2.09 Climate Vulnerabilities of the Swine Industry

J Rudek, Environmental Defense Fund, Raleigh, NC, USA
VP Aneja, North Carolina State University, Raleigh, NC, USA

2.09.1 Introduction

When considering how swine production is affected by climate, perhaps the best place to start is to consider the present day vulnerabilities of the industry. The swine industry, like most of the meat production industry, is based on intensive production (Aneja et al. 2009) with trends suggesting future increases in intensification. This industry model depends on cheap grain, cheap energy, and manageable disease control. Zhao et al. (2005) opined that plausible changes in temperature, and precipitation frequency and intensity may have direct impacts on nonintensive swine production, but is not likely to directly affect intensive production because the barn environment is controlled. However, an increase in the frequency of both severe storms' (e.g., hurricanes, tornadoes, etc.) intensity and severity is also plausible. Increased storm intensity might be expected to increase the likelihood of upset of large open-air lagoon treatment systems, and increased severity has the potential to inundate the barns (Aneja et al. 2001). This could lead to increased pressure on intensive operations to modify current manure treatment systems. Climate could have negative impacts on feed grain production which would affect its availability and price. Climate influences will also have indirect impacts on energy costs as demands for renewable energy increase which could also put upward pressure on feed grain prices as bioenergy production competes for feed grains. The climate impacts on growth, reproductive success, and distribution of diseases may impact the ability to manage disease. This concern may be heightened in intensive production relative to nonintensive systems due to the density of animals. Future greenhouse gas (GHG) mitigation efforts may produce costs or revenue opportunities for the swine industry. Last, the role of reactive nitrogen (Nr) in climate and other intertwined issues could be very important. Swine producers will need to adapt to all these effects to maintain production levels.

2.09.2 GHG Emissions

US Environmental Protection Agency (US EPA) listed methane (CH_4) and nitrous oxide (N_2O) emissions from manure management among its 19 key categories which exert significant influence over the US total inventory. (CAST 2011). GHG losses from swine production occur in the barn, during treatment and storage of manure, and during and after land application of manure. US swine manure management systems are relatively high in GHG emissions because most swine manures are stored wet rather than dry (CAST 2011). Direct emissions of GHG from animal production in the United States have been estimated to be 203 Mt CO_2 Eq (carbon dioxide equivalents), or about 2.9% of the total US emissions (6957 Mt CO_2 Eq) in 2008 (CAST 2011). Swine production in Canada has been estimated to be 1835 kt CO_2 Eq or about 0.3% of total Canadian emissions (CAST 2011). The majority of the Canadian GHG emission estimate is derived from CO_2 from respiration (with 37.5% of CO_2 coming from manure degradation in the pig house) (CAST 2011).

Disparity between these livestock industry-related GHG contribution estimates and the 18% of total GHG contribution estimated by the FAO (2006) is caused by the inclusion in the UN FAO calculations of land use changes to produce feed grain and pasture for livestock. Whether or not deforestation to establish feed crop fields (or new pasture) should be included in the livestock industry's GHG emissions' estimate has been debated. For example, the recent CAST report (2011) points out that deforestation is not happening in the United States and therefore GHG emissions from deforestation should not be considered as part of the US livestock industries carbon footprint.

2.09.2.1 Nitrous Oxide Emissions

Estimates of N_2O emissions from swine barns in the United States range from 0.8 to 21 g N_2O day^{-1} AU^{-1} (AU = animal unit = the number of animals equaling 500 kg) (Cast 2011).

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Estimates for N_2O losses from swine manure anaerobic lagoons in North America have been estimated at 20 g N_2O year^{-1} animal^{-1} (Cast 2011). Estimates of losses from anaerobic lagoons in North Carolina (USA) were reported as 0.3–0.4 kg N_2O day^{-1} ha^{-1} (Harper et al. 2004). (If one assumes the average anaerobic lagoon surface area of a 4000 head feeder to finish farm in North Carolina is approximately 3 acres (or 1.2 ha; Zehring et al. 2005), the Harper et al. (2004) estimate of N_2O emissions equals approximately 38 g N_2O year^{-1} animal^{-1}.) Swine manure composted in deep bedded straw has been estimated to emit 58.9 g N_2O ton^{-1} of compost (CAST 2011).

Land application of liquid swine manure has been estimated by Harper et al. (2004) to emit 2.6–3.8 mg N_2O day^{-1} m^{-2} (versus 0.0016 mg N_2O day^{-1} m^{-2} before application). A yearly N_2O flux from land application of hog manure has been estimated at 61.3 mg N_2O m^{-2} (CAST 2011). (The Harper et al. (2004) daily estimate would equal the annual flux reported by CAST (2011) in less than 20 days.)

On a global basis, FAO (2006) estimated that swine production is responsible for 0.44 million tons of N_2O emissions per year with 25% (or 0.11 million tons year^{-1}) coming from industrial agriculture (Table 1). Swine production in North America, which is primarily intensified production (or industrial as labeled in Table 1), was estimated at 0.04 million tons of N_2O year^{-1}. Nitrous oxide emissions estimates in China and Western Europe are approximately 5 and 2 times higher, respectively, than that estimated for North America.

2.09.2.2 Methane Emissions

Methane emissions from swine barns have been estimated at 48–54 g CH_4 day^{-1} AU^{-1} (CAST 2011), and up to 160 g day^{-1} AU^{-1} for deep pit and pull plug finishing barns (CAST 2011). Estimates of lagoons emissions of CH_4 have varied widely from 0 to 188 g CH_4 day^{-1} AU^{-1} (CAST 2011). Measurements of average CH_4 emissions have been reported as 154 g CH_4 day^{-1} AU^{-1} (CAST 2011) and 21.4 g CH4 day^{-1} AU^{-1} (CAST 2011). Swine manure composted in deep bedded straw has been estimated to emit 254 g CH_4 ton^{-1} of compost (CAST 2011). Methane emissions from land application of liquid swine manure vary by time of application and method of application. Fall applications of swine manure have been estimated to emit twice as much CH_4 as springtime application (5.5 kg CH_4 ha^{-1}, 2.35 kg CH_4 ha^{-1}, respectively (CAST 2011)) with 98% of the emissions occurring in first 4 days.

Manure management in the United States emitted approximately 1.9 million tons of CH_4 in 2004 (Table 2). Swine manure management contributes the largest share of methane emissions relative to poultry and other livestock – almost half of which are from industrial swine production. Globally, nearly one-fourth of total CH_4 emissions are from industrial hog production (FAO 2006).

2.09.2.3 Carbon Dioxide Emissions

Global fertilizer production for feedcrops is estimated to be responsible for annual emissions of more than 40 million tons of CO_2 (Table 3). The emissions from fertilizer production for feed grains in the United States is about 29% of the total (11.7 million tons of CO_2), second only to China (14.3 million tons of CO_2).

CO_2 emissions induced by on-farm fossil fuels use for feed production may be 50% higher than that from feed-dedicated N fertilizer production; that is, 60 million tons of CO_2 globally (FAO 2006). Carbon dioxide emissions from on-farm energy use in Minnesota for swine are estimated at approximately 0.6 million tons year^{-1} (Table 4). If this rate is used to estimate the

Table 1 Estimated total N_2O emissions from animal excreta in 2004

	N_2O emissions from manure management, after application/deposition on soil and direct emissions						
Region/country	*Dairy cattle*	*Other cattle*	*Buffalo*	*Sheep and goats* (million tons year^{-1})	*Pigs*	*Poultry*	*Total*
Sub-Saharan Africa	0.06	0.21	0.00	0.13	0.01	0.02	**0.43**
Asia excluding China and India	0.02	0.14	0.06	0.05	0.03	0.05	**0.36**
India	0.03	0.15	0.06	0.05	0.01	0.01	**0.32**
China	0.01	0.14	0.03	0.10	0.19	0.10	**0.58**
Central and South America	0.08	0.41	0.00	0.04	0.04	0.05	**0.61**
West Asia and North Africa	0.02	0.03	0.00	0.09	0.00	0.03	**0.17**
North America	0.03	0.20	0.00	0.00	0.04	0.04	**0.30**
Western Europe	0.06	0.14	0.00	0.07	0.07	0.03	**0.36**
Oceania and Japan	0.02	0.08	0.00	0.09	0.01	0.01	**0.21**
Eastern Europe and CIS	0.08	0.10	0.00	0.03	0.04	0.02	**0.28**
Other developed	0.00	0.03	0.00	0.02	0.00	0.00	**0.06**
Total	**0.41**	**1.64**	**0.17**	**0.68**	**0.44**	**0.36**	**3.69**
Livestock Production System							
Grazing	0.11	0.54	0.00	0.25	0.00	0.00	**0.90**
Mixed	0.30	1.02	0.17	0.43	0.33	0.27	**2.52**
Industrial	0.00	0.08	0.00	0.00	0.11	0.09	**0.27**

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 2 Global methane emissions from manure management in 2004

	Emissions (million tons of CH_4 $year^{-1}$ by source)						
Region/country	*Dairy cattle*	*Other cattle*	*Buffalo*	*Sheep and goats*	*Pigs*	*Poultry*	*Total*
Sub-Saharan Africa	0.10	0.32	0.00	0.08	0.03	0.04	**0.57**
Asia[a]	0.31	0.08	0.09	0.03	0.50	0.13	**1.14**
India	0.20	0.34	0.19	0.04	0.17	0.01	**0.95**
China	0.08	0.11	0.05	0.05	3.43	0.14	**3.84**
Central and South America	0.10	0.36	0.00	0.02	0.74	0.19	**1.41**
West Asia and North Africa	0.06	0.09	0.01	0.05	0.00	0.11	**0.32**
North America	0.52	1.05	0.00	0.00	1.65	0.16	**3.39**
Western Europe	1.16	1.29	0.00	0.02	1.52	0.09	**4.08**
Oceania and Japan	0.08	0.11	0.00	0.03	0.10	0.03	**0.35**
Eastern Europe and CIS	0.46	0.65	0.00	0.01	0.19	0.06	**1.38**
Other developed	0.01	0.03	0.00	0.01	0.04	0.02	**0.11**
Global Total	**3.08**	**4.41**	**0.34**	**0.34**	**8.38**	**0.97**	**17.52**
Livestock Production System							
Grazing	0.15	0.50	0.00	0.12	0.00	0.00	**0.77**
Mixed	2.93	3.89	0.34	0.23	4.58	0.31	**12.27**
Industrial	0.00	0.02	0.00	0.00	3.80	0.67	**4.48**

[a]*Excludes China and India.*

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options.* Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 3 CO_2 emissions from the burning of fossil fuel to produce nitrogen fertilizer for feedcrops in selected countries

Country	*Absolute amount of chemical N fertilizer (1000 tons of N fertilizer)*	*Energy use per tons fertilizer (GJ $tons^{-1}$ of N fertilizer)*	*Emission factor (tons C TJ^{-1})*	*Emitted CO_2 (1000 tons $year^{-1}$)*
Argentina	126	40	17	314
Brazil	678	40	17	1690
Mexico	263	40	17	656
Turkey	262	40	17	653
China	2998	50	26	14 290
Spain	491	40	17	1224
UK[a]	887	40	17	2212
France[a]	1317	40	17	3284
Germany[a]	1247	40	17	3109
Canada	897	40	17	2237
USA	4697	40	17	11 711
Total	**14 million tons**			**41 million tons**

[a]*Includes a considerable amount of N fertilized grassland.*

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options.* Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 4 On-farm energy use for agriculture in Minnesota, United States

Commodity	*Minnesota ranking within US*	*Crop area (10^3 km^2) head (10^6) tons (10^6)*	*Diesel (1000 m^3 ~ 2.65–10^3 tons CO_2)*	*LPG (1000 m^3 ~ 2.30–10^3 tons CO_2)*	*Electricity (10^6 kWh ~ 288 tons CO_2)*	*Directly emitted CO_2 (10^3 tons)*
Corn	4	27.1	238	242	235	1255
Soybeans	3	23.5	166	16	160	523
Wheat	3	9.1	62	6.8	67	199
Dairy (tons)	5	4.3	47	38	367	318
Swine	3	4.85	59	23	230	275
Beef	12	0.95	17	6	46	72
Turkeys (tons)	2	40	14	76	50	226
Sugar beets	1	1.7	46	6	45	149
Sweet corn/peas	1	0.9	9	–	5	25

Note: Reported nine commodities dominate Minnesota's agricultural output and, by extension, the state's agricultural energy use. Related CO_2 emissions based on efficiency and emission factors from the United States' Common Reporting Format report submitted to the UNFCCC in 2005.

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options.* Food and Agricultural Orgainzation fo the United Nations, Rome, Italy. ISBN 978-92-5-105571.

CO_2 emissions by on-farm fossil fuel use for the US swine population of 65 million head in 2011 (USDA 2011), the overall CO_2 emission would be approximately 8 million tons year^{-1}.

2.09.3 Disease

Increased temperatures, more acidic conditions, and higher salinities for freshwater ecosystems have resulted in lower avian influenza survival in lab experiments (Vandegrift et al. 2010). Although these conditions suggest decreased survival of influenza viruses in the environment, predicting net impacts of climate conditions requires consideration of how viruses interact with other factors such as smaller, shallower wetlands, increased crowding, stress, and contact rates among migratory species and between wild and domestic birds and transmission to the swine population.

Some have predicted that the affects of disease under plausible future climate would be more pronounced in developing countries in humid and subhumid tropical climates (Zhao et al., 2005). However, the most recent episode of a novel H1N1 virus, which was widely reported to have first appeared on a swine farm in Mexico, a tropical developing country, quickly spread across the globe. Swine are recognized as mixing vessels in which swine, avian, and human influenza strains mix and match. Concerns have been expressed that widespread use of influenza vaccinations in intensive swine production may be 'pressuring change' in influenza evolution, helping to select for unique variants (Wuethrich 2003). Although the positive benefits of vaccinations are felt to outweigh the immunological pressure on influenza, if there are changes in enhanced influenza distribution in response to alterations in local and regional climate, the role the swine population plays in influenza evolutionary biology could become increasingly problematic.

2.09.4 Reactive Nitrogen Loss during Swine Production and Waste Management

Emissions of Nr have a complex effect on climate by altering global radiative forcing (Butterbach-Bahl et al. 2011). They directly affect the GHG balance through N_2O emissions and indirectly affect it by increasing tropospheric O_3 levels, altering methane fluxes and biospheric CO_2 sinks (including Nr deposition and O_3 effects) (Figure 1). Conversely, aerosol formed from NO_x and NH_3 emission (not shown in Figure 1) also has a cooling effect.

Modern agriculture uses large quantities of inorganic commercial N fertilizer to enhance crop productivity, currently supporting the production of about half the food consumed by the human population (Erisman et al. 2008). However, the flip side of the coin is that high levels of Nr are being released into the environment, causing numerous undesirable symptoms (e.g., algal blooms, hypoxic zones, eutrophication, ground water contamination, acid rain, atmospheric N deposition, overfertilization of terrestrial areas, increased tropospheric ozone, decreased stratospheric ozone, fine particulate matter, increased GHG) (US EPA 2011). As a result of the high mobility of Nr, agriculture is a leaky system when it comes to Nr. Much of the Nr released to the environment is from commercial inorganic N (Figure 2).

An Nr flow model for a Danish swine farm shows an example of quantities of the nitrogen introduced to the swine farm as feed, fertilizer, seed, and atmospheric deposition and its distribution into animal and crop products and losses as gases (NH_3, N_2, N_2O), and in soluble forms (DON, NO_3) (Figure 3). NH_3 emissions vary by housing type; animal size, age, and type; manure management, storage, and treatment; and weather variables, and can be expected to be higher in liquid-based systems which are more common in the United States than in Denmark. In their review, CAST (2011) reported that across a multistate (US) set of measurements and life cycle aspects, average NH_3 emissions were 48 and 30 g day^{-1} AU^{-1} for gestating and farrowing sows. Average NH_3 emissions for finishing barns ranged from 102 to 130 g day^{-1} AU^{-1} in deep-pit systems and 77–81 g day^{-1} AU^{-1} from pull plug barns. Specially formulated diets (low protein with synthetic amino acids) have been found to reduce NH_3 emissions by almost half.

Open air storage and treatment of hog manure in earthen anaerobic lagoons, typical in the southern and southeastern United States, can emit 5−40 g NH_3 day^{-1} m^{-2} (CAST 2011). Concrete storage pits are more common for swine manure in the Midwest United States with ammonia emission rates typically around 5–50 g NH_3 day^{-1} m^{-2}. (It should be noted that anaerobic lagoons have a much larger footprint than concrete storage pits.) Land application of liquid manure from a lagoon can result in large losses of NH_3 with levels greater than 100 g NH_3 day^{-1} m^{-2}. Manure land application using deep or shallow injection and drag shoe methods can decrease ammonia loss from 90+, 80+, and 60+%, respectively.

The first assessment of the overall effect of Nr emissions (between 1750 and 2005) on radiative forcing was conducted in Europe (Figure 4) (Butterback-Bahl et al. 2011). The main warming effects are from N_2O emissions (average of 17 mW m^{-2} with a range from 15 to 19 mW m^{-2}) and from reduction in the biospheric CO_2 sink by tropospheric O_3 effects on plants (average of 4.4 mW m^{-2} with a range of 2.3–6.6 mW m^{-2}). The main cooling effects are estimated to be from increasing the biospheric CO_2 sink through fertilization effects of atmospheric Nr deposition on N limited ecosystems (average (−)19 mW m^{-2} with a range of (−)30 to (−)8 mW m^{-2}) and by light scattering effects of Nr containing aerosols (average (−)16.5 with a range of (−)27.5 to (−)5.5 mW m^{-2}). Overall, European Nr emissions are estimated to have a net cooling effect, with uncertainty bounds ranging from substantial cooling to a small net warming (average (−)15.7 with a range of (−)46.7 to (+)15.4 mW m^{-2}).

The largest uncertainties concern the aerosols and Nr fertilization effects. In addition, published estimates suggest that the default N_2O emission factor of 1% used by the IPCC for indirect emissions from soil following Nr deposition is too low. Davidson (2009) estimated that 2–5% of manure and fertilizer Nr was emitted as N_2O as a result of microbial activities subsequent to land application. Crutzen et al. (2008) estimated 3–5% of newly produced Nr was emitted as N_2O.

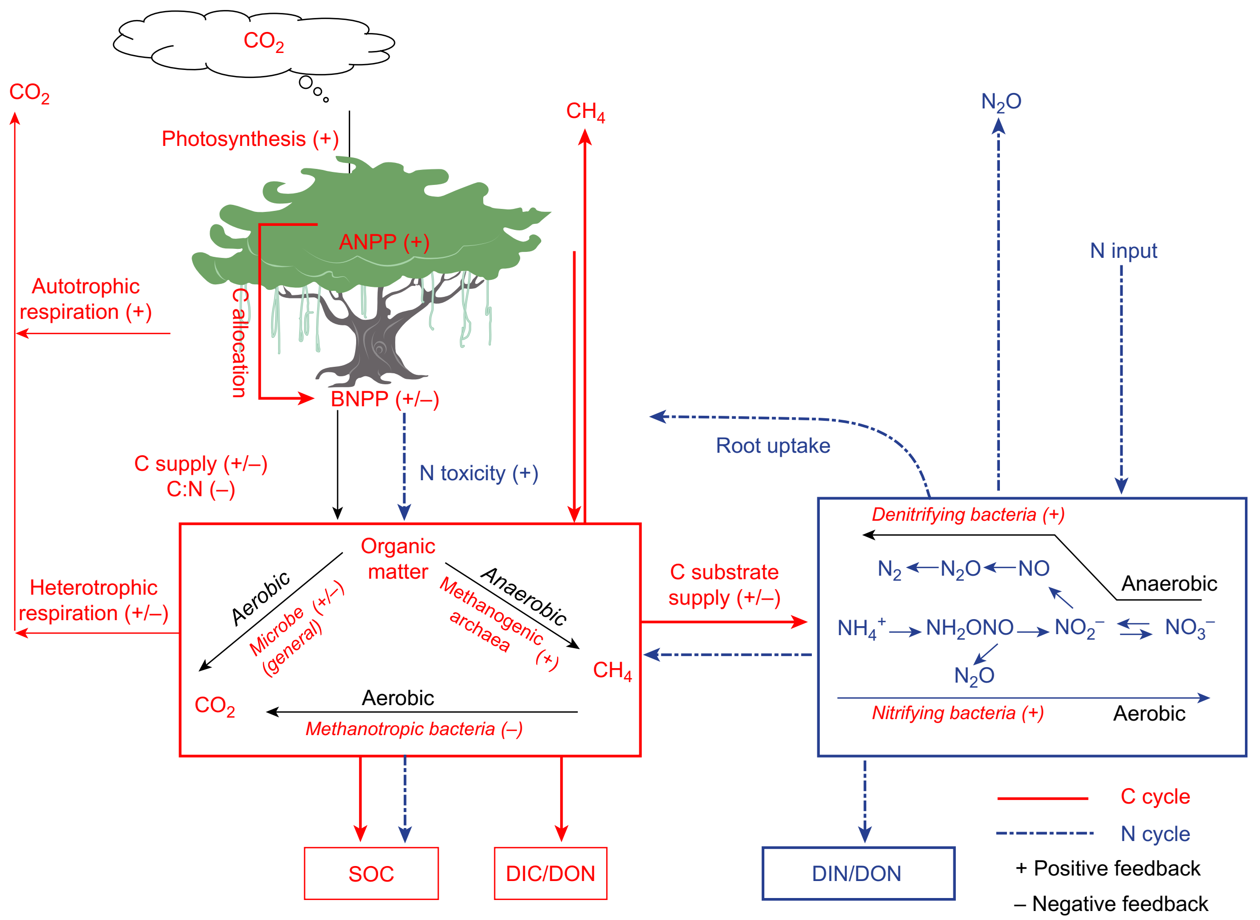

Figure 1 Potential mechanisms regulating the terrestrial ecosystem responses of CO_2, CH_4, and N_2O production and consumption in increased availability of N. ANPP, aboveground net primary productivity; BNPP, belowground net primary productivity; SOC, soil organic carbon; DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; DIN, dissolved inorganic nitrogen; DON, dissolved organic nitrogen. Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Livestock production and manure management exert various influences on the environment and make up a relatively large share of the total emission of N_2O. Most effects deal with land use changes and nutrient element cycling. These have increased over the last decades particularly in response to the trends in livestock production to scale up in size, intensification, specialization, and conglomeration in regional clusters. These trends are facilitated by the availability of cheap energy, transport infrastructure, and cheap Nr fertilizer for boosting the production of animal feeds (Erisman et al. 2011).

Though livestock production consumes less than 3% of the global net primary productivity, its contributions to the global burden of NH_3, CH_4, and N_2O to the atmosphere range from 10 to 40% (Butterbach-Bahl et al. 2011). In addition, globally livestock excrete about 100 Tg Nr year^{-1}, but only 20–40% of this amount is recovered and applied to crops. The rest is lost to the environment, wherein it moves among soil, water, and air media in a process known as the nitrogen cascade, resulting in undesirable public health risks and environmental damage (Galloway et al. 2003; US EPA 2011).

Industrial production of Nr may be considered as having increased along with livestock and human populations (Butterbach-Bahl et al. 2011; Erisman et al. 2008). Expected substantial net warming effects of these wider Nr interactions remain to be quantified. Although individual components of the Nr emissions have cooling effects, there are many opportunities for 'smart management' linking N and C cycles (Butterbach-Bahl et al. 2011). These can help mitigate GHG emissions while reducing the other Nr related threats. Efforts need to focus on reducing the warming effects, while recognizing that the adverse effects of particulate matter and nitrogen deposition on human health and biodiversity may more than outweigh their climate benefits. (Sutton et al. 2011).

2.09.4.1 Estimates of Damages from Nr Emissions

Estimates of the monetary damage resulting from efforts to manage Nr losses have been calculated for Europe. Although these estimates consider impacts outside those associated with climate, these costs will likely add to, and be comingled with, the climate mitigation pressures experienced by swine and

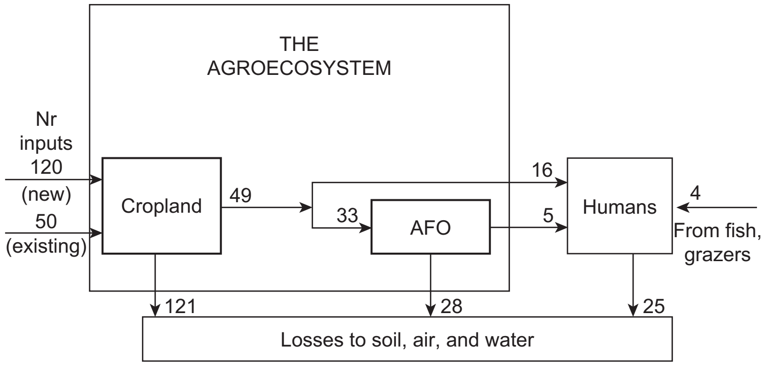

Figure 2 Major reactive nitrogen (Nr) flows in crop and animal production components of the global agroecosystem. Croplands create vegetable protein through primary production; animal production utilizes secondary production to create animal protein. Reactive nitrogen inputs represent new Nr, created through commercial processes and through cultivation-induced biological nitrogen fixation, and existing Nr that is reintroduced in the form of crop residues, manure, atmospheric deposition, irrigation water, and seeds. Portions of the Nr losses to soil, air, and water are reintroduced into the cropland component of the agroecosystem. Numbers represent teragrams of nitrogen per year. AFO, animal feeding operations. Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, B. J. Cosby, 2003: *BioScience*, **53,** 341–356.

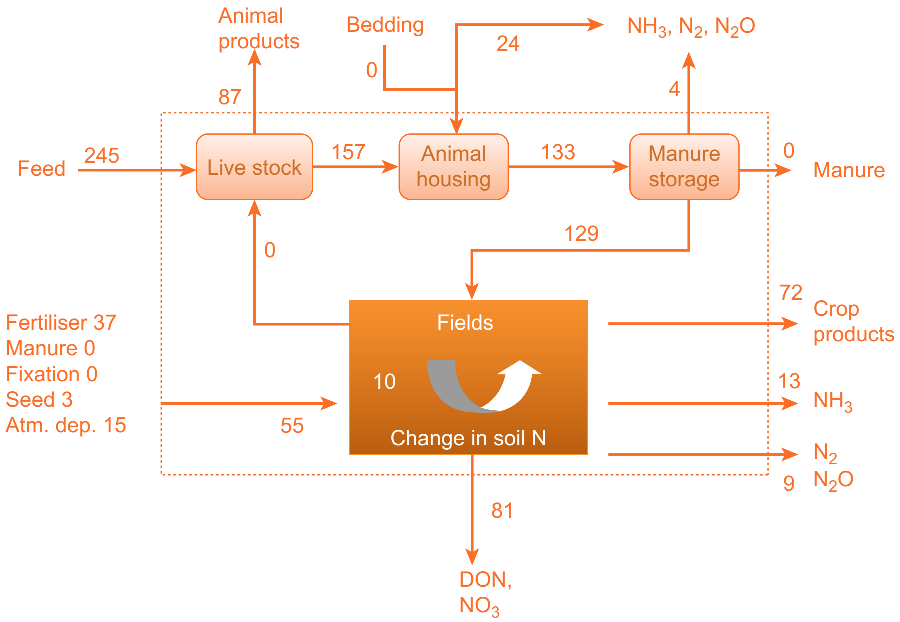

Figure 3 Annual nitrogen flows (kgN ha^{-1}) in a typical Danish swine farm. This example assumes no manure export. Jarvis, S., N. Hutchings, F. Brentrup, J. E. Olesen, K. ven de Hoek, 2011. Nitrogen flows in farming systems across Europe. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

other meat producers. European limits are already in place for land application of N in manure (170 kg ha^{-1}) for arable lands in Europe (Brink et al. 2011). These limits have increased costs for the pig and poultry sector by €10 ton^{-1}, amounting to a national cost of €90 million in 2006. About half of these costs are related to additional costs for remunerations to farmers for accepting the manure (transfer costs are not considered for national assessments) (Brink et al. 2011).

Estimates of the total annual damage in the 27 countries in the EU as a result of emissions of N_2O, NO_x, and NH_3 to air and water in 2000 from all sources, ranged from €70 to 320 billion. This corresponds to a welfare loss of €150–750 per capita, which is equivalent to 0.8–3.9% of the average disposable per capital income in 2000. About 60% of the damage costs are related to human health, 35% to ecosystem health, and 5% to the effect on GHG balance (Figure 5).

Figure 5 and Table 5 show that the unit damage costs for N_2O are small compared with other costs items, implying that N policies for agriculture should not focus on reduction of emission of N_2O alone. However, when part of the N addition is in the form of manure, the difference between externalities and net crop benefits will increase in view of the higher emission factors for ammonia (up to 70%) and the lower fertilizing efficiency of N in manure as compared with chemical fertilizer. In view of the high unit damage cost for ammonia, the use of manure without applying far-reaching low emission

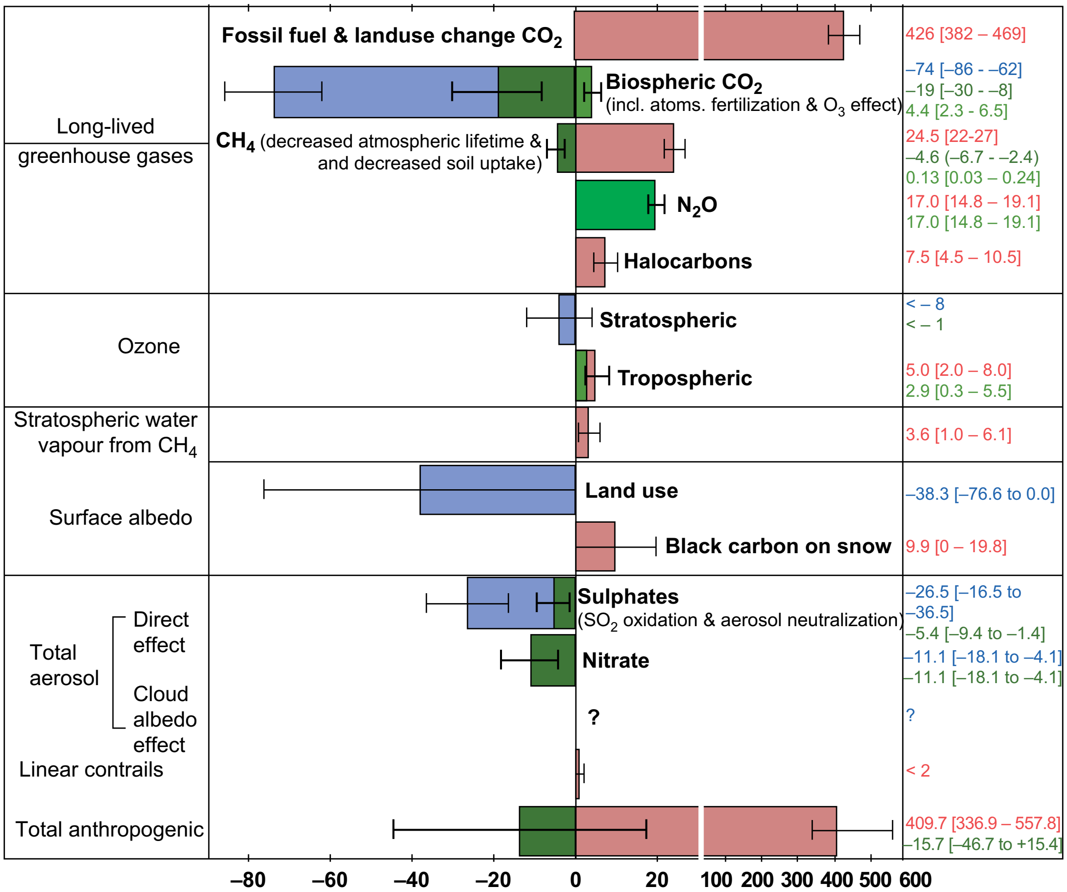

Figure 4 European contribution to global radiative forcing (mW m^{-2}). Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

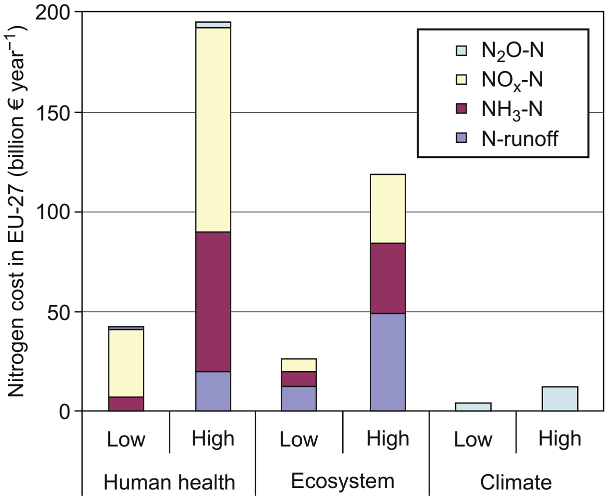

Figure 5 Low and high estimates of the total social damage in EU 27 as a result of environmental N-emissions in 2000. Brink, C., and Coauthors, 2011: Cost and benefits of nitrogen in the environment. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

techniques therefore would often be not beneficial for society. Stricter regulation of manure application and improved N efficiency would provide robust benefits for society.

Annual marginal social costs of N damages are between 20 and €150 billion, as compared with annual benefits of N fertilizer for farmers between €10 and 50 billion or €20 and 80 billion when including long-term benefits of secure soil N availability (Brink et al. 2011). These results suggest that at the present level of N fertilization, the marginal environmental costs tend to be close to the marginal agricultural benefit. As Nr emissions and social impacts increase proportionally with the use of N fertilizer, and effects on crop yield levels off, the risk of externalities exceeding crop benefits will tend to increase with higher inputs. However, it should be stressed that the upper bounds of the environmental costs are theoretical and have lower probability of occurrence than the empirically based upper bounds of the agronomic benefits.

So whether the drive to reduce Nr losses from swine production is propelled by climate concerns, public health risks, environmental damage, or some combination of all of these, pressure on swine producers to better manage Nr and prevent loss to air, water, and soil will increase. The intertwined trends in GHG emissions, population growth, and concern

Table 5 Emissions of Nr in EU 27 and estimated ranges of unit damage costs for the major Nr pollutants and, between parentheses, single values inferred from studies used in this assessment

	Emission-EU27		*Health*	*Ecosystem*	*Climate*	*Total*
	Tg Nr	*% agric*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*
Nr to water	4.9	60	0–4 (1)	5–20 (12)		5–24 (13)
NH_3–N to air	3.5	80	2–20 (12)	2–10 (2)		4–30 (14)
NO_x–N to air	3.4	10	10–30 (18)	2–10 (2)		12–40 (20)
N_2O–N to air	0.8	40	1–3 (2)		5–15 (9)	6–18 (11)

Adapted from Brink, C., and Coauthors, 2011: Cost and benefits of nitrogen in the environment. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

over public health and environmental risks are difficult to unravel (Table 6). However, opportunities to receive compensation for reduction in Nr losses might be best achieved by GHG emission reduction by way of offset credits. Thus elucidation of the role of Nr emissions in climate might be of benefit to the industry.

2.09.5 Diet Implications

If the impacts of climate become more apparent, the call for action among the common citizen, their elected representatives and regulatory agencies will likely get more urgent. This scenario presents a further risk to swine production as the full suite of climate impacts related to dietary choices would likely also come under scrutiny. As detailed above, not only are the direct emissions of CH_4 and N_2O from meat production and manure management involved in the accumulation of GHG, but the indirect role of Nr in climate and other undesirable effects on public health and environment are also of concern. The amount of Nr lost to the environment during the production of protein in milk, egg, and poultry is much less than in pork and especially beef, indicating a shift from beef to pork to poultry, and milk would also decrease the Nr use (Tables 7–9).

In a recent review by Winiwarter et al. (2011), several studies of human diet were discussed. In one study, three meal options with similar energy and protein contents were evaluated. GHG emissions varied from 0.42 (soybean) through 1.3 (pork) to 4.7 (beef) kg CO_2 eq. Another study compared four diets and included a 'healthy diet' based on sparing consumption of meat (daily intake of 10 g beef, 10 g pork, 46.6 g chicken meat and eggs, and 23.5 g fish per capita) (Table 10). Using annual meat production and shares of domestic production, the average intake of meat products and eggs per capita in the EU was compared with consumption in the case of the healthy diet. The reduction in consumption of pork relative to the healthy diet is highest at 87%. The total potential reduction in meat and egg consumption is 63%. As the milk demand is kept stable, there is no reduction in the number of dairy cattle. The number of cattle, pigs, and poultry can be reduced because of the decreased demand for their products. Simple calculations show that N excretion in the EU could decrease by about 44% and the ammonia emission by about 48%. The potential decrease in ammonia emissions is somewhat higher because the number of housed animals (which contribute more strongly to NH_3 emissions) decreases whereas the number of grazed animals remains constant. In essence, low meat diets may result in lower GHG emission and lower ammonia emissions (Table 10). Efforts to lower the Nr loss

Table 6 Quantifiable targets to avoid deterioration due to nitrogen

Environmental problem	*Nitrogen connection*	*Target*
Loss of ecosystems services due to: • Acidification • Eutrophication • Biodiversity loss	Atmospheric deposition of nitrate and/or ammonia	Critical loads (exceedance of soil specific values)
Adverse impact on plant species composition	Atmospheric concentration of ammonia	Critical levels (exceedance of critical NH_3 concentrations)
Crop damage	O_3 formation (NO_x chemistry)	Accumulated exposure over threshold
Human health	NO_x concentration O_3 formation (NO_x chemistry) PM formation (NO_x chemistry and ammonia) Nitrates in drinking water	Years of life lost Disablement Adjusted Life Years Quality standard (concentrations)
Climate change	N_2O emissions CO_2 emissions/uptake, as the natural C cycle is influenced by N in the environment O_3 formation (NO_x chemistry)	Global mean temperature (limit: 2 °C increase above preindustrial)

Adapted from Winiwarter, W., and Coauthors, 2011: Future scenarios of nitrogen in Europe. *The European Nitrogen Assessment.* M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 7 Summary of annual N in products and losses (kg ha^{-1}) derived from typical farm nitrogen budgets with losses also expressed per unit N in products

Farm management	*Nitrogen in crop and animal products (kg ha^{-1} $year^{-1}$ N)*	*Nitrogen losses (kg ha^{-1} $year^{-1}$ N)*	*N losses per unit N in products (as ratio)*
Arable	99	84	0.85
Pig	159	131	0.82
Beef	40	108	2.7
Dairy (conventional)	56	143	2.55
Dairy (organic)	39	75	1.92

Adapted from Jarvis, S., N. Hutchings, F. Brentrup, J. E. Olesen, and K. ven de Hoek, 2011: Nitrogen flows in farming systems across Europe. *The European Nitrogen Assessment*. M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 8 Total excretion of Nr by livestock and emission of N_2O (kilotons) from animal manure management systems in EU 27 in 2000

Livestock category	*Nr excreted*	*Housing and storage N_2O[a]*	*Land application N_2O*	*Grazing N_2O*	*Total N_2O*
Dairy cattle	2670	18	18	12	48
Other cattle	3210	18	14	27	59
Pigs	1687	9	17		26
Poultry	1750	7	9		16
Other	1055	2	3	24	29
Total	10 372	54	61	62	177

[a]*N_2O emissions given here are the sum of emissions from housing systems and storage and do not include losses from mineral fertilizer applications to soil.*

Adapted from Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 9 Non-CO_2 GHG emissions associated with the production of various food items. Units are 10^6 CO_2 eq $year^{-1}$, except column 6

	CH_4				
Food	*Enteric fermentation*	*Manure management*	*N_2O manure management*	*Sum*	*Approx percentage of total*
Eggs	–	2.08	0.62	2.70	1
Dairy	26.68	18.18	21.96	66.82	29
Beef	82.04	4.43	34.34	120.81	56
Pork	2.07	30.20	1.70	33.97	15
Poultry	–	2.31	0.68	2.99	1
Sheep	1.16	0.03	0.60	1.79	1
Goats	0.14	0.01	0.20	0.35	<1
				Total: 229.41	

Adapted from Eshel, G., P. A. Martin, 2006: Diet, energy, and global warming. *Earth Interact.*, **10,** 1–17.

Table 10 Meat/egg production and consumption, 2007, in the EU countries

Activity	*Meat/egg production (10^6 ton $year^{-1}$)*	*Share of domestic production*	*2007 diet (kg cap^{-1} $year^{-1}$)*	*Healthy diet (kg cap^{-1} $year^{-1}$)*	*Reduction in intake*
Ruminants[a]	9.3	96%	19.8	6.24	68%
Pigs	22.9	108%	44.8	5.66	87%
Poultry	11.4	103%	23.1	25.3	32%
Eggs	7.0		14.1		
Total meat + eggs	50.6		101.8	37.2	63%

[a]*Ruminants are cattle, sheep, and goats.*

Adapted from Winiwarter, W., and Coauthors, 2011: Future scenarios of nitrogen in Europe. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press; FEFAC 2008; healthy diet: Stehfest et al. 2009.

from swine operations could help reduce the GHG impacts of diets containing pork products.

2.09.6 Mitigation Opportunities

Given the array of undesirable impacts of swine production associate with GHG and Nr emissions, the industry would be well served to diligently explore opportunities to reduce such emissions. Perhaps one of the most straightforward mitigation opportunities lies in the capture of CH_4 emissions from manure storage/treatment systems using anaerobic digesters. The best use of the CH_4 captured by anaerobic digesters is renewable energy production, either electrical, heat, or both (i.e., cogeneration). In addition to energy, GHG offset credits could potentially also be sold on the voluntary or regulatory market. Even if the CH_4 is flared, given that CH_4 has a global warming potential (GWP) of 21 (IPCC 2007), the CO_2 emitted (with a GWP of 1) results in much lower radiative forcing. Currently the economics of anaerobic digestion are challenging. Registration and verification processes for GHG credit sales add additional hurdles. In addition, management of anaerobic digester effluent is also needed to prevent loss of NH_3. However, NH_3 emission controls also offer the potential for additional revenue from N water pollution offset credits or capture for sale as fertilizer (Rudek and Aneja 2011). Given the benefits to society of reducing commercial fertilizer use (e.g., less energy use, less Nr emissions) by recycling NH_3 captured from manure into a concentrated product that can be efficiently transported, a cogent argument can be made that incentive payments along the lines of those provided for biodiesel production would be in society's interest.

More widespread and efficient use of the Nr in manure is also needed to reduce undesirable impacts. Long-term changes could include a shift of the industry to areas that can use additional manure for crop fertilization. Once NH_3 losses are controlled, much more Nr will need to be managed. Many swine operations will not have the addition farm land or crop needs to absorb the additional Nr. Options for managing the additional Nr include denitrification, NH_3 capture and concentration, or production of a manure value-added product (e.g., compost, vermicompost). Care will need to be taken that denitrification treatment systems are optimized to avoid high levels of N_2O byproducts. With GWP of about 310 (IPCC 2007), even small percentages of N_2O can quickly add up to large increases in radiative forcing.

The swine industry has been effective in increasing the feed conversion efficiency, providing financial benefits in reduced feed costs, which could become increasingly important if feed grain prices increase. Modifications in swine diets could also help in reducing Nr concentrations in manure and hence Nr losses.

Adapting to possible increased precipitation and more severe storms translates into reducing the risk of upset of treatment systems and barn flooding. Excluding rainfall from manure treatment systems and moving barns and manure treatment systems out of flood plains seem the most reasonable modifications to minimize threats from precipitation pattern changes. Again anaerobic digesters may be the most prudent treatment system to adopt to exclude rainfall.

The potential for intensive swine production to become a source of novel influenza viruses as a result of alterations in climate patterns and increased density of swine production suggests that it would be prudent for both the swine industry and the society to increase its surveillance of novel influenza strains appearing in the swine herd.

2.09.7 Conclusion

Modern agriculture provides food for an increasing number of humans through intensive agriculture. To achieve this feat, agriculture has gone through major changes over the last few decades becoming increasingly intensified. Massive use of industrial fertilizers has improved crop yields, and efficient concentrated animal feeding operations (CAFOs) dominate the production of swine both in the United States and abroad. However, on a global basis, agriculture is now recognized as a major force pushing the environment beyond its 'planetary boundaries' (Rockstrom et al. 2009). Clearly something must be done to reform agriculture and particularly livestock production, to reduce its contributions to air, water, and soil pollution, and increasingly human health and climate concerns.

Wendell Barry is famously quoted as saying, "The genius of American farm experts is very well demonstrated here: they can take a solution and divide it neatly into two problems" (Barry 1996). If reduced meat consumption, often cited as one of the solutions from reducing agriculture's negative environmental impacts (see for example Foley et al. 2011), is not to be the only solution to reducing environmental impacts, modern livestock producers must show that its genius can be applied to greatly reducing the massive footprint of livestock agriculture. As Barry implies, capturing the resources inherent in manure must be part of the solution.

Agriculture (both animal and crop) do not have to be a source of human health, climate, air, water, and soil quality problems; they can and should be a source of solutions. Society must invest in the research needed to find solutions. However, it is also critical that farmers and livestock producers come to the table to join, and ultimately lead, the search for solutions.

References

Aneja, V. P., P. A. Roelle, G. C. Murray, J. Southerland, J. W. Erisman, D. Fowler, W. A. H. Asman, and N. Patni, 2001: Atmospheric nitrogen compounds II: emissions, transport, transformation, deposition and assessment. *Atmos. Environ.*, **35,** 1903–1911.

Aneja, V. P., W. H. Schlesinger, and J. W. Erisman, 2009: Effects of agriculture upon the atmospheric environment of the United States: research, policy and regulations. *Environ. Sci. Technol.*, **43,** 4234–4240.

Barry, W., 1996: *The Unsettling of America: Culture & Agriculture.* Sierra Club Books.

Brink, C., and Coauthors, 2011: Cost and benefits of nitrogen in the environment. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Council for Agricultural Science and Technology (CAST), 2011: *Air Issues Associated with Animal Agriculture: A North American Perspective. CAST Issue Paper 47*. CAST, Ames Iowa, [Available online at http://www.cast-science.org.]

Crutzen, P. J., A. R. Mosier, K. A. Smith, and W. Winiwarter, 2008: N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.*, **8,** 389–395.

Davidson, E. A., 2009: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.*, **2,** 659.

Erisman, J. W., M. A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter, 2008: How a century of ammonia synthesis changed the world. *Nat. Geosci.*, **1,** 636–639.

Erisman, J. W., H. van Grinsven, B. Grizzetti, F. Bouraoui, D. Powlson, M. A. Sutton, A. Bleeker, and S. Reis, 2011: The European nitrogen problem in a global perspective. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Eshel, G., and P. A. Martin, 2006: Diet, energy, and global warming. *Earth Interact.*, **10,** 1–17.

FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Organization of the United Nations, Rome, Italy. ISBN: 978-92-5-105571.

Foley J. A., and Coauthors, 2011: Solutions for a cultivated planet. *Nature*, **478**, 337–342.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, and B. J. Cosby, 2003: *BioScience*, **53,** 341–356.

Harper, L. A., R. R. Sharpe, B. B. Parking, A. De Visscher, O. van Cleemput, and F. M. Byers, 2004: Nitrogen cycling through swine production systems: ammonia, dinitrogen, and nitrous oxide emissions. *J. Environ. Qual.*, **33,** 1189–1201.

IPCC, 2007: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 996 pp. [Available online at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.]

Jarvis, S., N. Hutchings, F. Brentrup, J. E. Olesen, and K. van de Hoek, 2011: Nitrogen flows in farming systems across Europe. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Rockstrom, J., and Coauthors, 2009: A safe operating space for humanity. *Nature*, **461,** 472–475.

Rudek, J., and V. P. Aneja, 2011: Emissions from intensive agriculture. *EM Air Waste Manag. Assoc.*, 15–18.

Sutton, M. A., O. Oenema, J. W. Erisman, A. Leip, H. van Grinsven, and W. Winiwarter, 2011: Too much of a good thing. *Nature*, **472,** 159–161.

US Environmental Protection Agency (UA EPA), 2011. *Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options*. EPA-SAB-11–013. [Available online at http://www.epa.gov/sab.]

USDA, 2011. US Department of Agriculture National Agricultural Statistics Service. Accessed in July 2011. [Available online at http://www.nass.usda.gov/Charts_and_Maps/Hogs_and_Pigs/index.asp.]

Vandegrift, K. J., S. H. Sokolow, P. Daszak, and A. M. Kilpatrick, 2010: Ecolofy of avian influenza viruses in a changing world. *Ann. N. Y. Acad. Sci.*, **1195,** 113–128.

Winiwarter, W., and Coauthors, 2011: Future Scenarios of nitrogen in Europe. *The European Nitrogen Assessment*. M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizetti, Eds., Cambridge University Press.

Wuethrich, B., 2003: Chasing the fickle swine flu. *Science*, **299,** 1502–1505.

Zehring, K., and Coauthors, 2005: *Cost and Returns Analysis of Manure Mmanagement Systems Evaluated in 2004 under the North Carolina Attorney General Agreements with Smithfield Foods. Premium Standard Farms and Front Line Farmers*. Animal and Poultry Waste Management Center, NC State University, Raleigh, NC. [Available online at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase2report05/cd,web%20files/B1a.pdf.]

Zhao, Y., C. Wang, S. Wang, and L. V. Tibig, 2005: Impacts of present and future climate variability on agriculture and forestry in the humid and sub-humid tropics. *Clim. Change*, **70,** 73–116.