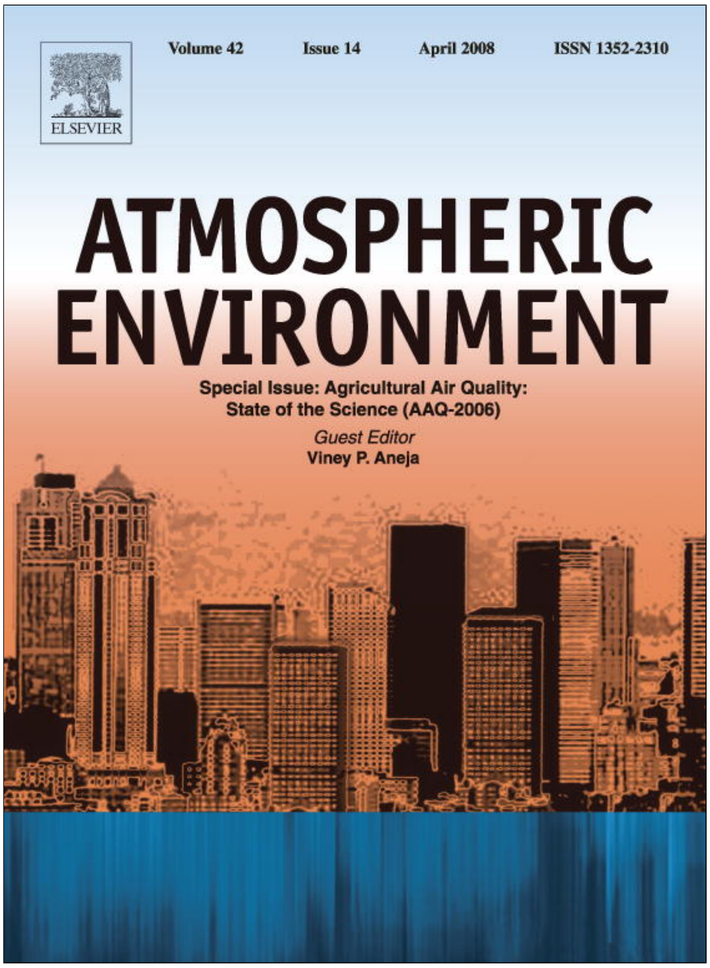
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Workshop on Agricultural Air Quality: State of the science

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Abstract

The first Workshop on Agricultural Air Quality: State of the Science was held at the Bolger Center in Potomac, Maryland from 4 to 8 June 2006. This international conference assembled approximately 350 people representing 25 nations from 5 continents, with disciplines ranging from atmospheric chemistry to soil science. The workshop was designed as an open forum in which participants could openly exchange the most current knowledge and learn about numerous international perspectives regarding agricultural air quality. Participants represented many stakeholder groups concerned with the growing need to assess agricultural impacts on the atmosphere and to develop beneficial policies to improve air quality. The workshop focused on identifying methods to improve emissions inventories and best management practices for agriculture. Workshop participants also made recommendations for technological and methodological improvements in current emissions measurement and modeling practices.

The workshop commenced with a session on agricultural emissions and was followed by international perspectives from the United States, Europe, Australia, India, and South America. This paper summarizes the findings and issues of the workshop and articulates future research needs. These needs were identified in three general areas: (1) improvement of emissions measurement; (2) development of appropriate emission factors; and (3) implementation of best management practices (BMPs) to minimize negative environmental impacts. Improvements in the appropriate measurements will inform decisions regarding US farming practices. A need was demonstrated for a national/international network to monitor atmospheric emissions from agriculture and their subsequent depositions to surrounding areas. Information collected through such a program may be used to assess model performance and could be critical for evaluating any future regulatory policies or BMPs. The workshop concluded that efforts to maximize benefits and reduce detrimental effects of agricultural production need to transcend disciplinary, geographic, and political boundaries. Also, such efforts should

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involve natural and social scientists, economists, engineers, business leaders, and decision makers. The workshop came to the conclusion that through these collaborative efforts improvements in air quality from agricultural practices will begin to take effect.

Keywords: Nitrogen; Ammonia; Sulfur; Hydrocarbons; Biogenic VOCs; Odor; Emissions; Emission factor; Transport; Transformation; Crop and animal agriculture; Measurements; Modeling; Best Management Practices; Policy

1. Introduction

Some scientists argue that the first synthesis and mass production of ammonia (NH_3), a reactive nitrogen specie, from its elements (nitrogen and hydrogen) by Nobel Prize laureates Fritz Haber and Carl Bosch in the early 1900s was the most profound scientific discovery in recent history. This high-pressure reaction, known as the Haber–Bosch process, fixes nitrogen (N) to form NH_3 in an efficient, economical manner, albeit with considerable inputs of energy. While the computer, airplane and automobile certainly make our lives convenient, the world's population growth, from ~1.5 billion at the beginning of the 20th century to ~6 billion today (and projected to be more than 9 billion by 2050), would not have been possible without this process to produce nitrogen fertilizer to enhance crop growth and maximize agricultural production on limited land areas. Fig. 1 shows the parallel increase in human population and fertilizer usage over the past century. Currently, the global production of fertilizer is more than 80 Tg of N yr^{-1}, compared with ~1 Tg only 50 years ago (The Fertilizer Institute, 2000; International Fertilizer Industry Association (IFA), 2004).

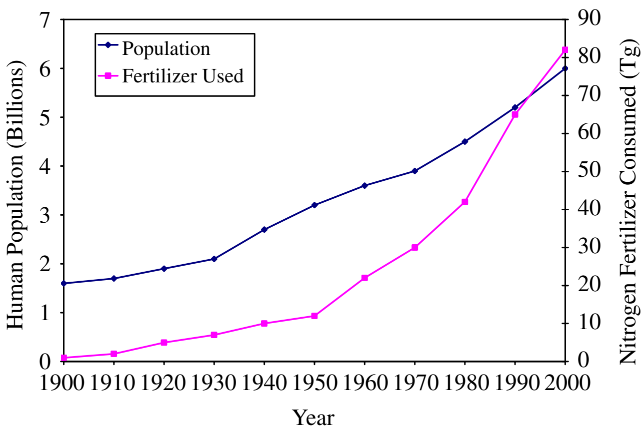

Fig. 1. Graph showing population increase and use of nitrogen fertilizer from 1900 to 2000.

Globally, synthetic fertilizers and agricultural crops contribute about 9 Tg NH_3-N (ammonia-nitrogen) yr^{-1} to the atmosphere (Schlesinger and Hartley, 1992). The human demand for food production requires the extensive use of nitrogen-containing fertilizers on crops, as well as the large-scale production of domestic livestock (animal agriculture). Nitrogen is an essential element in the dietary needs of animals; currently NH_3-N emissions from animal waste are even larger than the inadvertent losses from fertilizer application. Ammonia is released from animal wastes as a result of the inefficient conversion of dietary nitrogen to animal product. Domestic animals are the largest source of atmospheric NH_3 [32 Tg NH_3-N yr^{-1}], comprising approximately 40% of natural and anthropogenic emissions combined. Gaseous deposition of nitrogen contributes to eutrophication and acidification of some downwind ecosystems (Paerl, 1997; Krupa, 2003). Release of NH_3 into the atmosphere from crop and animal production has, therefore, recently become the subject of intense scientific research and regulatory interest.

While NH_3 is quantitatively the largest emission from agricultural operations, many other agricultural air pollutants are also of major environmental concern, including other reactive nitrogen species [e.g., nitrogen oxides ($NO_x = NO + NO_2$), and nitrous oxide (N_2O)], volatile organic compounds (VOCs) (e.g., methane (CH_4)), odor emissions (e.g., organic acids), particulate matter (PM) (e.g., particulates from tillage and burning, and gas-to-particle conversion), and gaseous sulfur compounds (e.g., hydrogen sulfide (H_2S)). Trace gases and PM emissions occur from most major agricultural practices including confined animal feeding operations (CAFOs), crop production, where animal manure and fertilizers are applied, tillage, and biomass burning (Aneja et al., 2006a).

In many areas of the US and Europe, intensively managed crop and livestock operations have grown parallelly to world population and subsequent need for food. In recent years, these modern livestock facilities have increased in size resulting in greater concentrations of animals (Aneja et al., 2006a). Studies of the emissions of air pollutants during agricultural operations comprise an important emerging research area (Aneja et al., 2001, 2006a, b), best addressed with interdisciplinary approaches that can inform policy makers of the costs and benefits of various mitigation options. Data on agricultural emissions of regulated pollutants, nuisance odors, and fugitive dust often are insufficient to develop appropriate policies, both nationally and internationally. For some pollutants and some sectors, there are no data in the public domain and peer-reviewed research.

The first Workshop on Agricultural Air Quality: State of the Science, was structured to help scientists, industry, policy makers and regulators make optimal choices about issues confronting agricultural practices in order to maximize the benefits and reduce the detrimental environmental effects of current food, fiber, and feed production activities. At the outset, the workshop's steering committee recognized that improvements are needed in emission inventories from agriculture, measurement and monitoring methodologies, and modeling and best management practices to mitigate air pollutant emissions from agricultural sources.

The workshop showcased presentations from 88 academic papers, 3 poster sessions totaling 184 posters, a roundtable discussion on the present status and future needs of the science of agricultural air quality, and addresses from Ralph J. Cicerone, president of the US National Academy of Sciences, James Oblinger, Chancellor of the North Carolina State University, and Colien Hefferan, administrator of USDA-CSREES. Presentations covered a variety of topics including agricultural emissions, international perspectives, scaling: field experiments and measurements, impacts, fate and deposition, air quality policies and standards, biomass burning and deposition, odor, emissions approaches and uncertainties for crops and animals, developing appropriate new technologies, agricultural air quality modeling, best management practices, economics, particulate matter, public policy and agricultural air quality, and agricultural air quality perspectives.

2. Emissions and emission factors

Table 1 lists the estimated global atmospheric budgets for NH_3, NO_x, N_2O, H_2S, VOCs, and PM. Agricultural soils and domestic animal waste are responsible for a large majority of the oxidized and reduced nitrogen emissions, respectively. Hydrogen sulfide and VOCs are also emitted from animal waste; however, no global estimates are available for these gases, largely due to a lack of accurate data. Generally, limited data exist for estimating agricultural emissions of air pollutants (e.g., NH_3, H_2S) and gases that can create public nuisances (e.g., odors, fugitive dust). Credible estimates of air emissions from CAFOs are also complicated by processes that affect the amounts and dispersion of emissions in the atmosphere. Emissions occur throughout the food production system and all must be quantified accurately in order to address critical air quality issues (Aneja et al., 2006a).

At the workshop, a number of papers and posters presented air emissions and concentration data for many compounds including NH_3, NO_x, CH_4, N_2O, carbon monoxide (CO), carbon dioxide (CO_2), VOCs, fine and coarse PM (PM_{fine} and PM_{10}, respectively), total suspended particulates (TSPs), and odor. Measurements have been conducted on geographic scales ranging from national to regional and farm-scale. Research presented at the workshop provided perspectives on the breadth of agricultural emissions and source types. These measurements included onsite and downwind locations at swine, poultry, and dairy CAFOs, agricultural crop soils, and biomass burning sites in the US, UK, Denmark, Germany, Korea, India, and several other countries.

An "emission factor" is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant (EPA (US Environmental Protection Agency), 2007). Applied to emissions from CAFOs, an emission factor integrates the annual mean emission from housing, manure storage/treatment, and land application or other means of disposing of manure (EPA (US Environmental Protection Agency), 2007). Fig. 2 provides a diagram that describes the main sources from animal and crop agriculture that are necessary in order to determine comprehensive NH_3 emission factors. This diagram describes NH_3 sources for the UK, but in reality could be applied to any compound or any region, with slight modifications based on local farming practices.

The development of accurate emissions factors and their resulting inventories is difficult, largely due to a lack of data with adequate temporal and

Table 1
Global atmospheric budgets of selected trace gases, volatile organic compounds, and particulate matter

Source	NO_x[a] ($Tg\,N\,yr^{-1}$)[g]	N_2O[b] ($Tg\,N\,yr^{-1}$)	NH_3[c] ($Tg\,N\,yr^{-1}$)	H_2S[d] ($Tg\,N\,yr^{-1}$)	VOCs[e] ($Tg\,N\,yr^{-1}$)	PM[f] ($Tg\,N\,yr^{-1}$)
Domestic animal waste		1.6	32			
Biomass burning	8.0	0.4	5		25–80	80
Fossil fuel combustion	21	0.5	2	3.3	36–62[i]	130[h]
Natural gas					2–14	
Organic solvent use					8–20	
Ocean	<1.0	5.7	13	1.8	2.5–26	1300[j]
Salt marshes/ Estuaries/wetlands				0.7		
Human excrement			4			
Lightning	8					
NH_3 oxidation by OH	1	0.6				
Stratospheric input	0.5					
Soil emissions	20.2	10.7	19	0.002	<3	
Mineral dust						1500
Volcanoes				1.1		33
Tropical forest				0.4		
Vegetation				0.4		
Grasslands					<26	
Foliage					812–1493	
Biogenic material						50
Other[k]		6.3				
Secondary production[l]						
Sulfate						242
Nitrate						58
Hydrocarbons						65
Total Sources	59	26	75	7.7	815–1530	3450

[a] *Source*: Levine (1991).
[b] *Source*: Bouwman et al. (1995); stratospheric sink from Houghton et al. (1995).
[c] *Source*: Schlesinger and Hartley (1992).
[d] *Source*: Watts (2000).
[e] *Source*: Warneck (2000).
[f] *Source*: Andreae (1995).
[g] $1\,Tg = 10^{12}\,g$.
[h] Includes transport, stationary sources, industrial process, solid waste disposal, and miscellaneous.
[i] Petroleum-related sources and chemical industry.
[j] Sea salt.
[k] Includes adipic and nitric acid production, nitrogen fertilizer, land use change, and other small N sources.
[l] Includes both anthropogenic and biogenic contributions.

spatial resolution, and also due to the large number of factors (seasonality, time of day, temperature, humidity, wind speed, solar intensity, and other weather conditions, ventilation rates, housing type, manure properties/characteristics and animal species, stocking density, and animal age) involved in the generation and dispersion of airborne materials. For example, information on nitrogen emissions from fertilizer applications often provides only annual averages and disregards seasonal variations, planting times, and pulsing effects from rain events. Furthermore, the uncertainties associated with these estimates are large, and emissions estimates applied for one set of conditions or for one type of agricultural operation may not translate readily to others. Table 2 lists ammonia emission factors from CAFOs reported for some countries in Europe (Aneja et al., 2007). To date, emissions factors from emerging agricultural producers in Southeast Asia (e.g., China and India) and other developing countries are limited or non-existent. Research is also sparse in the subtropical regions of South America. By the year 2020, scientists estimate that, in some areas of the world, ammonia will be the

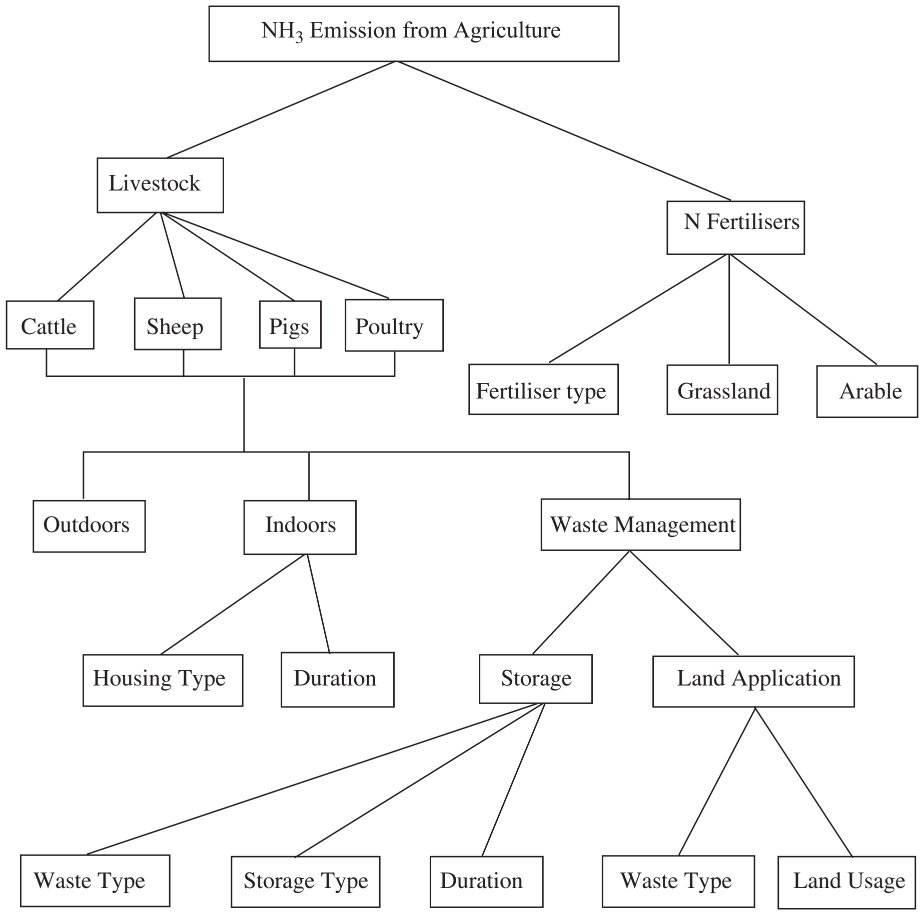

Fig. 2. Main sources of ammonia emissions from livestock facilities (*Source*: Misselbrook et al., 2000).

largest contributor to soil acidification and eutrophication, and a major contributor to PM_{fine} formation. Scientists in agronomy perceive an urgent need for a better understanding of emission source strengths and the processes that shape gas-to-particle conversion.

Currently, under the guidance of the US EPA, the animal agricultural industry is funding a 2-year, large-scale measurement program, the National Air Emissions Monitoring Study, which will characterize, for each industry involved, atmospheric emissions from all major CAFOs (swine, dairy, poultry) in various geographic areas of the US. Measurements will be made ''to initiate a process-based consideration of the entire animal production process and its effects on atmospheric emissions'' (Thorne, 2006). Beginning in 2007, continuous emissions measurements will be made at each facility along with detailed farm information including measurements of animal age, weight gain, diurnal animal activity levels, animal feeding schedules, indoor and outdoor meteorological conditions, and analyses for total nitrogen and sulfur in animal feed, water, and manure, among several other farm-related processes. Results from this study are expected to contribute significantly to the scientific knowledge of air emissions from CAFOs in the US.

3. Environmental effects

Generally, trace gases released into the atmosphere from anthropogenic or natural sources participate in atmospheric reactions (e.g., gas-to-particle conversion), are transported by winds, return to the surface by wet and dry deposition processes, and could possibly cause adverse effects on human health and the environment (Fig. 3). This holds true for trace gases and particulates emitted from agricultural activities.

Scientific information suggests that reactive nitrogen is accumulating in the environment, and that excess nitrogen cycling through biogeochemical pathways has a variety of negative environmental

Table 2
Ammonia emission factors for individual animal categories in Europe[a]

Animal category	Czech Republic 2002[b] Emission factor (kg NH_3 animal^{-1} year^{-1})	Denmark 2005[c] Emission factor (kg NH_3 year^{-1})	The Netherlands 2006[d] Emission factor (kg NH_3 animal place^{-1} year^{-1})
Dairy cows	27.9	26.92	
Grazing			9.5
100% housed			11
Cows	16.2		
Beef cattle 6–24 months			7.2
Heifers	16.2		
Heifers 6 months-calving		5.49	
Heifer calves <6 months		4.00	
Calves	16.2		2.5
Bull calves 6–14 months		8.45	
Bull calves <6 months		3.51	
Bulls	16.2		9.5
Other cattle	16.2	9.00	5.5
Farrowing sows (incl. piglets)			8.3
Dry and pregnant sows			4.2
Total sows	17.44	7.60	
Sucking-pigs	6.5	0.18	
Large pen			0.75
Small pen			0.60
Pigs	8.3	1.01	
Large pen			3.5
Small pen			2.5
Broiler breeders <19 weeks			0.250
Broiler breeders			0.580
Broilers	0.21	26.60	0.080
Layers	0.27	36.95	
Layers <18 weeks (deep pit)			0.170
Layers + layer breeders(deep pit)			0.315
Turkey cocks and hens	0.92	29.00	0.680
Other poultry	0.21		
Geese and ducks	0.73	7.54	
Ducks; outside keeping			0.019
Ducks; inside keeping			0.210
Horses	8	8.32	
Sheep	1.34	2.41	
Goats	1.34	2.33	

[a] *Source*: Aneja et al. (2007).
[b] *Source*: Zapletal and Chroust (2006).
[c] *Source*: Gyldenkaerne (2007).
[d] *Source*: Starmans and Van der Hoek (2007).

consequences. Once released into the atmosphere, reactive nitrogen compounds can subsequently lead to several environmental imbalances including soil acidification[1]; eutrophication of ecosystems, yielding harmful algal blooms and decreased water quality; tropospheric ozone formation; increased photochemical oxidant formation; decreased visibility owing to increased aerosol production; changes in biodiversity; and elevated nitrogen concentrations in ground and surface waters (Paerl, 1995, 1997; Paerl and Whitall, 1999; Aneja et al., 2001, 2006a, 2007; Galloway et al., 2003). On land, extra nitrogen applied or deposited is rapidly taken up by plants, stimulating their growth and leading to changes in species distribution and a loss of biodiversity. Examining a hypothetical ecosystem, Fig. 4 demonstrates how nitrogen loading will

[1] Ammonia is an interesting chemical species, since it has alkaline properties in the atmosphere, but yields acidification of soils where it is subject to nitrification, with the production of H^+ ions.

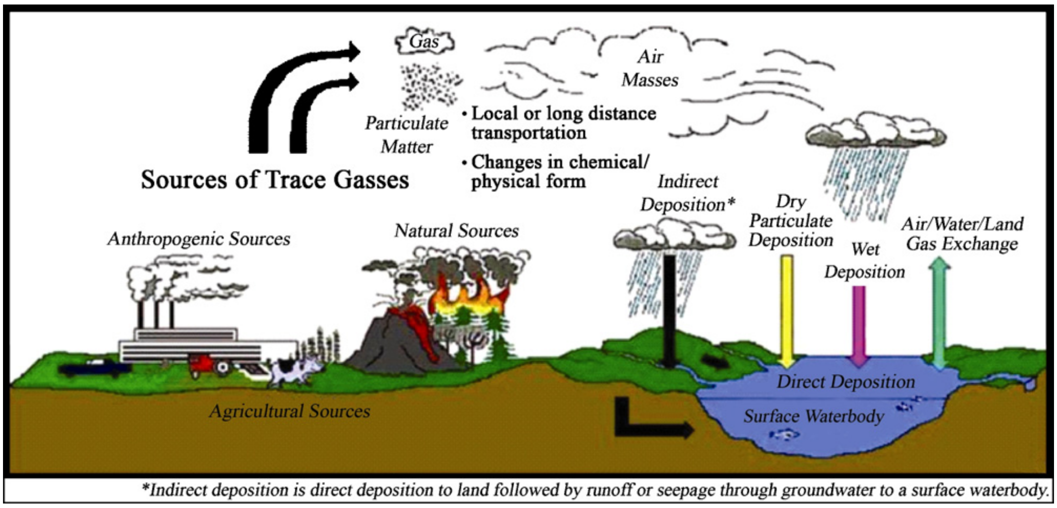

Fig. 3. Atmospheric emissions, transport, transformation and deposition of trace gases (*Source*: Aneja et al., 2003).

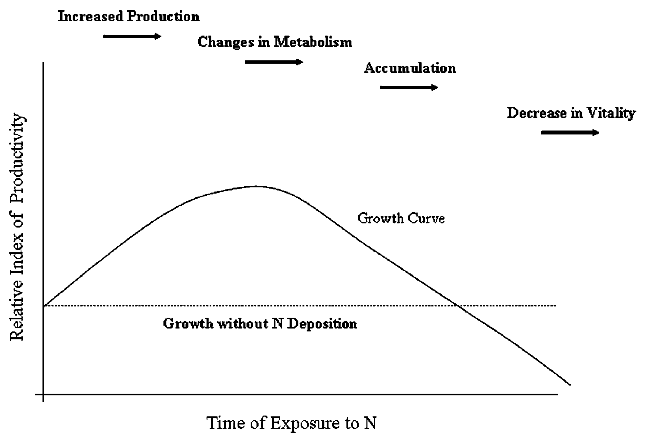

Fig. 4. Hypothetical growth curve for an ecosystem, given different lengths of exposure to nitrogen (*Source*: Gundersen, 1992).

initially increase productivity until excessive levels are reached, when the nitrogen then actually causes damage to the ecosystem (Gundersen et al., 1992; Paerl, 1997; Erisman et al., 1998). The horizontal line symbolizes a crop which receives no atmospheric N deposition, and as indicated by the vertical axis, has a stable index of productivity. As N is initially added to the system, the index of productivity steadily increases to the point of diminishing returns, where any additional N loading can reduce productivity (Schlesinger, 1997). For example, excess N deposition can cause the above ground portion of the plant to grow rapidly, leaving the root system relatively small, weak, and more susceptible to disease and harsh weather conditions (Lekkerkerk et al., 1995).

Nitrous oxide (N_2O), with an estimated atmospheric lifetime of 100–150 years (Warneck, 2000), is a persistent and strong, infrared-absorbing greenhouse gas in the Earth's atmosphere- with ~300 times more warming potential compared with CO_2 (Wang and Sze, 1980; Delwiche, 1981; Galloway et al., 2003; Schnell, 2007). N_2O is transported from the troposphere to the stratosphere, where it is an intermediate in the destruction of the stratospheric ozone (Crutzen, 1970; Khalil and Rasmussen, 1992; Bouwman, 1998). Thus, nitrous oxide while contributing to ozone destruction in the stratosphere is relatively inert in the troposphere, where it contributes to climate change as a greenhouse gas.

Reduced sulfur compounds and volatile fatty acids contribute to odor emissions which can create negative physical and psychological responses in human populations residing downwind from sulfur-emitting regions. Sulfur compounds released into the atmosphere eventually form sulfate aerosols and acidic compounds (i.e., sulfuric acid or methanesulfonic acid) which occur primarily as aerosol particles of sub-micrometer size. Sulfate acid deposition can be detrimental to ecosystems, harming aquatic animals and plants, and damaging a wide range of terrestrial plant life.

Fugitive dust and other particulates (both fine and coarse), which are composed mainly of organic matter, metals, nitrates, sulfates, and elemental carbon, have been linked to human health problems (e.g., respiratory ailments) and decreased atmospheric visibility. VOCs, through their interactions with NO_x, play an important role in atmospheric photochemistry. These compounds can act as a precursor to ozone formation in the troposphere. Elevated ozone concentrations can enhance the potential for atmospheric greenhouse effect, and ozone deposition can decrease productivity of crops, forests, and natural ecosystems (Heck et al., 1988). Ozone also has serious impacts on human health (Pope III et al., 1995).

4. Emission reduction strategies

Air quality issues associated with crop and animal production are being addressed in Europe and the US. For example, in the US, a landmark initiative known as the Smithfield/PSF Agreement is charged with identifying environmentally superior technologies (ESTs) that may reduce emissions of odors, pathogens, and nitrogen compounds from CAFOs (Aneja, 2001). These may be viewed as an engineered solution to solving a complex problem. Three characteristics together define an EST as (1) any technology or combination of technologies permitted by the appropriate government authority which (2) has been determined technically, operationally, and economically feasible for an identified category or categories of farms, and (3) meets the following performance standards:

1. eliminates the discharge of animal waste to surface waters and ground water through direct discharge, seepage, or runoff;
2. substantially eliminates atmospheric emissions of ammonia;
3. substantially eliminates the emission of odor that is detectable beyond the boundaries of the parcel or tract of land on which the swine farm is located;
4. substantially eliminates the release of disease-transmitting vectors and airborne pathogens; and
5. substantially eliminates nutrient and heavy metal contamination of soil and groundwater.

Additionally, several best management practices (BMPs) to curtail ammonia emissions from agricultural sources have recently been tested by various researchers. A relatively simple solution was undertaken by Lefcourt and Meisinger (2001), who tested the addition of alum and zeolite to cattle slurry in an effort to curb the volatilization of ammonia. When alum was added at 2.5% and 6.25%, reductions of $58\pm6\%$ and $57\pm10\%$, respectively, occurred. Slightly lower reductions of $22\pm6\%$ and $47\pm10\%$ were seen with the 2.5% and 6.25% addition of zeolite. Similar tests were performed by Berg (2006) in an attempt to lower ammonia emissions from cattle slurry by acidifying it with lactic and nitric acid. Lactic acid was applied to reach pH levels of 5.7, 5.1 and 4.2, yielding decreased emissions by 65%, 72% and 88%, respectively. Frank and Swensson (2002) found that as the crude protein in the cattles' diet was reduced, the NH_3 concentrations were reduced in parallel. In addition, when condensed tannin was added to the drinking water of both cattle and sheep, less ammonia was volatilized. The amount of nitrogen in solid and liquid waste was similar to that of tap water, but the nitrogen was nitrified/denitrified rather than volatilized into ammonia (Kronberg, 2006).

Both simple and detailed BMPs have been tested for the reduction of ammonia from swine sources. One solution was the addition of the manure additive, Alliance®, to swine manure which resulted in a 24% reduction in ammonia emissions (Heber et al., 2000), whereas an example of a more complicated solution involves ventilation and indoor air climate control (Hartung et al., 2006). A reduction of 10–14% of ammonia was reported in correlation with a reduction of indoor air temperature and ventilation rate. To obtain these results, an evaporative indoor air cooling system with an ''optimization of the fogging control with regard to a continuously complete evaporation of water'' was needed. Other solutions are more complicated in design and setup, but are easier to use. Using biotrickling filters for the manure, Hansen and Jensen (2006) were able to reduce both odor and ammonia emitted from manure. Loyon et al. (2006) found that with the use of a storage spreading system with biological treatment of manure, a 30–50% reduction occurred with separated manure and a 68% reduction with unseparated manure.

Promising results have been reported for reducing odor, ammonia, and pathogen emissions from swine manure through the use of an ''engineered system'', i.e. a treatment plant with solid–liquid separation. Szögi (2006) reported a 73% reduction in ammonia emissions with the implementation of a treatment plant system. Vanotti (2006) found that the application of manure from such a system produced a ~99% reduction in greenhouse gases emissions, as well as increased income through the Supersoil program for the use of cleaner technology. Additionally, when organic fertilizers with gypsum were applied, a 11% reduction in ammonia volatilization was achieved (Model, 2006).

Colletti et al. (2006) planted multi-row vegetative environmental buffers (VEBs) consisting of eastern red cedars, hybrid willows, and limber pines at a poultry farm in Iowa. Three rows of trees were planted 25, 35, and 45 feet in front of the barn exhaust fans, and initial evidence indicates that VEBs can effectively mitigate odor, PM, and NH_3 from these facilities.

In order to minimize soil erosion and PM_{10} emissions during high winds, Schillenger et al. (2006) employed the undercutter method of summer fallow farming, which reduced tillage from the traditional eight operations to as few as three operations during tillage. This method increased surface residue, surface clod mass, and surface roughness compared with traditional tillage, thus reducing soil erosion. Additionally, less diesel fuel is required for fewer tillages, thereby making this practice economically and environmentally beneficial as well.

The usage of ventilation systems with electrostatic dust collection systems and the usage of oil and water sprayings in poultry, cattle and swine barns have also yielded positive reductions in particulates and dust. These electrostatic dust collection systems have been shown to have a particulate reduction of 80–100% (Mitchell et al., 2002). Ellen et al. (2000) showed that spraying a 10% oil–water mixture or pure water in a poultry house caused a 50–65% reduction in inhalable dust. Similar results were found using daily water sprinkling, soybean oil, and rapeseed/canola oil (Cassel et al., 2003; Heber et al., 2004; Takai et al., 1995; Nonnenmann et al., 2004). These systems were also found to successfully reduce dust from feed crops at rates of 57–75% for corn and 64–72% for wheat (Brabec et al., 2004).

Energy production from manure has also provided promising results. This process can decrease methane and carbon dioxide by 3.03 and 1.03 tons per cow per year, respectively. Energy production can also completely reduce nitrous oxide, biological oxygen demand, and pathogens from manure. These manure digesters can produce about 5.5 kWh per cow per day and add $86 587 per year to the net farm income (Nelson et al., 2002; Martin et al., 2005).

Currently in the US, no federal regulations exist for the control of agricultural air polluting emissions; however, some states (e.g. California) are developing regulations to curb emissions of ammonia and hydrogen sulfide. Currently, the most developed incentives to reduce criteria pollutants from agriculture are primarily aimed at preventing soil loss by wind erosion processes, and are not aimed at controlling gaseous emissions. Scientific observation and measurement show that policies and control measures are needed in order to successfully decrease gaseous emissions (e.g. nitrogen) and their related problems. In the past, policies to control criteria pollutants mainly focused on single pollutants, while addressing, in general, single effects. Today, multi-pollutant/multi-effect approaches are being considered, thus offering unique opportunities for the development of abatement measures with integrated approach strategies.

5. Fundamental issues and research needs for agricultural air quality

The Agricultural Air Quality Workshop highlighted areas which require further research and consideration both in the US and internationally. Fig. 5 summarizes the major elements in agricultural air quality that need to be addressed by environmental managers and researchers. Much of the science related to agricultural air quality has grown out of the synthesis of specialized field measurements that were developed for urban air quality monitoring. These federal reference methods applied to agricultural air quality may be inappropriate and inaccurate to estimate emissions from agricultural source regions. Accurate estimates of air emissions from agricultural crops, CAFOs, and agricultural-related biomass burning are needed to gauge possible primary and secondary adverse impacts and the subsequent implementation of control measures. The species type and number of animals, their diet, housing facility type, waste management, and climatic factors, all affect emissions and complicate the emissions inventory process. Therefore, the research and development of animal process-based emission modeling could provide essential support to the successful management of agricultural environments.

Air quality models (AQMs) that account for emissions, transport, transformation, and removal of air pollutants provide a powerful tool to simulate the fate, distributions, and impact of agriculturally emitted air pollutants. The National Research Council has identified a need for three-dimensional (3-D) transport/transformation models in order to provide an adequate scientific basis for the development of relevant pollutant emission mitigation

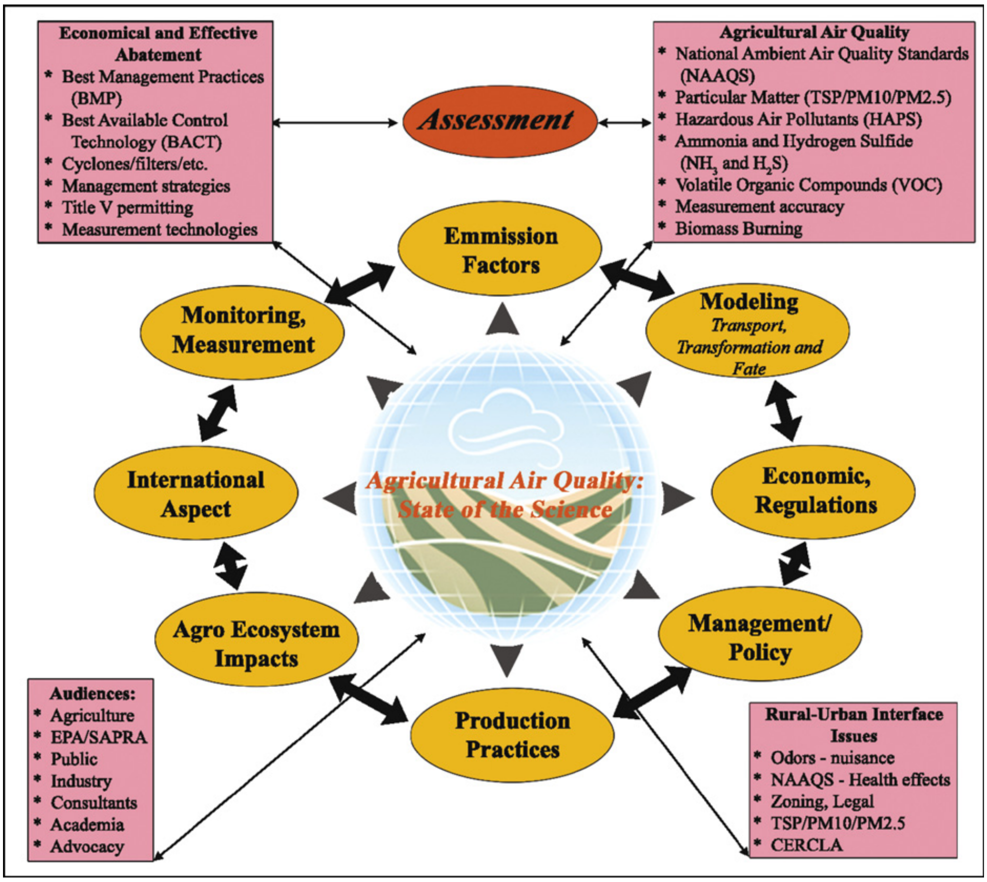

Fig. 5. Interactions and assessment of agricultural air quality.

strategies (NRC, 2003). In order to accomplish this goal, more field measurements and modeling analyses are needed to estimate deposition of nitrogen and sulfur compounds in the vicinity of agricultural operations. Improved coupled multimedia (air, water, soil) models would benefit and support the accurate prediction of the biogeochemical cycling of pollutants in the environment.

The increasing size and geographic concentration of CAFOs, and growing concerns about emissions from them, have led regulators and policy makers to focus on mitigating the harmful effects of CAFO emissions. Various BMPs have focused on methods for reducing various agricultural emissions, including odors, gases, PM, and pathogens. These BMPs include the implementation of buffer zones and new tilling techniques, improved barn design and layout, adding scrubbers on animal housing facilities, and addition of solutions to animal slurry, and diet variation. These preliminary results indicate that several promising techniques and procedures can be used to mitigate emissions. These processes still need further investigation to determine the most appropriate technologies and their accurate applications under various environmental conditions or for certain crop or animal types.

Odor continues to be difficult to quantify for several reasons: its comprehensive chemical and physical structure; it evokes many types of physiological responses; it often produces unpredictably intense emotional reactions; the range of odors humans can detect is large (more than 10,000); a large variety of gas mixtures can stimulate odor response; and humans can have an odor response in some instances triggered by very low gas concentrations (Schiffman, 1998; Schiffman et al., 2001). The most efficacious odor measurement methods, environmental and physiological characteristics affecting odor analysis, and health effects associated with these odors are now being researched. Evaluations of techniques for monitoring and characterizing odors and aerosols are in demand by the scientific and regulatory communities (Aneja et al., 2006b). Agronomists and environmental scientists are researching proper measurement protocols and instrumentation to measure and characterize odor, gases, and PM within field/facility and at edge-of-field/facility boundaries at agricultural operations.

Although there has been extensive research on small-scale BMPs, the feasibility on their implementation on any large scale has not been studied. There has also been a lack of economic analyses on many of the proposed BMPs, which will most likely be a deciding factor on their implementation. In addition, more frequent application of BMPs on a national level is needed. Also, the current practice of evaluating the effect on air quality of a BMP as an afterthought needs to change. Air quality should be just as much a criteria for a BMP as water, soil or crop production.

Finally, the lack of measurements has brought attention to the need for a national network monitoring system for atmospheric gas concentrations and emissions from agricultural facilities, and their subsequent deposition to surrounding areas. Information collected through such a program could be used to assess model performance. Additionally, a national monitoring system could be critical for evaluating any future regulatory policies or for assessing BMPs.

6. Summary and conclusions

The workshop presented significant results and insight into the status of agricultural emissions, introduced technologies which show promise for emission reductions, emphasized areas that need further research, and proposed suggestions for future research.

The current lack of scientific knowledge of nitrogen, sulfur, VOCs, and PM emissions from intensively managed agriculture and the ultimate fate of these compounds is directly comparable with the insufficient understanding of agricultural non-point sources of nutrient contamination of water in the 1980s. Just enough information is available to allow researchers and policy makers to recognize that a serious problem exists, but not enough information is available to understand the extent of the problem or to make scientifically credible solutions. Inaction or ill-informed action could negatively influence air, soil, and water quality, human health, and the overall economy of agricultural regions.

Scientists, industry, policy makers, and regulators need to make good choices about issues confronting agriculture, in order to maximize the benefits and reduce the detrimental effects of food production activities. Improvements are needed in agricultural air pollutant inventories, measurement and monitoring methodologies, modeling, and best management/production practices to mitigate air pollutant emissions from agricultural sources.

Air pollutants emitted during agricultural operations are an important emerging research area, best-studied with interdisciplinary approaches that can inform policy makers of the costs and benefits of the various potential mitigation options. Agriculture, forest, and range production practices are increasingly subject to regulations intended to protect air resources. However, frequently data on agricultural emissions of regulated pollutants, nuisance odors, and fugitive dust either do not exist or are insufficient to develop appropriate policies and/or guidelines, both in the US and worldwide.

Programs are needed to provide incentives to reduce atmospheric emissions (e.g., NH_3, H_2S, nuisance odors) from agriculture in the US Given the success of control measures used for SO_2, NO_x and anthropogenic VOCs, it is now time to address harmful atmospheric emissions from agriculture through a comprehensive strategy.

Economically feasible BMPs as well as engineered solutions are necessary to help reduce emissions from agriculture operations. Through the use of innovative methods, farms may be able to aid in the reduction of damaging particulates as well as gases from the atmosphere. Information based on scientifically credible evidence to inform rational decisions regarding improved agricultural practices is critically needed (US EPA, 2001; NRC (National Research Council), 2002, 2003; Hagenstein, 2006; Aneja et al., 2006a).

One of the major challenges for the scientific community is to find ways to maximize the beneficial use of reactive nitrogen, sulfur, and carbon while simultaneously minimizing their adverse environmental impacts. One way to approach this challenge is through the deliberate integration of reactive nitrogen, sulfur, and carbon research, management, and control strategies. Integrated research and control strategies that consider urban–rural air quality connections and interactions are necessary for optimal agricultural trace gas and PM emission management. Production agriculture has adopted modern technologies and science to maximize productivity, but it has not been subjected to the same environmental regulations that other modern industries must obey. Farms do not have to be a source of air quality problems; they can and should be a source of solutions.

The first workshop on Agricultural Air Quality: State of the Science served to bring together established experts in the related disciplines and inspired US and international students who will be the scientists, researchers and policy makers of the future, working on a national/international platform. All the proceedings 〈http://ncsu.edu/airworkshop/〉 and other conference details can be found on the workshop website at: 〈http://www.esa.org/AirWorkshop〉.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2007.07.043.

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