Environmental Challenges Ahead for the U.S. Dairy Industry

Wendy Powers
Departments of Animal Science and Biosystems Engineering
Michigan State University, East Lansing
wpowers@msu.edu

INTRODUCTION

The dairy industry faces increasing environmental challenges. While efforts to improve management of dairy farms has reduced the environmental impact of milk production, regulatory and social pressures mandate that further improvements be made to reduce the pollution potential even more. Concerns over air and water quality to date have been related, primarily to nutrient issues. Nutrient-related water quality concerns have focused on nitrogen and phosphorus contributions to ground and surface waters, respectively. Air emission concerns include odor, nitrogen and sulfur emissions. More recently, states have addressed emissions of volatile organic compounds. Greenhouse gases (GHG) are being addressed at both state and federal levels. Non-nutrient challenges such as pathogens, antimicrobials, and endocrine disrupting compounds have received considerable attention. Retailers are taking a more active role in sourcing supplies based on production practices and environmental impact. Policymakers are under constant pressure to address constituent concerns regarding livestock production and the impacts on neighbors, the environment and the animals themselves. And while policymaking can be swift, the unintended consequences of new policies may not be fully explored.

AIR QUALITY CHALLENGES

Nuisance

Concerns over air emissions from dairy operations range from nuisance conditions to human health impacts to ecological impacts. The varying scales of concerns, alone, pose a challenge to producers. Local concerns of neighbors include nuisance events such as odors (NRC, 2003) and attraction of flies. While odor nuisance is likely the underlying cause of local concerns, odor regulation is difficult. Several states have odor standards, such as Colorado and Pennsylvania, while other states, such as Iowa, have considered an odor standard but not adopted one. Reports of psychological as well as physiological impacts of exposures to malodors exist but variability from one individual to the next coupled with the challenges of measuring transient odors and isolating health effects from emotional effects has made regulation and effective mitigation of livestock odors a formidable task.

Human Health

Neighbors might also share the concerns of rural residents, in general, that relate to human health impacts such as incidence of asthma and infant mortality (Sneeringer, 2009). Numerous reports exist that discuss the negative consequences of livestock production on human health. Sneeringer (2009) reports that her work suggests that a county-wide increase in animal numbers by 100,000 animal units corresponds to123 more deaths of infants under one year per 100,000 births, and 100 more deaths of infants under twenty-eight days per 100,000 births. Her conclusions imply that doubling animal numbers increases infant mortality by 7.4%, citing counties with average increases in animal units of 35% between 1982 and 1997 experienced. These counties reportedly had a corresponding 2.8% increase in infant mortality, equaling an additional 3,500 infant deaths. Sneeringer (2009) concludes that the rise in deaths is driven by respiratory disease from air pollution, having ruled out water-related causes in her analyses. While the data are corrected for concurrent increases in 15 other industries, changes in population densities, traffic patterns, and additional ancillary consequences of a growth in livestock are not taken into account. Others have made similar conclusions regarding livestock production impacts on air quality. Heederik et al. (2007) reviewed the literature and concluded that most of the information presently available regarding exposure and health impacts is based on worker exposure rather than data from community exposures. The worker exposure data demonstrate declines in lung function, attributable to endotoxin exposure with little impact from gases on respiratory function (Heederik et al., 2007). However, data that document endotoxin and gas levels in communities are unavailable and findings from worker studies may not be applicable in surrounding communities where populations are different from the worker population (range of age, susceptibility, willingness to tolerate conditions).

Air emissions from livestock operations and the impacts on human health remain at the media forefront. The livestock industries have been proactive in addressing concerns by funding the National Air Emissions Monitoring Study. The study, scheduled to conclude by the end of 2009, is intended to provide information regarding the range in emissions of ammonia, hydrogen sulfide and particulates that occurs from livestock operations around the country. Emissions are measured at the exhaust air from housing and from some outdoor manure storages. While the number of operations monitored over the 2-year period is not a statistically representative sample of the industry, nor are the measurements made beyond facility property lines, the data that results will make an important contribution to the limited data that currently exist. The study, however, will not address the paucity of date that exists for plume dispersion models that are applicable for use in predicting downwind concentrations from livestock operations (Bunton et al., 2007). What US EPA will do with the data and what new standards may result are unknown at the present time.

Recent Regulatory Activity

To address concerns related to air emissions from livestock facilities, in advance of reviewing the data from the National Air Emissions Monitoring Study, the United States Environmental Protection Agency (US EPA) has taken action. In December 2008, President Bush signed a ruling that requires a Concentrated Animal Feeding Operation (CAFO) to report emissions under the Emergency Planning, Community Right-to-Know Act (EPCRA; Federal Register: December 18, 2008 (Volume 73, Number 244) DOCID:fr18de08-14). As a result of the ruling, reports must be filed with local and state authorities; however no mitigation action is required. The challenge in completing the reports has been identifying data for a producer that represents an individual operation.

Reports include a high and low estimate of daily emissions for any particular gas covered under EPCRA and while most consider only ammonia and hydrogen sulfide to be relevant, finding data for just those two gases can be difficult. Previously, US EPA had ruled that agricultural sources could be considered and regulated for both coarse and fine particulate matter. In February the US EPA's decision to include agriculture as a source of coarse particulate matter was upheld. Now it is up to states to determine if they will restrict particulate emissions from agricultural sources as part of a State Implementation Plan that must be submitted to address areas within a state that are in non-attainment for the current standard. With respect to fine particulate matter, or that fraction that has respiratory impacts, the US Court of Appeals remanded the standards back to US EPA for further review, finding some portions of the standard contrary to law and unsupported (American Farm Bureau Federation and National Pork Producers Council v. US EPA; http://www.eenews.net/public/25/9867/features/documents/2009/02/24/document_gw_02.pdf). To date, US EPA has not issued a revised proposal.

Greenhouse Gases

Climate change and global warming are widely discussed topics in the U.S. and around the world. Greenhouse gas emissions are one example of how dairy operations contribute to concerns that are of global scale (Steinfeld et al., 2006). Steinfeld et al. (2006) make the case that feed and pasture fertilization in 11 countries, account for 20% of global fertilizer N consumption. The U.S. leads the 11 countries, using one third of the total and therefore contributing that portion of the fossil fuel use in fertilizer production and resulting carbon emissions. Livestock production are attributed to other sources of carbon release as well, i.e. deforestation in Argentina, desertification in arid regions, soil cultivation for feed production, methane production in rice cultivation where animal manures are present, releases from burning of pastures as a management practice. While it is arguable how much blame towards the livestock industry for the above practices, what is indisputable is methane production as a result of enteric fermentation. The US EPA (2004) estimated that methane production by domesticated ruminants accounts for 19% of the national production. In North America, dairy cattle are estimated to contribute 20% of methane production from enteric fermentation (Steinfeld et al., 2006). The US EPA (2004) estimates that 10 million metric tonnes of methane are produced from manure storage, representing 4% of worldwide anthropogenic methane production or approximately 12% of worldwide enteric methane production. The U.S. produces approximately 20% of the anthropogenic methane from manure storage (US EPA 2004). Steinfeld et al. (2006) calculate over 17 million tonnes of methane produced from manure storage, almost double the US EPA estimate, with dairy manure still accounting for 17% of the methane produced. Considering processing, transport, and all cropping-related activities, Steinfeld et al. (2006) conclude that livestock production accounts for 40% of all anthropogenic GHG emissions. Others estimate agriculture's contribution (livestock plus cropping systems) to be 14% of anthropogenic GHG emissions, excluding transportation and processing impacts (IPCC, 2007) and identify energy supply, transport and industry, as the sectors increasing in GHG emissions at the greatest rate. Residential and commercial buildings, forestry (including deforestation) and agriculture sectors are identified as growing but at a lower rate (IPCC, 2007).

Given the conclusions made in recent reports coupled with the U.S.'s acute interest in GHG, it is no surprise that animal agriculture has received considerable attention. In March 2009, the US EPA announced a plan to mandate reporting of GHG (FR Docket ID No. EPA-HQ-OAR-2008-0508). While a final rule is not available, public hearings have been announced (Federal Register/ Vol. 74, No. 56). The proposal entails reporting emissions from all sources emitting greater than 25,000 metric tons of CO2 equivalents (the equivalent of 4,500 passenger vehicles). Enteric emissions are not included. However, CO2 emissions resulting from combustion associated with engines in anaerobic digesters are included in the calculation. At present, US EPA estimates that 40 to 50 of the largest livestock operations in the U.S. will need to report. It is plausible that future decisions will require remediation or mitigation of emissions. Most commonly, agriculture is viewed as a carbon credit generator but without clear U.S. policy at the present time, it is difficult to assess if that will remain the case or if agriculture will become a capped entity. Should the country follow California's lead, there can be opportunities for agriculture in carbon markets.

Reactive Nitrogen

Reactive N (Nr) refers to all forms of biologically active, chemically reactive and radiatively active forms of nitrogen, including ammonia, nitrous oxide, and nitrogen oxides (INC, 2008). The US EPA Science Advisory Board has convened a panel of scientists to

1. Identify and analyze, from a scientific perspective, the problems nitrogen presents in the environment and the links among them;
2. Evaluate the contribution an integrated nitrogen management strategy could make to environmental protection;
3. Identify additional risk management options for EPA's consideration; and
4. Make recommendations to EPA concerning improvements in nitrogen research to support risk reduction.

In a draft report, the Integrated Nitrogen Committee (INC) presents four overarching research and management recommendations to assist EPA in developing an integrated nitrogen management strategy, and five specific recommendations proposed to decrease the amount of Nr lost to the US environment by 25%. Within the recommendations, several pertain to agriculture. One recommendation is to maximize the N efficiency of both crop and livestock production systems and to develop strategies for avoiding increased Nr load in the environment. A second recommendation promotes a policy, regulatory, and incentive framework to improve manure management to reduce Nr load and ammonia losses. The INC recommends a goal of decreasing livestock derived NH3 emissions to approximately 80% of 1990 emissions, a decrease of 0.5 Tg N/yr (by a combination of BMPs and engineered solutions). While the report is a draft and does not presently represent the consensus of the committee, it is a strong indication that recent regulatory activity may be the beginning of what may follow under a new administration.

WATER QUALITY CHALLENGES

Nutrients

Nutrients into water supplies, conveyed through either direct discharge or following land application of manures continues to be an important area of management for dairy operations. Following the 2002 CAFO rule, many states have adopted rules intended to address nutrient losses into water supplies. Implementation of state rules continues with a completion timeline of 2010. While many states adopted, for the first time, standards addressing P application, other states have faced different challenges.

Pathogens

Pathogens in the environment are a prominent concern of consumers and citizens (Powers and Angel, 2008). Considerable work is underway to identify if sources of pathogens in water supplies are of human or animal origin (Scott et al., 2003). Burkholder et al. (2007) reviewed the literature and concluded that current manure storage, handling and land application practices do not adequately or effectively protect water resources from pathogen contamination. Not surprising is that pathogenic microorganisms have been documented at high densities in receiving surface waters following manure spills (Burkholder et al., 1997). However, the extent to which contributions result when good management practices are in place is still to be determined as is the extent to which management practices that protect against pathogen contamination are in use by the dairy industry as a whole. Recent work by Haack and Duris (2008) provided inconclusive results regarding management practice influence on nutrient and pathogen presence in subsurface agricultural drains following land application of liquid dairy manure. In the future, more emphasis may be placed on controlling the release of pathogens by using treatment technologies to trap or destroy pathogens. Pathogen destruction may be required in some situations prior to land application of excreta and/or litter. Manure or litter storage alone does not completely destroy pathogens; however, biological or chemical treatments such as composting, thermophilic anaerobic digestion, or liming demonstrate some pathogen destruction (Spiehs and Goyal, 2007).

Antibiotics

In addition to pathogens, the general public is very much aware of antibiotic use in food production. While antibiotic use as a growth promotant has waned considerably (reviewed by Powers and Angel, 2008) pressure to make greater reductions is likely to occur. Gilchrist et al. (2007) support the World Health Organization’s call for a phase out of antimicrobial growth promotants based on their review of, what they admit to be, limited data to support that overuse of antibiotics occurs in livestock production and can be traced to causing antibiotic resistance in humans. Regardless of the lack of data to support a motion, the scientists promote restriction of antimicrobial use to therapeutic use by prescription, only (Gilchrist et al., 2007). Powers and Angel (2008) suggest that proliferation and transport of antibiotic-resistant bacteria will continue to be prominent challenges and the need for mitigation strategies to further reduce the need for antibiotic use is warranted. While the ecosystem impacts of antibiotic-resistant bacteria and pathogens are less documented than the human health impacts of exposures, both topics are of interest to regulatory agencies. The sentiment that recent outbreaks of virulent strains of influenza around the world have arisen in cases where swine and poultry have been raised in close proximity (Gilchrist et al., 2007) has the potential to have widespread effects on livestock production, including dairy, if policies are adopted restrict cross-species proximity.

Endocrine disrupting compounds

Endocrine disrupting compounds are a class of compounds either synthesized or present naturally in nature that are suspected to have adverse effects in animals and humans. The primary source of EDCs in manure is the animal itself. Natural hormones produced by animals are shed in manure and may persist in ecosystems (Herman and Mills, 2003). Recently endocrine disrupting compounds (EDCs) have started to receive scrutiny both from regulatory agencies as well as the general public (Nichols et al., 1997; NRC, 1999). They affect organisms primarily by binding to hormone receptors and disrupting the endocrine system by either mimicking natural hormones or by interfering with their binding (Colborn et al., 1993). Monitoring for the presence, concentration, and distribution of these compounds in the environment and in food is becoming an important issue because of the potential negative consequences these compounds can have when present at relatively low levels (Fischer et al., 2005). Testing for these compounds in food products, litter, and water is still a developing science. As defined, EDCs include pesticides, herbicides, plant phytoestrogens, and other chemicals that interact with endocrine systems (reviewed by Powers and Angel, 2008).

All animals can produce EDCs, in the form of steroid hormones that are excreted in feces. The steroids of greatest concern are estrone and 17β-estradiol because they are often found in the environment at concentrations above lowest effect levels. While data are limited for dairy manures (Dyer et al., 2001), research with poultry litter demonstrates minimal degradation during storage (Fisher et al., 2005). Data that are available for dairy manure demonstrates that estrogen (17β-estradiol) occurs in measurable concentrations. Conventional tillage, as compared to “no till”, greatly decreases losses to water of steroid hormones from soils where litter has been applied (Nichols et al., 1997 as reviewed by Powers and Angel, 2008). A similar response could be expected with dairy manure. As EDCs come under regulatory control, a better understanding of the impact of age and growth rate on excretion of EDCs by poultry will become more important.

RESOURCE UTILIZATION

When productivity (unit of output per unit of input) is reduced, more resources (energy, water, nutrients) are needed to meet the same level of output. With a finite amount of earth, feeding an increasing population will eventually lead to a situation of competing resources, likely resulting in environmental insult to the land resources or a prioritization of need for generated products (e.g., housing for an increasing population versus land for food production).

Elferink and Nonhebel (2007) found that optimizing feed composition to incorporate highest yield feed crops and regional sources for feed will reduce land area requirements for pork, chicken and beef, but the authors acknowledge that the world's optimal feed production regions are insufficient to meet the world's meat demand when land use intensity is reduced. Crops generally require greater inputs of fossil fuel-based fertilizer, pesticides, and irrigation water to achieve high yields (Ward et al., 1993). These upstream inputs of chemicals and energy will contribute negatively to the environmental, human-health, and ecological impacts of an animal-based production system. Ideally, agriculture finds means to reduce resource inputs, particularly those with negative environmental consequences, while maintaining or improving production, thereby increasing overall efficiency. Efforts to improve the efficiency of milk production span from nutritional to genetic to biotechnological means. While gains have been made, setbacks have occurred as well. Recombinant bovine somatotropin (rbST) reduces total feed requirements by over 8% (Capper et al., 2008); yet its use by the dairy industry has been controversial with respect to social acceptability by the general public.

Energy use has received considerable attention as supplies and sources of fossil fuels are questioned, energy prices are increasing, and environmental issues are increasing. With that come the environmental issues related to fossil fuel consumption, and analyses to assess process-wide fossil fuel use, such as the carbon footprint (Moroto-Valer et al., 2002). Even renewable energy production faces environmental challenges such as ecosystem diversity (Tsur and Zemel, 2007). Energy use in food production will likely face greater scrutiny in the future as consumer awareness of energy use issues continues to increase. Calculation of the carbon footprint of an industry allows one to tally the energy use from farm to table.

There is increasing interest in assessing the impact an industry has on multiple parameters, simultaneously, rather than continuing to research topics with a single-issue approach. Thomassen and de Boer (2005) propose the use of Life Cycle Analysis (LCA) as a means of evaluating the environmental impact of dairy production because LCA is inclusive of impact categories such as land use, energy use, global warming potential, acidification and eutrophication potentials, and focus on on-farm emission. Other methods, such as mass balance and ecological footprint are effective in addressing single issues but do not consider all of the environmental impact categories in sufficient detail (Thomassen and de Boer, 2005). Capper et al. (2008) report that use of rbST corresponds to 6.8% reduction in manure mass per unit of milk produced and a 7.3% reduction in methane output per unit of milk. In their analyses, industry-wide use of rbST reduced arable land requirements for grain production, soil erosion, nutrient excretions, and the global warming potential of the equivalent of 400,000 passenger cars.

Climate change has effects on water availability. Bates et al. (2008) propose that land areas classified as 'dry' have doubled since 1970 and will continue to increase in some areas of the world while rising oceans will make other areas less able to support food production due to saltwater. Projections suggest that water stored in glaciers and snow melt will decline, reducing supplies in regions where more than one-sixth of the world's population currently live (Bates et al., 2008). Even regions of the U.S. typically not considered dry, such as Georgia and Florida are recognizing that water is the world's fastest diminishing resource (FAO, 1995). Population growth, industrialization, and increased standards of living all contribute to an increasing demand on a finite supply of freshwater. "Water use has been growing at more than twice the rate of population increase in the last century, and, although there is no global water scarcity as such, an increasing number of regions are chronically short of water. By 2025, 1 800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under stress conditions" (FAO, 1005). The World Bank (1993) estimates that 90% of the world's water demand comes from agriculture and more than two-thirds (up to 90% by some estimates) of the water withdrawn from the earth's rivers, lakes and aquifers is used for irrigation. And some already question the value returned: "agriculture is not only the world's largest water user in terms of volume, it is also a relatively low-value, low-efficiency and highly subsidized water user" (FAO, 1995). Irrigation is an important mechanism to meet food demands of a growing population; 80% of the additional food supplies required to feed the world will depend on irrigation (Bates et al., 2008). However, FAO (1990) estimates that 60% of the water diverted or pumped for irrigation is wasted and irrigation performance indicators are falling short of expectations for yield increases, area irrigated and technical efficiency in water use. When supplies become limited, animal agriculture could very well be caught in the middle with consumers questioning agricultural use of water supplies relative to the services provided.

CONFLICTION OBJECTIVES

One of the greatest challenges in meeting environmental objectives is that the breadth of the regulations are increasing beyond what has been customary water quality and, to a more limited extent, air quality regulations. But regulations tend to still be approached from a single- issue mindset. As one issue is addressed, it may be at the expense of another; thereby producing unintended consequences (Siegford et al., 2008). Likewise, research often is conducted considering only a limited number of outcomes, without addressing or even identifying potential unintended consequences. Work by Wu-Haan et al. (2007) illustrates this point. While ammonia emissions from birds fed a diet containing gypsum were reduced by almost 40%, hydrogen sulfide emissions increased 3-fold. Ogino et al. (2008) conducted a LCA of Japanese dairy systems, comparing a rice silage-based system to a conventional (corn-based system) and concluded that while the difference was small, the dairy farming system using rice silage had smaller environmental impacts for acidification, eutrophication, and energy consumption, but a larger global warming potential compared with conventional farming. Including factors outside of the farm boundary resulted in an overall 1.1% lower environmental impact of the rice silage system.

Steinfeld et al. (2006) report that dairy cattle in grazing systems contribute one-third of enteric methane; two thirds of dairy cattle are housed in mixed systems which are estimated to contribute two thirds of enteric methane production. This suggests that moving a greater portion of the dairy industry to grass-based production systems would not change enteric methane output. Cederberg and Mattsson (2000) report little difference between pasture-based (organic) and conventional production systems, though statistics are not provided. Their assessment includes GHG production that results from fertilizer production and use in the conventional system and a higher methane output in the conventional system than reported by others (IPCC, 2007). Pasture-raised poultry production may reduce the concentration of excreta in one location as a result of reduced bird numbers per unit area, but gross nitrous oxide emissions can be considerable in grass systems (Petersen et al., 2004). In order to mitigate in dairy systems, overgrazing (Xu et al., 2008) may be recommended. Xu et al. (2008) found that long-term over-grazing suppressed denitrification and N2O production, observing a general trend that cumulative denitrification and N2O production decreased as grazing intensity increased. Increasing concentrate intake in grazing operations may reduce total GHG emissions by decreasing methane output (Lovett et al., 2006) while maintaining the appeal of a pastoral system. A LCA conducted on dairy farms in the Netherlands found that conventional farms had greater energy use and eutrophication potential per kg milk when compared to organic dairy farms (Thomassen et al., 2007). However, the organic farms, where animals maximized time outdoors during the grazing season, resulted in higher on-farm acidification and global warming potential per kg milk in addition to greater land use per kg milk (Thomassen et al., 2007). Cederberg and Mattsson (2000) compared conventional and organic dairy farming in Sweden using a LCA and report lower energy use (35%) and pesticide use (90%, attributable largely to pesticide use in soybean production for the conventional farm) in the organic system, per unit of product. However, land use in the conventional system was 56% of that in the organic system, per unit of product. Nutrient surplus per unit land area was greater in the conventional system; however N emissions in the form of ammonia, nitrate and nitrous oxide were smaller in the conventional system. The LCA is a useful tool to illustrate the tradeoffs that occur with every decision.

As retailers and consumers continue to push livestock and poultry production to change common production systems, we need to recognize and address our current limited understanding about the environmental costs of ethical animal production (Siegford et al., 2008). Often consumers may inherently associate livestock-intensive systems with environmental degradation while considering non-confined systems, such as those often promoted as animal-friendly, better for the environment. While efforts to improve animal well-being are well-intended, the consequences of mandated production practices may not be thoroughly thought through nor studied. Data are limited documenting the environmental impact of production systems designed to improve animal well-being. Thorne et al. (2009) looked at air emissions from conventional swine housing and hoop housing. Hoop houses are deep-bedded systems without stalls or crates and perceived by many to be more animal friendly. Thorne et al. (2009) found that while particulates, hydrogen sulfide and odor concentrations were less in the hoop houses, endotoxin and total microbes were greater. Endotoxin is a well-known contributor to respiratory ailments, more so than specific gases. Botheras et al. (2006) observed similar findings following a comparison of caged and cage-free hen housing. While data are limited that addresses animal-friendly dairy production, if ‘animal-friendly’ means grass-based systems, there is evidence that tradeoffs will include more land use per kg milk and greater global warming potential if milk output remains the same.

CONCLUSIONS

The challenges facing the dairy industry are vast and while not all of the current and pending challenges have an environmental component, it is often difficult to distinguish where environmental issues start and stop. Arguments made critics of the dairy industry often incorporate the environmental impact of livestock production even in discussions regarding animal care. As society proceeds to adopt greater regulation of the dairy industry in order to achieve less impact on the environment a system-wide approach is needed to evaluate policy implications in order to avoid unintended and undesirable consequences.

REFERENCES

Bates, B. C., Z. W. Kundzewicz, S. Wu and J. P. Palutikof, Eds. 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Botheras, N., P. Hemsworth, G. Coleman, and J. Barnett. 2006. Animal welfare as related to egg production systems: cage and non-cage/alternative systems (barns, aviaries, free-range). Ohio State University Extension Fact Sheet. http://ohioline.osu.edu/as-fact/0016.html

Bunton, B., P. O'Shaughnessy, S. Fitzsimmons, J. Gering, S. Hoff, M. Lyngbye, P. S. Thorne, J. Wasson, and M. Werner. 2007. Monitoring and modeling of emissions from concentrated animal feeding operations: overview of methods. Environ. Health Persp. 115(2):303-307.

Burkholder, J. M., M. A. Mallin, H. B. Glasgow, L. M. Larsen, M. R. McIver, G. C. Shank, N. Deamer-Melia, D. S. Briley, J. Springer, B. W. Touchette, and E. K. Hannon. 1997. Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. J Environ Qual 26:1451–1466.

Burkholder, J., R. Libra, P. Weyer, S. Heathcote, D. Kolpin, P. S. Thorne, and M. Wichman. 2007. Impacts of waste from concentrated animal feeding operations on water quality. Environ. Health Persp. 115(2):308-312.

Capper, J. L., E. Castañeda-Gutiérrez, R. A. Cady, and D. E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. PNAS 105:9668-9673.

Cederberg, C. and B. Mattsson. 2000. Life cycle assessment of milk production – a comparison of conventional and organic farming. J. Cleaner Prod. 8:49-60.

Colborn, T., F. S. vom Saal, and A. M. Soto. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. Environmental Health Perspectives 101:378-384.

Dyer, A. R., D. R. Raman, M. D. Mullen, R. T. Burns, L. B. Moody, A. C. Layton, and G. S. Sayler 2001. Determination of 17b-estradiol concentrations in runoff from plots receiving dairy manure. Paper number 012107, 2001 ASAE Annual Meeting, Sacramento, CA. ASABE, St. Joseph, MI.

Elferink, E. V. and S. Nonhebel. 2007. Variation in land requirements for meat production. Cleaner Production 15:1778-1786.

FAO. 1990. An international action program on water and sustainable agricultural development (IAP-WASAD). FAO, Rome.

FAO. 1995. Water sector policy review and strategy formulation: a general framework. FAO Land and Water Bulletin 3. FAO, Rome.

Fisher, D. J., K. W. Staver, L. T. Yonkers, M. A. Ottinger and S. Pollack. 2005. Poultry litter-associated contaminants: Environmental fate and effects on fish. Grant final report written for the Maryland Center for Agro-Ecology, Inc. P.O. Box 169, Queenstown, MD, (agroecology.widgetworks.com).

Gilchrist, M. J., C. Greko, D. B. Wallinga, G. W. Beran, D. G. Riley, and P. S. Thorne. 2007. The potential role of concentrated animal feeding operations in infectious disease epidemics and antibiotic resistance. Environ. Health Persp. 115(2):313-316.

Haack, S.K. and J. W. Duris. 2008, Chemical and microbiological water quality of subsurface agricultural drains during a field trial of liquid dairy manure effluent application rate and varying tillage practices, Upper Tiffin Watershed, southeastern Michigan: U.S. Geological Survey Open-File Report 2008–1189, 38 p. Date Posted: July 30, 2008: [http://pubs.water.usgs.gov/ofr20081189/]

Heederik, D., S. Torben, P. S. Thorne, J. N. Kline, R. Avery, J. H. Bønløkke, E. A. Chrischilles, J. A. Dosman, C. Duchaine, S. R. Kirkhorn, K. Kulhankova, and J. A. Merchant. 2007. Health effects of airborne exposures from concentrated animal feeding operations. Environ. Health Persp. 115(2):298-302.

Herman, J. S. and A. L. Mills. 2003. Biological and hydrogeological interactions affect the persistence of 17B-estradiol in an agricultural watershed. Geobiology. 1:141-151.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Lovett, D. K., L. Shalloo, B. Horan, P. Dillon, and F. P. O'Mara. 2006. Effect of Holstein–Friesian strain and feeding system on greenhouse gas emissions from pastoral dairy production systems. International Congress Series. 1293:335-338.

Moroto-Valer, M. M., C. Song, and Y. Soong. 2002. Environmental challenges and greenhouse gas control for fossil fuel utilization in the 21st century. Kluwer Academic/Plenum Publishers, New York.

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

Nichols, D. J., T.C. Daniel, P.A. Jr. Moore, D. R. Edwards, and D. H. Pote. 1997. Runoff of estrogen hormone 17beta-estradiol from poultry litter applied to pasture. J. Envir. Qual. 26:1002-1006.

Ogino, A., M. Ishida, T. Ishikawa, A. Ikegichi, M. Waki, H. Yokoyama, Y. Tanaka, and H. Hirooka. 2008. Environmental impacts of a Japanese dairy farming system using whole-crop rice silage as evaluated by life cycle assessment. Anim. Sci. J. 79(6):727-736.

Petersen, S.O., S. Stamatiadis, and C. Christofides. 2004. Short-term nitrous oxide emissions from pasture soil as influenced by urea level and soil nitrate. Plant Soil. 267:117-127.

Powers, W. and C. R. Angel. 2008. A review of the capacity for nutritional strategies to address environmental challenges in poultry production. Poult Sci. 87:1929-1938.

Scott, T. M., S. Parveen, K. M. Portier, J. B. Rose, M. L. Tamplin, S. R. Farrah, A. Koo, and J. Lukasik. 2003. Geographical variation in ribotype profiles of Escherichia coli isolates from humans, swine, poultry, beef, and dairy cattle in Florida. Appl. Environ. Micro. 69:1089-1092.

Siegford, J. M., W. Powers, H. G. Grimes-Casey. 2008. Environmental aspects of ethical animal production. Poult. Sci. 87:380-386.

Sneeringer, S. 2009. Does animal feeding operation pollution hurt public health? A national longitudinal study of health externalities identified by geographic shifts in livestock production. Amer. J. Agric. Econ. 91(1):124-137.

Spiehs, M. and S. Goyal. 2007. Best management practices for pathogen control in manure management systems. University of Minnesota Extension Publication M1211.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations, Rome, Italy.

Thomassen, M. A., and I. J. M. de Boer. 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agric. Ecosystems Environ.111(1-4):185-199.

Thomassen, M.A., K. J. van Calker, M. C. J. Smits, G. L. Iepema, and I. J. M. de Boer, I.J.M.. 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. Agric. Systems. 96(1-3):95-107.

Thorne, P. S., Ansley, A. C. and Spencer Perry, S. 2009. Concentrations of bioaerosols, odors, and hydrogen sulfide inside and downwind from two types of swine livestock operations. J Occ. Environ Hygiene 6:211-220.

Tsur, Y. and A. Zemel. 2007. Bio-economic resource management under threats of environmental catastrophes. Ecol. Res. 22:431-438.

US EPA. 2004. U.S. Emissions inventory 2004: inventory of U.S. greenhouse emissions and sinks: 1990-2002 [April 2004]. US Environmental Protection Agency, Washington, D.C.

Ward, G. M., K. G. Doxtader, W. C. Miller, and D. E. Johnson. 1993. Effects of intensification of agricultural practices on emission of greenhouse gases. Chemosphere 26:87-93.

World Bank. 1993. Water Resources Management: A Policy Paper. The World Bank, Washington DC.

Wu-Haan, W., W. J. Powers, C. R. Angel, C. E. Hale, III, and T. J. Applegate. 2007. Effect of an acidifying diet combined with zeolite and slight protein reduction on air emissions from laying hens of different ages. Poult. Sci. 86:182-190.

Xu, Y., S. Wan, W. Cheng, and L. Li. 2008. Impacts of grazing intensity on denitrification and NO production in a semi-arid grassland ecosystem. Biogeochemistry. 88(2):103-115.