Diurnal air temperature (mean $\pm$ SE) in floor-raised (FR), high-rise (HR), and manure belt (MB) laying hen houses, along with the corresponding outside temperature, during winter conditions in the Midwest (Green et al., 2009). I = inside; O = outside.

Effects of Manure Application on Water Quality

Hen manure, like all poultry manure, is an excellent organic fertilizer. However, it has a relatively low nitrogen:phosphorus ratio (often 2 or lower), whereas plants require approximately 8 times more nitrogen than phosphorus. Therefore, when poultry manure is applied based on the nitrogen needs of a crop, it results in an overapplication of phosphorus (Sims et al., 2000). When poultry manure is applied annually at rates to meet the nitrogen requirements of crops, the phosphorus level builds up in the soil, which can lead to phosphorus runoff (Pote et al., 1996). However, phosphorus concentrations and loads in runoff water can be high after poultry manure has been applied, even when soil test phosphorus levels are low (Edwards and Daniel, 1992, 1993; Moore et al., 2000).

In 2008, the EPA finalized the concentrated animal feeding operations rule, which requires large animal feeding operations to develop a nutrient management plan (**NMP**) for proper manure management. The EPA has worked with the USDA-Natural Resources Conservation Service on the strategy for nutrient management planning. The rule states that if a farmer designs, constructs, operates, and maintains his or her facility such that a discharge will occur, a permit is needed. In the case of poultry manure, a "discharge" of poultry manure may include manure that is exhausted from ventilation fans. The USDA-Natural Resources Conservation Service has given states the opportunity to decide between 3 methods of developing these NMP: 1) based on agronomic soil test phosphorus recommendations, 2) based on an environmental soil test threshold, and 3) based on a phosphorus index. The phosphorus index is a field-scale risk assessment tool that determines the risk of phosphorus runoff by accounting for various source and transport factors. Source factors include soil test phosphorus levels, manure management, and soluble phosphorus levels in manure, whereas transport factors include the amount of erosion, runoff, leaching, flooding frequency, the distance to a receiving water body, or the best management practices used (Sharpley et al., 2003). At the present time, 47 states are using the phosphorus index to write NMP (Sharpley et al., 2003). Although many phosphorus indices simply calculate the relative risk of phosphorus runoff, a few actually predict the load of phosphorus in runoff from given fields (Sharpley et al., 2003; DeLaune et al., 2004a,b).

Phosphorus runoff is the biggest water quality concern with respect to hen manure because phosphorus is normally the limiting nutrient for eutrophication in freshwater systems (Schindler, 1977). The EPA contends that eutrophication is the biggest water quality problem in US surface waters (EPA, 1996). Eutrophication in lakes and rivers can lead to oxygen deprivation, causing fish kills. Algal blooms can also cause problems for municipal water suppliers, such as taste and odor problems. One of the compounds causing taste problems is geosmin (*trans*-1,10-dimethyl-*trans*-9-decalol), which is a by-product of algae (Izaguirre et al., 1982). The majority (80 to 90%) of phosphorus in runoff from pastures fertilized with poultry manure is in the soluble form (Edwards and Daniel, 1993), which is the form most readily available for algal uptake (Sonzogni et al., 1982). In fact, the dominant variable affecting phosphorus runoff from pastures fertilized with manure is the soluble phosphorus content of the manure (Kleinman and Sharpley, 2003; DeLaune et al., 2004a).

Best management practices to reduce phosphorus runoff from poultry manure include proper nutrient management planning (Edwards and Daniel, 1992, 1993; DeLaune et al., 2004b), utilizing buffer strips (Chaubey et al., 1993), dietary modifications to lower phosphorus contents of diets using phytase enzymes (Plumstead et al., 2007), and chemical precipitation of phosphorus in manure using compounds such as alum (Moore et al., 2000, Wilson, 2004; Moore and Edwards, 2007).

As with phosphorus, nitrogen runoff from manure can cause eutrophication. Atmospheric ammonia can also negatively impact surface water quality via atmospheric nitrogen loading into the aquatic environment (Hutchinson and Viets, 1969; Elliott et al., 1971; Denmead et al., 1974; Schroder, 1985). Nitrogen entering streams and rivers through atmospheric fallout contributes to eutrophication in the same manner as nitrogen entering through runoff. Atmospheric nitrogen loading via wet fallout tripled in Denmark between 1955 and 1980, corresponding to nitrogen losses from agriculture during this period (Schroder, 1985).

Another potential water quality threat from manure is nitrate leaching into groundwater. Nitrate leaching can pose a health threat, due to methemoglobinemia, to infants less than 3 mo old if they consume water with high levels of nitrates. This syndrome is the result of poor oxygen transport in the blood due to oxidation of ferrous iron to ferric iron by nitrite. In order for this to occur, nitrate must first be reduced to nitrite in the stomach (a reaction that is dependent on microorganisms that function at relatively high pH, which does occur in older humans). As a result of this problem, the EPA limits the concentration of nitrate in drinking water to 10 mg of nitrate-nitrogen/L (EPA, 1985). Adams et al. (1994) found that nitrate leaching from hen manure was dependent on the application rate of manure, with rates of 20 Mg/ha resulting in nitrate-nitrogen concentrations in soil solutions far in excess of 10 ppm. As a result, they recommended that hen manure be applied at rates below 11.2 Mg/ha. It should be noted that because most states in the United States use the phosphorus index to recommend manure application rates for agricultural fields, the application rates would be below this critical threshold.

Process-Based Models

Understanding the range of emissions from poultry facilities and related processes is a major prerequisite

for designing the best management strategies. At present time, regulatory agencies such as the EPA estimate emissions based on factors per animal. Such estimates can have severe limitations because they fail to take into account the great variations in emissions on actual farms due to variations in management practices (e.g., litter management and feeding practices) as well as environmental factors such as climate and soil conditions.

In 2003, the National Academy of Sciences (NRC, 2003) recommended that the EPA's current emission estimation methodologies be improved by using process-based models instead of an emission factor approach. The recommendation stems from the complexity of measuring and monitoring animal air emissions and emission reductions because the emission sources are dispersed and largely driven by biological activity with significant variability over time, space, and management practices. Emissions are further affected by local and regional meteorological and soil conditions. This complexity results from the interactions of a suite of biogeochemical processes such as decomposition, hydrolysis, nitrification, denitrification, fermentation, and ammonia volatilization. These microorganism-mediated processes are highly sensitive to the quantity and quality of manure that are affected by feed sources, as well as the environmental factors (e.g., temperature, moisture, and pH), which are driven by the local climate, soil, and management measures.

A comprehensive process-based model would enable a better assessment of the environmental impacts by different housing systems and variations in management practices under each production system. Efforts have been ongoing to develop and validate such process-based models for prediction of agricultural, especially concentrated animal feeding operations, emissions (Zhang et al., 2005). Frameworks for farm-level process modeling have been developed for livestock and poultry through funding from USDA and the animal industry. However, the progress suffers from availability of certain fundamental data for development and validation of the models. A team of scientists (Zhang et al., 2009) developed a white paper that describes the available process-based models for air emissions and identifies the gaps of knowledge needed to fully develop and validate the models.

Life Cycle Assessment

Life cycle assessment (**LCA**) is a unique method of analyzing the complete inventory and flow of raw materials, energy, and waste products during the production and lifecycle of a given product (e.g., egg). The basic idea of the LCA is to analyze and quantify all of the inputs and outputs used in the lifetime or life cycle (i.e., birth to death) of a product to quantify the total energy and raw materials used during the lifespan of that product. More specifically, developing a LCA for a product involves creating a "cradle to grave" analysis of each raw material including extraction of the raw materials, production, distribution, consumption, possible reuse or recycling, and disposal. This type of "cradle to grave" analysis requires quantifying the impact of first generation consumption (i.e., raw materials and energy consumed during production of the product), second generation consumption (raw materials and energy consumed during production of materials that will be used in the first generation consumption), and so on all the way to the extraction or mining of the original unadulterated raw materials (e.g., fertilizers that were used to nurture crops that were then made to feed). For example, a LCA can reveal the number of trees and amount of pulp, electricity, and water required to produce a specific quantity of paper.

Although LCA has been used since the 1970s for manufacturing and some environmental studies, their applications within food systems are more recent. For a food system, the appeal of an LCA analysis is that it allows stakeholders (manufacturers, regulators, and consumers) to perform a complete spatial, quantitative, and qualitative analysis of the impact of that food product on the surrounding environment, thereby creating an efficient and science-based mechanism for analysis mitigation. A recent application of LCA was by Pelletier (2008), who conducted a LCA for US broiler poultry production, predicting the broader, macroscale environmental impacts of the material and energy inputs and emissions along the US broiler supply chain. The author concluded that feed provision accounts for 80% of supply chain energy use, 82% of GHG emissions, 98% of ozone-depleting emissions, 96% of acidifying emissions, and 97% of eutrophying emissions associated with the cradle-to-farm gate production of broilers. It would be desirable to perform such LCA on different laying hen production systems.

FURTHER RESEARCH NEEDS

This review of the state of science has identified the following lack or gaps in knowledge and thus future research needs:

1. Quantification of indoor air quality, barn emissions, thermal conditions, and energy use in alternative hen housing systems (e.g., single-story floor, multistory aviary, and enriched cage systems), along with conventional housing systems under different production conditions;
2. Evaluation of environmental footprint for different US egg production systems through life cycle assessment;
3. Investigation of practical means to mitigate air emissions from different production systems;
4. Development and validation of process-based models for predicting air emissions and their fate; and

5. Assessment of interactions between air quality, housing system, worker health, and animal health and welfare.

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