Review

ghg GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Mitigation of greenhouse gas emissions from animal production

Zifei Liu and **Yang Liu**, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, KS, USA

Abstract: The accurate quantification of the carbon footprints of animal products and the related development of greenhouse gas (GHG) mitigation strategies are of interest to consumers, the general public, and the academic community. The objective of this review was to summarize recent advances in GHG emission quantification, life-cycle assessment applications, and mitigation technologies for animal production in the USA, to assist the development of system-based solutions for mitigation of GHG emissions from animal production. The GHG emissions from animal production mainly come from feed production, enteric fermentation, and manure management. Opportunities to mitigate emissions from feed production largely rely on continuous improvements in animal and feed production efficiency. This is in general agreement with the economic interest of the industry. To mitigate emissions from manure, many technologies can be chosen, depending on the given economic and regulatory environments. It is possible to minimize GHG emissions from manure through manure energy recovery when this is economically feasible. For enteric emissions, there are limited opportunities to reduce GHG emissions through dietary manipulation, feed management, or feed supplementations. Improving environmental stewardship of consumers and reducing food waste will reduce animal protein demand and are important bottom-line strategies to mitigate GHG from animal production systems. © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: livestock; animal protein; life-cycle assessment; causal-loop diagram; systems thinking; sustainability

Introduction

Concerns about the impact of animal production on climate have produced significant debate among producers, consumers, and scientists. The greenhouse gases (GHG) emitted from animal production mainly include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The CO_2 emitted by an animal is considered to be biogenic in nature and therefore is often excluded or deferred in accounting for total GHG emissions.[1] The US Environmental Protection Agency (EPA) estimated that enteric fermentation and manure management in US livestock production systems are responsible for 2.2% and 1.1% of the total human-induced GHG emissions in the USA, respectively.[2] The GHG from enteric fermentation is mainly CH_4, whereas the GHGs from manure management include both CH_4 and N_2O. For CH_4 emissions from enteric fermentation in ruminants, beef and dairy cattle remain the major

Correspondence to: Zifei Liu, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, KS 66506, USA.
E-mail: Zifeiliu@ksu.edu

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contributors, accounting for 71% and 25%, respectively; for GHG emissions from manure management, dairy cattle are considered the largest contributor (46.7%), followed by swine (31.2%), beef cattle (15%), and poultry (6.1%).[2]

The carbon footprint (CF) measures the impact of a product or activity on the environment. The CF for animal production resulting from life-cycle assessment (LCA) includes not only direct GHG emissions on the farm but also indirect GHG emissions for the whole life cycle of animal production, including emissions associated with feed production, transportation, product processing, packaging, distribution, retail, and consumer waste. The Food and Agriculture Organization of the United Nations (FAO) attempted a rough LCA and announced that 18% of human-induced GHG emissions come from livestock.[3] The FAO estimation was discredited by other researchers based on the argument that the value was based on inappropriate or inaccurate scaling of predictions, and an equally holistic approach was not used for other sectors such as transportation.[4] The estimation of the real contribution of animal production to GHG emissions remains highly uncertain.

Accurate quantification of CF of animal products and the development of GHG mitigation strategies are therefore of interest for the academic community as well as the consumers. A breakdown of CF by life-cycle stage and comparing CFs by species, and the use of systems thinking, may provide critical information about decision-making processes for the mitigation of GHG emissions from animal production. The objective of this review was to summarize recent advances in GHG emission quantifications, LCA applications, and mitigation technologies for animal production in the USA, to assist in the development of system-based solutions for mitigation of GHG emissions from animal production.

How much is emitted?

Emission from enteric fermentation

Enteric CH_4 emissions are produced by ruminants as a result of the microbial breakdown of carbohydrates in the rumen. Typical rumen gases include 66% CO_2 and 27% CH_4.[5] The quantity of CH_4 produced depends on the type of digestive tract, age, and weight of the animal, and the quality and quantity of the feed consumed. As it represents an unproductive loss of dietary energy, one of the predominant enteric CH_4 emission estimation procedures is driven by first estimating daily gross energy intake (GEI) by individual animals and then multiplying it by an estimate of the methane conversion factor Y_m.[6]

$$EF_e = GEI \cdot Y_m / 55.65 \tag{1}$$

In which, EF_e is enteric CH_4 emission factor, kg CH_4/head/year; GEI is gross energy intake, MJ/head/year; Y_m is enteric CH_4 conversion factor, expressed as percentage of gross energy in feed converted to CH_4; the factor 55.65 MJ/kg CH_4 is the energy content of CH_4. Equation (1) is used to estimate enteric CH_4 emissions in the Intergovernmental Panel on Climate Change (IPCC) Tier 2 approach,[6] which has been recognized to have the best prediction accuracy for a collection of individual data when comparing with eight other enteric CH_4 prediction equations used in whole-farm GHG models.[7]

Based on Eqn (1), the higher the feed intake, the higher the CH_4 emission; although emission is also affected by the composition of the diet. Using highly digestible feed can result in lower feed intake and thus lower emissions. Gross energy intake can be converted to dry matter intake (DMI) by dividing it with the energy density of the feed, typically 18.45 MJ/kg of dry matter in cattle feed.[8] A typical Y_m value of 6.5% corresponds to 21.4 g CH_4 kg^{-1} DMI. Typical daily DMI is 2 to 3% of the body weight of the cattle. For high-producing dairy cattle, the daily DMI may exceed 4% of body weight.[6] The forage-to-concentrate ratio of the diet profoundly affects the energy intake of animals.[9] Default values of Y_m in IPCC[6] are 3% for feedlot cattle that are fed diets contains 90% or more concentrates, and 6.5% for dairy cattle that are fed more forage and less concentrates, and for other cattle that are primarily fed low quality crop residues and byproducts. Literature values for Y_m depends on several interacting feed and animal factors, and range from 2% to 11% of GEI. Liu *et al.*[10] conducted a meta-analysis on Y_m from different cattle and feed combinations and found that lower forage-to-concentrate ratios were associated with higher digestibility and lower Y_m. For grazing cattle, feed digestibility is affected by stage of maturity, forage species, and environmental conditions.[11,12] Increased forage digestibility is expected to decrease Y_m.[13] Higher Y_m for grazing cattle as compared with housed cattle was observed as grazing cattle generally had lower feed digestibility than most housed cattle.[10]

Increasing feed intake may also decrease Y_m.[14–17] However, due to the complex interaction, a clear relationship among feed intake, feed digestibility, and Y_m has not been established. The relationship is clearer when the CH_4 conversion factor is expressed on a digestible energy basis. It has been demonstrated that increasing feed intake and feed digestibility can reduce CH_4 conversion factor on a digestible energy basis, and thus have the potential to decrease the CH_4 emission per unit of digestible feed intake or animal product.[10]

Emission from manure management

Manure management CH_4 emissions are produced from decomposition of manure under anaerobic conditions during storage and treatment. The quantity of CH_4 produced depends on the amount of manure and the portion of the manure that decomposes anaerobically. The manure management CH_4 emission factor can be calculated based on the quality and quantity of the excreted volatile solid (VS) and the manure management CH_4 conversion factor (MCF), which depends on how manure is managed.[6]

$$EF_m = VS \cdot 365 \cdot B_o \cdot MCF \cdot 0.67 \qquad (2)$$

In which EF_m is the manure management CH_4 emission factor, kg CH_4/head/year; VS is the daily excreted volatile solid, kg/head/day; B_0 is the maximum methane producing capacity of manure, m^3/kg of VS; MCF is the manure management CH_4 conversion factor, the percentage of VS actually converted to CH_4 compared to B_0; the factor 0.67 kg/m^3 converts m^3 CH_4 to kg CH_4. Manure VS depends on feed intake and digestibility; typical VS in the USA is 5.4 and 2.4 kg/head/day for dairy cow and beef cattle respectively. B_0 varies by species and diet; a typical B_0 in the USA is 0.24 and 0.19 m^3/kg of VS for dairy cow and beef cattle respectively.[6] The MCF depends on the manure management system, temperature, and retention time of the storage unit. The MCF for liquid manure systems (lagoons, tanks) is much larger than that for dry manure systems (stacks, piles) as liquid systems tend to have more anaerobic conditions and thus produce more CH_4. The MCF is 50 to 80% for anaerobic lagoons and 2 to 5% for dry manure, solid storage.[6] Higher MCFs are also associated with higher temperatures and longer retention times in the storage unit.

Most of the nitrogen (N) loss from manure is in the form of ammonia (NH_3) but a small part of N loss is in the form of N_2O and mono-nitrogen oxides (NO_x). Direct N_2O emissions occur via combined nitrification and denitrification of N contained in manure. Oxidized forms of N are first formed through nitrification with a sufficient supply of oxygen, and then transformed to N_2O through denitrification in an anaerobic environment. For uncovered anaerobic lagoon or liquid/slurry, direct N_2O emissions are negligible, while N loss as direct N_2O is estimated to be 2%, 0.5%, and 0.5% of manure N for dry lots (including feedlots), solid storage, and liquid/slurry with crust cover, respectively.[18] Indirect N_2O emissions result from other forms of N loss from manure. About 1% of N loss in the forms of NH_3 and NO_x can be accounted as indirect N_2O emissions.

Agricultural soils receiving animal manure are also an important source of N_2O emissions. Literature values for N_2O emissions[19–21] after manure land application generally agreed with the IPCC default N_2O emission factor for managed soil (1%),[6] while the C to N ratio of the soil amendments, precipitation, soil texture and drainage are main sources of variations.[19]

Average emission factors

The average CH_4 and N_2O emission factors for animal production in the USA were estimated based on data from EPA[2] and IPCC,[6] and were expressed in CO_2-equivalent units (CO_2e) by multiplying the amount of CH_4 and N_2O by their respective global warming potential (GWP) for better comparison (Table 1). The 100-year GWP of CH_4 and N_2O is 25 and 298 times that of CO_2, respectively.[22] Average enteric emission factors were based on average annual conditions, on net energy estimates, and feed characteristics of various animal types, and average manure management emission factors were decided by the manure distribution among different waste management systems. For beef cattle, horses, sheep, and goats, enteric emissions account for the majority of their GHG emissions. Dairy cattle have more enteric emissions due to more GEI and lower digestibility compared with feedlot animals. Nevertheless, for dairy cattle, GHG emissions from manure are equally important as enteric emissions due to the wide use of liquid manure systems. For swine and poultry, enteric emissions are minimum and GHG emissions from manure deserve the most attention.

The emission factors per gallon of milk produced from dairy cow enteric fermentation have declined in

Table 1. Average GHG emission factors for animal production.

	GHG emission factors (kg CO_2e/head/year)			
	Enteric fermentation[a]	Manure management[b]		
	CH_4	CH_4	N_2O	Total
Dairy cattle	2457	1953	434	4844
Beef cattle	1575	34	93	1702
Horses	378	57	35	470
Sheep	168	12	64	244
Goats	105	7	10	122
Swine	32	302	30	364
Poultry	–	1.3	0.8	2.1

[a]Dairy and beef cattle emission factors were calculated based on net energy estimates, feed characteristics and the CH_4 conversion factor for 2012 from EPA;[2] others are default emission factors from IPCC.[6]
[b]Calculated based on total US emissions and livestock population for 2012 from EPA.[2]

the last two decades due to improved productivity, although the emission factors per cow had a tendency to increase. From 1990 to 2012, dairy emissions increased only 6% while milk production increased 36%.[23] However, due to the increasing use of liquid manure systems, the national CH_4 emissions from manure management in dairy industries increased from 1990 to 2012 although the population of dairy cattle was relatively stable.[2]

Carbon footprint (CF) from LCA studies

Beef cattle production

Most existing beef LCA studies followed a 'cradle to farm-gate' approach and they reported CFs of feedlot finished beef production in the USA in the range of 14 to 27 CO_2e per kg carcass weight.[24–30] The variations in CF among studies were mainly due to differences in finishing weight and time spent in the feedlot, types and amount of feed, manure handling practices, region variability, and methods used. These production systems include either three phases (cow-calf to stocker to feedlot) or two phases (cow-calf to feedlot). Existing studies agreed that the cow-calf phase contributed 67% to 72% of the CF for the overall beef production system.[25,28–30] The cow-calf phase requires the maintenance of the large number of breeding animals to produce the calves.[25] Breeding animals may live on the land for a full year to produce a calf, and was responsible for the majority of the CF. Around 66% of total feed consumption to produce beef was allocated to the cow–calf phase.[30] In a Canadian study, it was estimated that about 84% of enteric CH_4 was from the cow–calf phase, mostly from mature cows.[31] The cow-calf phase therefore deserves significant attention when developing GHG mitigation strategies.

Enteric CH_4 emissions were consistently the largest contributors to the total CF, while both manure management and feed production also make substantial contributions. The CF from feed production contributed 11% to 33% to the total CF.[26,27,29] In the feedlot phase, feed production was the main contributor, and may account for 60% to 79% of the CF in this phase.[29] Improving feed utilization could be an important strategy to reduce CF for feedlot operations.

The reported CF of grass-fed beef cattle in the USA was around 37% higher than feedlot finished beef cattle,[26,27,32] which was partly due to longer finishing time, lower finishing weight, and higher forage diet.[27] A 38% reduction in CF through a shift from extensive pasture production of cattle to intensive feedlot production was reported in a Canadian study.[33] For grass-fed beef cattle, N_2O emission from grazed pastures was a major contributor to CF, second to enteric CH_4 emission.[32] Better management practices in grazing systems could reduce enteric CH_4 emissions by as much as 22%.[34] For grazing systems with positive soil organic carbon sequestration potential, substantial reduction in CF may be achieved.[26]

A simulation of changes in beef production practices and their effect on CF estimated that the CF of beef cattle decreased 6% from 1970 to 2005, primarily due to improvement in crop productivity; however, the CF remained stable from 2005 to 2011, indicating that the negative effect of feeding of distillers grain on CF had offset the small improvement obtained through genetic improvement of corn yield.[28]

Dairy production

A national LCA study based on data from 2007–2008 in the USA reported that the CF of milk, from farm to table, averaged 8.0 kg CO_2e per gallon (2.0 kg CO_2e per kg) of milk consumed, and ranged from 6.9 to 9.4 kg CO_2e per gallon of milk consumed due to regional variability.[35] The contribution to overall CF by supply chain was 20.3% for feed production, 51.5% for milk production, 5.7% for processing, 3.5% for packaging, 7.7% for transportation/distribution, 6.5% for retail, and 4.9% for consumers.[35] The study included retail and consumption losses of 12% and 20%.

Increasing milk yield per cow is a common strategy to reduce CF from milk production. The dairy system may provide both milk and byproduct beef. When allocation of CF to the byproduct beef from dairy cows is considered, increasing milk yield does not necessarily reduce the CF per kg milk.[36] The milk and beef systems need to be considered in an integrated approach to identify optimum mitigation strategies.

Swine production

A national LCA study estimated the CF of US swine production to be 9.9 kg CO_2e per kg of boneless pork consumption, and the contribution to the overall CF by supply chain was 62.1% for live animal production (9.6% for sow barn and 52.5% for nurse to finish), 5.6% for processing, 1.3% for packaging, 7.5 for retail, and 23.5% for consumers (refrigeration, cooking, and CH_4 from food waste in landfill).[37] Feed production and manure management were two major contributors, accounting for 42% and 39%, respectively, for the CF in the live animal production phase. As a comparison, 3.9 to10 kg CO_2e per kg of pork product were reported in several European studies.[38]

Poultry production

The CF of US broiler production has been estimated to be 2.5 kg CO_2e per kg of edible chicken product.[39] The US poultry supply chain typically depends on concentrated feed production far from the poultry farm itself, and the upstream feed production, processing, and transportation account for 82% of the total CF of poultry production.[39] As a comparison, 3.7 to 6.9 kg CO_2e per kg of edible chicken product were reported in several European studies.[38]

Summary

The reported CFs of various activities are presented in Table 2. It should be noted that these data are from different LCA approaches and caution should be applied when comparing them. Nevertheless, it is understandable that pork and chicken have less CF than beef due to the facts that they produce less CH_4 and require less feed and less breeding stock per kg of meat produced.[38]

Table 2. Comparison of carbon footprints (CF) of various activities.

Activities	CF (kg CO_2e)	Reference
Consuming 1 kg of beef	18.8	Roop *et al*., 2014[29]
Consuming 1 kg of boneless pork	9.9	Thoma *et al*., 2011[37]
Consuming 1 gallon of milk	8.0	Thoma *et al*., 2013[35]
Consuming 1 kg of chicken	2.5	Prlletier, 2008[39]
Driving a car and consuming 1 gallon of gasoline	9	Walser, 2013[40]
Consuming 1 kWh electricity that generated from coal	0.9	WNA, 2011[41]

Strategies and technologies for GHG mitigation

Animal production is a complex and dynamic system. Systems thinking is needed to understand the dynamic complexity of the system and to identify the leverage points for sustainable change. Figure 1 is a causal-loop diagram (CLD) that provides a visual representation of dynamic interrelationships in the animal production system and its effects of on GHG emissions. In Figure 1, the letter 'B' represents a balancing feedback loop; arrows represent the causal direction of influence between variables; '+' represents two variables that change in the same direction; '−' represents two variables that change in the opposite direction.

Animal production is increasing with the ever-increasing human population. Land use for feed and feed production is generally in balance with animal production through dynamic changes in feed price, and feed production is ultimately limited by the availability of feed land. Increasing feed prices has resulted in continuous improvement in feed production efficiency and animal production efficiency. In Fig. 1, it is clear that improvements in production efficiency are the major opportunities to affect positively the balance among feed land use, feed production, and animal production. Improving feed production efficiency can reduce feed land use per unit of feed production. Improving animal production efficiency can reduce feed required per unit of animal production. Improving productivity therefore does not contradict

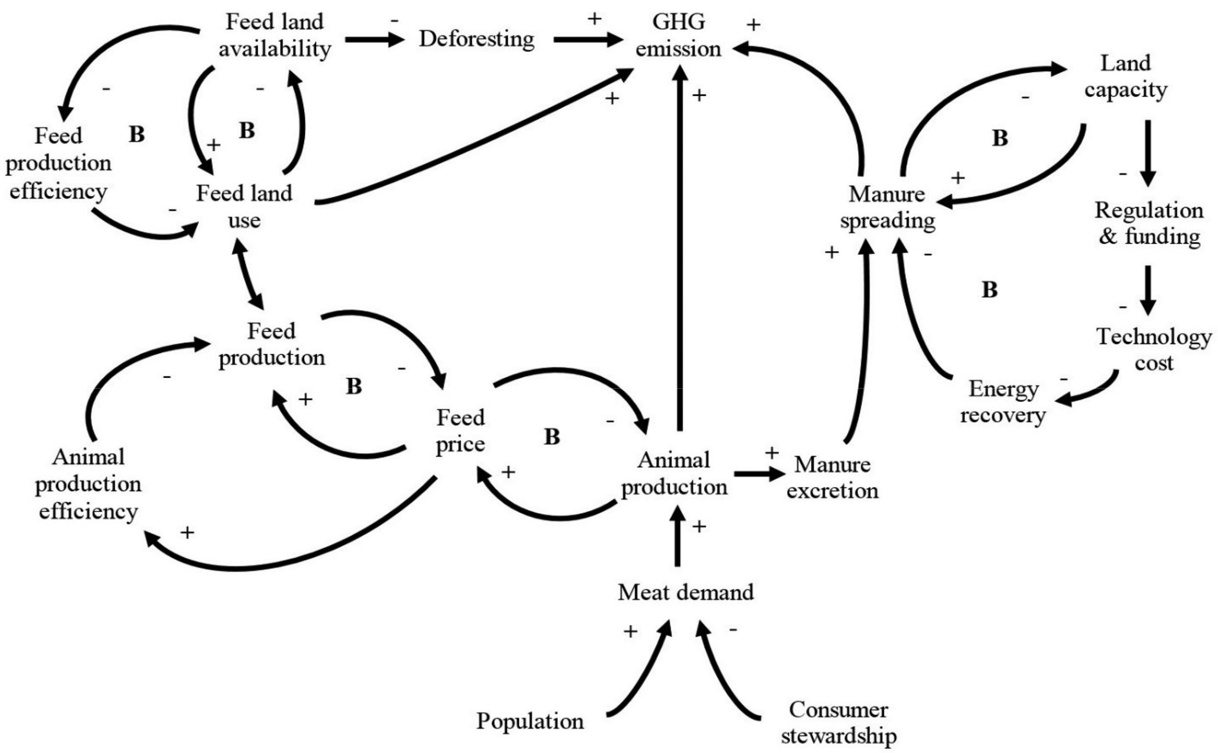

Figure 1. Causal loop diagram on effects of animal production on GHG emissions (inspired by the USDA multi-state project S1032).[42]

but instead is a major contributor towards the mitigation of GHG emissions from feed production. For GHG emissions from manure, solutions include prevention of manure from entering an anaerobic state, while the ultimate solution is manure energy recovery through the capture and use of biogas. However, the adoption of manure energy recovery is limited by barriers in technology cost, which may be affected by regulatory compliance requirements and economics of manure transportation/application, and will ultimately be decided by land capacity for accepting manure. The emission factors (emissions per head) for GHG from enteric fermentation are relatively stable. Improving consumer stewardship, reducing food waste and thus reducing animal protein demand are always a practical and bottom-line strategy for mitigating GHG from enteric emissions.

Mitigating enteric emissions

Other than reducing animal protein demand, many strategies have been proposed to mitigate GHG from enteric emissions by reducing emissions per kg of meat produced. Most of the mitigation strategies were based on dietary manipulation, feed management or feed supplements, and they are summarized in Table 3.

As previously mentioned, increasing feed intake and feed digestibility can both reduce CH_4 conversion factor on a digestible energy basis. This can be achieved by increasing the proportion of concentrate in feed.[10] Improved forage quality in forage-based diets can also result in increased feed intake and feed digestibility. Concentrates or high-quality forage generally provide more digestible nutrients, and thus increase animal productivity,[67,68] resulting in lower GHG emissions per animal product. Feed processing can also be an effective mitigation practice through its effect on feed digestibility. Dietary supplementation with fat is a potential mitigation strategy, but the long-term effects have not been well established and there are challenges to identify fat sources in a cost-effective manner. High oil byproduct feeds, such as distiller's grains, may be an economically feasible alternative to fat supplementation but their higher fiber content needs to be evaluated to avoid counteracting the GHG mitigating effect, depending on diet composition.[69] Supplementation with tannins or nitrates has also been reported to be effective. Other attempts in modification of rumen function have had very little success for sustained reduction in enteric CH_4.[70]

Table 3. Strategies and technologies for mitigating enteric GHG emissions.

Strategies and technologies		References	Notes
Increasing proportion of concentrate in feed		Lovett *et al*., 2003;[43] Sauvant & Giger-Reverdin, 2009;[17] McGeough *et al*., 2010;[44] Aguerre *et al*., 2011;[45] Liu *et al*., 2017[10]	Caution must be taken to prevent negative effects on fiber digestibility and potential loss of animal[46]
Improving forage quality		Archimède *et al*., 2011;[47] Sun *et al*., 2012;[48] Doreau *et al*., 2014;[49] Liu *et al*., 2017[10]	Corn and legume silages have an advantage over grass silage, and effective preservation will improve silage quality[13]
Feed processing		Hales *et al*., 2012[50]	Additional energy cost may counteract GHG mitigating effect
Feed supplements	Dietary fats	Giger-Reverdin *et al*., 2003;[51] Eugène *et al*., 2008;[52] Beauchemin *et al*., 2009;[53] Grainger *et al*., 2010;[54] Moate *et al*., 2011;[55] Grainger & Beauchemin, 2011;[56] Patra, 2013[57]	Caution must be taken to prevent potential negative effects on animal productivity[58,59]
	Tannins	Sliwinski *et al*., 2002;[60] Jayanegara *et al*., 2012;[61] Goel and Makkar, 2012[62]	May reduce nutrient absorption when dietary crude protein is inadequate[63]
	Nitrates	Leng, 2008;[64] Van Zijderveld *et al*., 2011;[65] Hulshof *et al*., 2012[66]	Caution must be taken for potential toxicity and gradual adaptation of the animal[64]

Based on the LCA results, the majority of enteric CH_4 was from breeding stock in the cow–calf phase. When considering mitigation of enteric GHG emissions, breeding stock should be given the first priority. The largest reductions are achieved when mitigation practices target breeding animals.[71] In addition to the strategies and technologies summarized in Table 3, genetic selection could be another potential strategy to improve feed efficiency and to mitigate enteric GHG emissions.[72] Liu *et al.*[10] demonstrated that breed of cattle may affect CH_4 emissions. Thai native, Brown Swiss, and Brahman cattle had higher Y_m than Holstein cattle; and Nellore cattle had lower Y_m than Holstein cattle.

Mitigating emissions from manure

Major strategies and technologies for mitigating the GHG emissions from manure are summarized in Table 4.

Optimizing the animal diet to improve N use efficiency and reduce excreted N is effective to reduce manure NH_3 and indirect N_2O emissions, although the effects on direct N_2O emissions were not consistent in the literature.[95–97] The choice of manure management systems has a significant effect on GHG emissions. Greenhouse gas emissions from anaerobic liquid manure systems (lagoons, tanks) are larger than from dry manure systems (stacks, piles). Manure treatment for dairy and swine operations deserve more attention due to the wide use of liquid manure systems. Composting and use of storage cover are two common practices that can be used to mitigate GHG emissions in addition to the benefit of odor control during manure storage. Reducing storage time,[98] reducing manure temperature,[99] and preventing anaerobic conditions[100] all help to minimize GHG emissions. Manure acidification may reduce CH_4 and NH_3 emissions,[101] but it might increase H_2S emissions as well as N_2O emissions following land application.[91] Biofilters can be effective to reduce CH_4 and NH_3 from mechanically ventilated animal housing; however, careful management is required to mitigate N_2O and the overall GHG emissions.[102,103] Optimization of the manure application method has been shown to control the amount of N available for nitrification and denitrification in soil, to promote the aerobic metabolic path and reduce CH_4 emission from land application.[104] Use of cover crops could also be an effective tool for GHG mitigation through improved soil quality, enhanced soil organic C sequestration, and reduced use of N fertilizers.[92,105,106]

Anaerobic digestion (AD) with combustion of the biogas produced is probably the most effective end-of-pipe method for mitigation of GHG emissions from manure. Compared to conventional manure-management practices, an AD system usually costs more to install and manage but it can also generate additional revenue. Whether an AD system is feasible for a livestock operation depends on type and scale of the operation, how the manure is handled, the

Table 4. Strategies and technologies for mitigating GHG emissions from manure.

Strategies and technologies		References	Notes
Reduce N excretion by reducing dietary protein		Külling *et al*., 2001;[73] Velthof *et al*., 2005[74]	Caution must be taken to prevent potential negative effects on animal performance[75]
Manure treatment	Composting	Thompson *et al*., 2004;[76] Brown *et al*., 2008;[77] Jiang *et al*., 2011;[78] Park *et al*., 2011[79]	Depending on composting intensity, NH_3 losses during manure composting can be significant[80]
	Storage cover	Guarino *et al*., 2006;[81] VanderZaag *et al*., 2008[82]	Semipermeable covers can reduce NH_3, CH_4, and odor emissions, but they could increase N_2O emissions[83]
	Anaerobic digestion with biogas recovery	Liu, 2015;[84] Roos *et al*., 2004;[85] Clemens *et al*., 2006;[86] Prapaspongsa *et al*. 2010[87]	Require high initial costs and careful maintenance, and therefore, may not be economically feasible for small operations[84]
Improved timing and techniques for manure application		Nyakatawa *et al*., 2011;[88] Powell *et al*. 2011;[89] Dell *et al*., 2011[90]	Wet soils tend to promote N_2O emissions and avoiding application before a rain can avoid spikes in emission. Subsurface injection reduce NH_3 and CH_4 emissions but can result in increased N_2O emissions[91]
Use cover crops and other soil conservation practices		Christopher and Lal, 2007;[92] Petersen *et al*., 2011;[93] Garland *et al*., 2011[94]	Cover crops can reduce N_2O production, but the results on overall GHG emissions were not consistent[91]

frequency of manure collection, the potential uses for the recovered biogas, and the local market for the end products. Smaller operations may make AD feasible through special design, such as including co-digestion of manure and other organic substrates such as food waste.[84]

Maurer *et al.*[107] provided a comprehensive review and performance data for technologies to mitigate air pollutants (including GHG) from animal housing and manure management, and the data indicated the tradeoffs associated with different mitigation strategies and the importance of a holistic approach for mitigating emissions of both GHG and other air pollutants.

Mitigating emissions from feed production

The GHG emissions from animal feed production contributed 11% to 33% to the CF of beef cattle,[26,27,29] 20.3% to CF of dairy cattle,[35] and 26% to CF of swine.[37] Avoiding feed waste and improving feed efficiency are obvious choices for the mitigation of GHG emissions from feed production. Continuous improvements in feed production efficiency may reduce feed land use per unit of feed production, and improvements in animal production efficiency may reduce feed required per unit of animal production. They both represent very good opportunities for mitigation GHG emissions from animal feed production.

Conclusion

Providing animal protein to the world's growing population with a smaller CF is a big challenge. The reduction of GHG emissions for animal production may be achieved by a combination of reducing emissions per head and reducing the population of animals. Animal production is a complex system, and systematic approaches should be considered when developing GHG mitigation strategies. The GHG emissions from animal production mainly come from feed production, enteric fermentation, and manure management. Opportunities to mitigate emissions from feed production largely rely on continuous improvements in feed and animal production efficiency. This is in general agreement with the economic interest of the food industries. Many technologies can be chosen to mitigate emissions from manure, depending on the economic and regulatory environments. It is possible to minimize GHG emissions from manure through manure energy recovery when economic feasibility is achieved. For enteric emissions, there are limited chances to reduce the methane conversion factor through dietary manipulation, feed management, or feed supplementation. Improving environmental stewardship of consumers, reducing food waste, and thus reducing animal protein demand and animal population are critical bottom-line strategies for mitigating GHG from animal production systems.

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Zifei Liu

Dr Zifei Liu is an assistant professor in the Department of Biological and Agricultural Engineering at Kansas State University. He hold a PhD in biological and agricultural engineering from North Carolina State University and an MS in environmental engineering from the University of Cincinnati. His work involves research and extension activities in environmental topics with a focus on agricultural air quality. The goal is to effectively inform and influence producers and consumers to move agricultural production toward practices that are environmentally sound and economically viable, and to assist Kansas in addressing critical air quality issues that impact the sustainability of local communities. Dr Liu has authored 27 peer-reviewed journal papers with an h-index of 10. He has been an associate editor for the Plant, Animal, and Facility Systems Division and the previous Structures and Environment Division of the American Society of Agricultural and Biological Engineers (ASABE) since 2013. He received an ASABE Outstanding Reviewer award in 2016.

Yang Liu

Yang Liu is a PhD student in the Department of Biological and Agricultural Engineering at Kansas State University. Her research interests in agricultural air quality are focused on vegetative environmental buffers, $PM_{2.5}$ source apportionment using receptor models, and life-cycle assessment of agricultural production. In the vegetative environmental buffer project, Yang participated in experimental design, and planned and established the vegetative buffer in different patterns by the ventilation of swine facility. She established a real-time gas-collecting system with a mobile lab that monitoring ammonia and hydrogen sulfate from six locations simultaneously. Reception air modeling experience was gained through $PM_{2.5}$ source apportionment analysis. She identified the source composition of ambient $PM_{2.5}$ in both rural and urban Kansas, investigated the source profile and estimated the secondary organic aerosol contributed by annual prescribed burning. Yang is currently working on a systematic review of the life-cycle assessment of beef production in the USA; the results will quantify the environmental impact of beef cattle production and provide a better understanding for sustainable agriculture.

