Meat and Muscle Biology™

Environmental Sustainability of Livestock Production

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Abstract: The environmental impact of livestock production has become an important and controversial global issue, primarily due to reported impacts on global warming. This concern applies to all meat animals, but especially beef cattle due to their emission of enteric methane. Livestock production contributes to global warming, but the importance of its contribution may be overstated. Its effect on climate is primarily through methane production, which does not have a long-term effect on the atmosphere. Global livestock numbers and emissions from their manure are increasing, so there is a short-term effect through increased rate of emission. Other effects of meat production may be of more concern for long-term sustainability. Through a full life cycle of meat, the dominant impact is loss and waste, which adversely effects all measures of sustainability. An important environmental concern is reactive nitrogen losses, among which ammonia emission from manure is of most concern. Global estimates suggest that 63% of all ammonia emissions come from agriculture, with 44% of the total from livestock manure. Ammonia emissions have adverse effects related to acidification of ecosystems, eutrophication of surface waters, and human toxicity through formation of small particulate matter in the air we breathe. Water consumption is another important concern. Global estimates suggest that agriculture uses about 70% of freshwater withdrawals, with 20% used for livestock feed production. Although livestock production is not a large energy consumer, fossil fuels are a limited resource, and conservation is important. Many technologies and strategies exist for mitigating environmental impacts of livestock production, but finding economical solutions is challenging. Mitigation must start with the reduction of consumer waste. Other livestock impacts are best reduced using intensive practices to produce animals in less time and with fewer resources. Diets that accurately meet animal nutrient needs are an important mitigation option for efficient and sustainable meat production.

Key words: cattle, pig, chicken, life cycle assessment, global warming potential, footprint
Meat and Muscle Biology 4(2): 11, 1–18 (2020) **doi:10.22175/mmb.11103**
Submitted 13 April 2020 Accepted 26 May 2020

This paper was accepted as a contribution to the 2020 International Congress of Meat Science and Technology and the AMSA Reciprocal Meat Conference.

Introduction

The global demand for livestock products is increasing (OECD/FAO, 2018). This is due to both increasing population and the need for high-quality protein in human diets, particularly in developing countries. As economies have developed, the purchase of animal products has increased (WHO, 2020). As the demand has increased, concern over environmental impacts of livestock production has also increased (Steinfeld et al., 2006). These environmental impacts vary widely depending upon climate and production practices used.

Most of the environmental concern for livestock products has focused on greenhouse gas (GHG) emissions. This began with the publication of the report "Livestock's long shadow," which concluded that livestock production contributed more GHG emissions globally then all of transportation (Steinfeld et al., 2006). There was a flaw in their comparison that was later corrected (Gerber et al., 2013); nevertheless, this brought much public attention to livestock agriculture, and this attention continues. Discussion on this topic has led to claims that livestock production is unsustainable. This implies that livestock agriculture does not have a role in meeting the future food needs of our world.

So what is sustainability? The general definition is something like "Meeting our present needs without compromising the ability of future generations to meet their needs" (Basiago, 1995). When we get more specific, there are probably as many definitions as there are people defining sustainability, and the definition tends to focus on the interests of the definer. If we want to make claims about sustainability, then there is the need to develop measures and to quantify those measures. This type of quantification becomes difficult. Sustainability is much more than GHG emissions and their effects on climate. Sustainability generally includes environmental, economic, and social issues (Basiago, 1995). Within the environmental category, a much broader view must include the use of limited resources and all emissions affecting our environment. Quantifying and integrating all of the important aspects of sustainability for a product or service is essentially impossible. At best, we can work with a few of the more important aspects to get an indication of sustainability.

The objective of this paper is to review current work related to quantifying the environmental sustainability of global livestock production, determine important concerns, and discuss strategies for mitigating those concerns. This paper focuses on environmental issues of sustainability. Economic and social issues are equally important, but they vary greatly across regions, cultures, and economies, making them more difficult for global quantification and assessment.

Assessment of Environmental Sustainability

Assessment of environmental sustainability must consider many factors, including use of limited resources and various emissions and losses to the environment. Importance of these various factors varies across regions. Fossil energy use and GHG emissions are important on a global scale, but issues such as water use and nutrient losses from production systems are more important at a local level or within specific regions (Rotz and Veith, 2013). Water consumption may be very important in dry regions but not so important in regions with abundant precipitation. Likewise, runoff of nutrients such as nitrogen and phosphorus may be very important in watersheds with high precipitation but not so important in dry climates. This diversity in importance adds complexity to the assessment of sustainability. A given practice considered sustainable in one region may not be in another.

To assess sustainability, we need to quantify and integrate the important factors to be considered. A common approach is use of emission factors. Using empirical data, a factor is developed to represent a specific emission or other impact from a given source. This approach has been widely applied to GHG emissions. The Intergovernmental Panel on Climate Change (IPCC, 2006) has outlined factors used to estimate GHG emissions from important sources in agricultural production, including those from livestock. They have a 3-tiered approach in which tier 1 is the simplest, using general factors such as emissions per animal of a given species. Tier 2 provides more detail with emission factors related to diet, climate, and management strategy. These factors have been widely applied to the analysis of livestock production systems (e.g., Pelletier et al., 2010; MacLeod et al., 2013).

Integrating the data from multiple sources can become cumbersome. To ease the process, software tools have been developed to assimilate all important factors for a comprehensive and rapid assessment (e.g., Holos; AAFC, 2020). These or similar factors are also used to estimate national (USEPA, 2020b) and global (FAO, 2020) GHG emissions. Tier 3 of the IPCC's (2006) approach is less common and requires more sophisticated tools to predict emissions. This approach uses complex models, such as process-level simulation, to quantify emissions and resources used. An example is the Integrated Farm System Model, used to study environmental and economic impacts of beef cattle and dairy production systems (USDA-ARS, 2020).

To obtain a comprehensive environmental assessment of foods, use of life cycle assessment (LCA) has become common practice (Mogensen et al., 2009). This provides a broader assessment over a partial or full life cycle of a product or service. For livestock production, a common partial LCA is to consider all factors up to the farm gate, i.e., everything involved in producing livestock up to the point of leaving the farm, ranch, or feedlot. A full life cycle includes farm-gate values plus those for transportation, harvest, processing, retail, consumer, and waste. GHG emissions or global warming potential is normally considered in an LCA, but many other metrics may also be considered. Common metrics include eutrophication potential, acidification potential, ozone depletion potential, photochemical ozone creation potential, water consumption, energy use, solid waste production, and land use (Saling et al., 2002; Mogensen et al., 2009). Software tools are available for obtaining inventory data (e.g., Ecoinvent Centre, 2020) and conducting LCA (e.g., openLCA, 2020; Simapro, 2020) to simplify and expedite analyses.

LCA is an environmental accounting procedure in which emission and other inventory data are gathered from various sources and integrated to estimate various metrics. As such, results of an LCA are heavily influenced by the quality of inventory data used and assumptions of the person or team preparing the assessment. Standards (ISO, 2006) and recommended guidelines (FAO, 2016, 2018) are available and normally used, but considerable variation still occurs across studies. As such, caution is needed in comparing results for different products or the same product done through different studies. The best comparisons are made using the same procedure or software and inventory database across comparisons. Perhaps the best use of LCA is to compare a product to itself, such as studying changes or improvements over time. When evaluating over time, it is important that changes in the inventory data represent real changes and not just a different database.

LCA may be linked to other tools, such as process-based simulation, to obtain more specific representation of inventory data (Kim et al., 2019). By simulating alternatives in production, predicted inventory data can vary with changes in management and technologies used to produce the livestock. This is particularly useful in comparing alternative production systems in which process simulation can more accurately predict the many changes and interactions among components as influenced by changes in production practices.

All metrics considered in an assessment must be expressed based on a common unit referred to as the functional unit. For the full life cycle of meat, the functional unit is normally mass of consumed meat. For a partial LCA to the farm gate, the functional unit may be live weight (LW) or projected carcass weight (CW) of animals leaving the producing operation. Use of this functional unit provides a basis for comparing systems producing the same product. It may also be useful in comparing the production of similar products such as beef and pork. Although attempts are often made (Mogensen et al., 2009; Hsu et al., 2018), this type of functional unit cannot be used to compare different foods due to the considerable variability in nutrient content or nutritional value of foods. Mass of protein has been used as a functional unit, but this also does not fully capture nutritional value. To assess and compare sustainability of foods, a functional unit is needed that adequately integrates all important nutritional aspects of food to a common unit. Efforts such as this are being made (Saarinen et al., 2017; Weidema and Stylianou, 2019), but appropriate representation of important nutritional aspects across all foods is difficult at best. Until such a scientific basis is developed and standardized, comparing the sustainability of different foods is not possible.

Carbon footprint

Because so much attention has been given to GHG emissions, this topic will be discussed in detail. A total of all GHG emissions related to production and use of a product or service is often referred to as carbon footprint. Important GHG in livestock production are methane, nitrous oxide, and carbon dioxide (CO_2). A relatively simple method is normally used for integrating the effects of various GHG emissions on global warming. A global warming potential for each gas is assigned a value based upon its radiative forcing (heat-trapping ability) and lifetime in the atmosphere compared with CO_2. Values commonly used are that 1 kg of methane in the atmosphere has a warming potential equivalent to 28 kg of CO_2 considering a 100-y time horizon, and nitrous oxide has a warming potential equivalent to 268 kg of CO_2 (Myhre et al., 2013). A sum of the 3 gases converted to CO_2 equivalents (CO_2e) provides a footprint for a production system, region, nation, etc., or the total can be expressed as an intensity, i.e., emission per functional unit.

A number of studies have determined farm-gate carbon footprints of livestock production. Through a summary of reported studies on cattle production, Rotz et al. (2013, 2019) found a range of 10–15 kg CO_2e/kg LW or 16–24 kg CO_2e/kg CW. In a national assessment of beef cattle produced in the United States, an average intensity of 21.3 kg CO_2e/kg CW was determined (Rotz et al., 2019). An assessment of pork production conducted by Thoma et al. (2011) determined a farm-gate emission intensity of 3.8 kg CO_2e/kg CW. In comparison to previous studies for pork, primarily in Europe, they found intensities ranging from 2.6 to 5.6 kg CO_2e/kg CW. In a more recent assessment (Putman et al., 2018), this group determined a farm-gate intensity of about 4.1 kg CO_2e/kg CW (3 kg CO_2e/kg LW) for US pork production. For chicken production, Skunca et al. (2018) summarized a number of assessments for various production systems in several countries. Farm-gate intensities varied from 1.4 to 6.8 kg CO_2e/kg LW with an average around 2.6 kg CO_2e/kg LW. Slaughter-gate values ranged from 2.2 to 8.5 kg CO_2e/kg CW.

These data come from many different studies that used different approaches, system boundaries, and inventory data, and this variation inhibits precise comparison. A summary of the available data does indicate, though, that GHG emission intensity of chicken production may be a little less than that of swine (MacLeod et al., 2013) and both are much less than that of beef cattle. A major difference among these species is methane produced by enteric fermentation in the rumen of cattle.

Fewer studies have determined full life cycle carbon footprints of livestock. In an assessment of beef production and consumption in the US, Asem-Hiablie et al. (2018) determined a footprint of 48 kg CO_2e/kg of consumed meat. In the study of Thoma et al. (2011), the full life cycle intensity of pork was 10 kg CO_2e/kg of consumed meat. This again indicates about a 5-fold difference between the carbon footprint of beef and pork. A similar assessment through consumption including consumer waste was not found for chicken. Skunca et al. (2018) provided a full chain assessment up to product delivery to the consumer with a value of 3.6 kg CO_2e/kg of product.

This illustrates that the global warming assessment procedure outlined by the IPCC (2006; Myhre et al., 2013) produces relatively large footprints for meat coming from ruminant livestock. To fully understand livestock's impact on global warming, a more process-oriented evaluation should be considered. The lifetime of methane in the atmosphere is relatively short compared with CO_2, so methane has a very high warming potential for a relatively short period. Methane oxidizes in the atmosphere by hydroxyl radicals through a chain of reactions (Wuebbles and Hayhoe, 2002; Myhre et al., 2013). Through this oxidation process, methane in the atmosphere has a half-life of 7 y. Thus, most of the methane is removed from the atmosphere within 10–12 y of its release with a small amount absorbed in soil (Lynch, 2019a). Through these processes, all carbon released as methane is transformed back to CO_2, and perhaps a small amount of other compounds, completing a natural cycle (Figure 1). Through photosynthesis, CO_2 is extracted from the atmosphere and fixed as carbohydrates in plant material. Cattle consume these carbohydrates, which are in part decomposed in the animal whereby some of the carbon is transformed to CO_2 and methane gases that are respired back to the atmosphere. Other carbon is excreted in manure, where decomposition creates further methane emissions. This methane is then oxidized, primarily in the troposphere, transforming the carbon back to CO_2.

If we compare the emissions from cattle to those emitted by vehicles through the combustion of fossil fuels, both affect the heat-trapping ability of the atmosphere. However, there is a major difference between these 2 sources of GHG. When fossil fuels are burned, carbon stored in the earth since prehistoric times is converted to CO_2 and released to the atmosphere. For every liter of fuel consumed, about 2.4 kg of CO_2 are created and released (USEPA, 2020a). Some of this CO_2 is absorbed by oceans and soil, but this gas

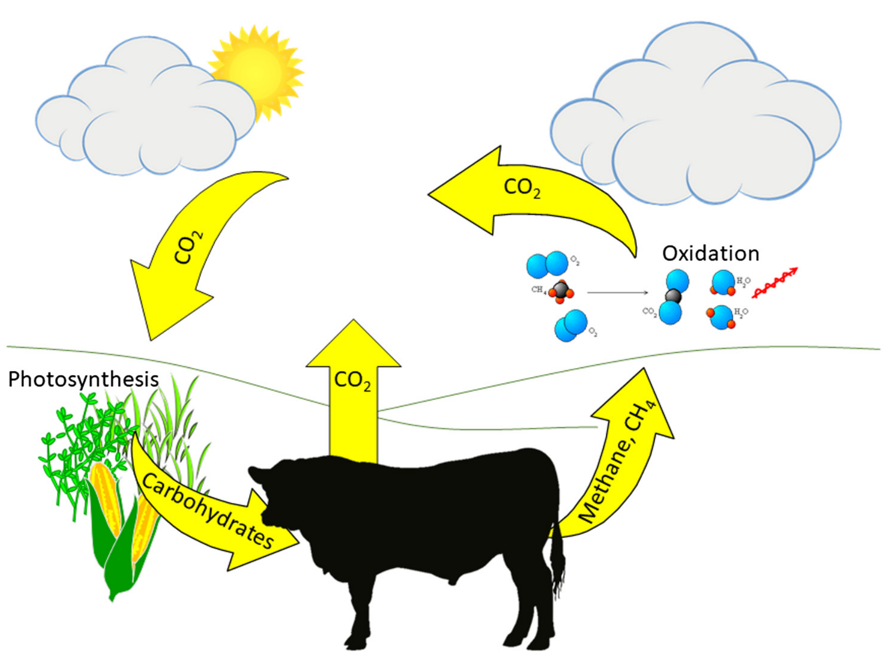

Figure 1. Methane produced by cattle and other livestock is part of a natural cycle in which the methane is oxidized in the atmosphere transforming the carbon back to carbon dioxide, the form that was originally used to fix carbohydrates in the growing feed crops.

is being released more rapidly than it can be absorbed. For this reason, we are observing a relatively rapid increase in atmospheric CO_2 concentration, and this effect on the atmosphere will be with us for thousands of years (NASA, 2019). Whereas cattle are part of a natural cycle with short-term impact, burning of fossil fuels has a more permanent impact (Myhre et al., 2013).

Given that methane produced by livestock and their manure is oxidized and returns to CO_2, they do not have a long-term effect on global warming unless the rate of methane production is increasing. Thus, livestock's effect on global warming is primarily related to the number of animal units maintained. In the US, Canada, much of Europe, and other developed countries, cattle numbers have decreased over the past 40–50 years as production systems have become more intensive (FAO, 2020). By producing animals in less time, fewer resources are used, and fewer emissions occur during their life cycle (Stackhouse-Lawson et al., 2012b). Therefore, for these regions of the world, cattle's effect on global warming and climate change is less than commonly promoted. Nevertheless, global numbers of all livestock and manure produced are increasing, which is contributing to an increasing rate of methane emission.

Because of this short-term effect, other methods are being considered to better represent methane's effect on global warming (Allen et al., 2018; Lynch, 2019b). If we can assume that enteric methane emissions have little effect in regions where cattle numbers are not increasing, the carbon footprint for those production systems is reduced considerably. Using data from the national assessment of beef cattle production in the US (Rotz et al., 2019), removing enteric emissions reduces the carbon footprint by about 60%, giving an intensity of 8.5 kg CO_2e/kg CW. For the full life cycle of consumed beef, the reduction is 47% for an intensity of 25 kg CO_2e/kg of consumed meat. Thus, removing the effect of enteric fermentation of cattle brings the carbon footprint of beef closer to that of pork, but it appears to remain a little greater. An advantage for pork production is the much greater number of offspring produced per sow, so the environmental impact of maintaining breeding stock is greater for cattle. Since a cow and a portion of a bull must be maintained for a full year to produce a calf, maintenance of the breeding stock can contribute 69%–80% of the total GHG emissions in beef cattle production (Beauchemin et al., 2010; Stackhouse-Lawson et al., 2012a).

Methane concentration in the atmosphere is increasing, with a 10% increase over the past 30 y (NOAA, 2020). Many sources are contributing to this increase. A major source is the increased use of natural gas—i.e., methane—and other fossil fuels. Methane leakage in the extraction and handling of fossil fuels is being recognized as a greater source than previously thought (Barkley et al., 2019). Other sources include landfills, forest fires, wet lands, and patty rice fields (USEPA, 2020b). On a global basis, cattle numbers are increasing so they are contributing to the short-term increase as well. Estimates of total cattle on the planet show a 38% increase over the past 50 y (FAO, 2020), which indicates a similar potential increase in the rate of emissions.

Comprehensive LCA

As stated earlier, an assessment of environmental sustainability must include many metrics in addition to global warming. In a full cradle-to-grave LCA of beef, Asem-Hiablie et al. (2018) reported values for 11 environmental metrics (Figure 2). This assessment included all aspects of beef through consumption and the handling of waste. For most metrics, the large majority was in cattle production (Figure 2). Some exceptions were ozone depletion level and solid waste, for which a larger portion came from the restaurant sector. Within cattle production, the majority of most metrics was in producing feed and maintaining the cow-calf phase of production. Feedlot finishing operations had an important role in abiotic depletion potential and acidification potential. Abiotic depletion was primarily due to the use of zinc (a limited resource) as a feed supplement in finishing rations. Acidification was primarily due to ammonia emissions from cattle manure and secondarily from fossil fuel combustion in producing electricity and other resources used on feedlots.

For pork production, a couple of studies have reported just a few environmental metrics, and each study has used different metrics and functional units. Putman et al. (2018) reported farm-gate values for water use, land use, and energy use along with global warming potential. Over the 55-y period from 1960 to 2015, they reported rather small decreases in the intensities of water use, energy use, and global warming potential. They found a large decrease in land use due primarily to increased feed crop yields over that period. Winkler et al. (2016) studied acidification potential and eutrophication potential of pork along with global warming potential in Austria. In a full LCA, they found that 95% of eutrophication potential and 98% of acidification potential occurred up to the farm gate.

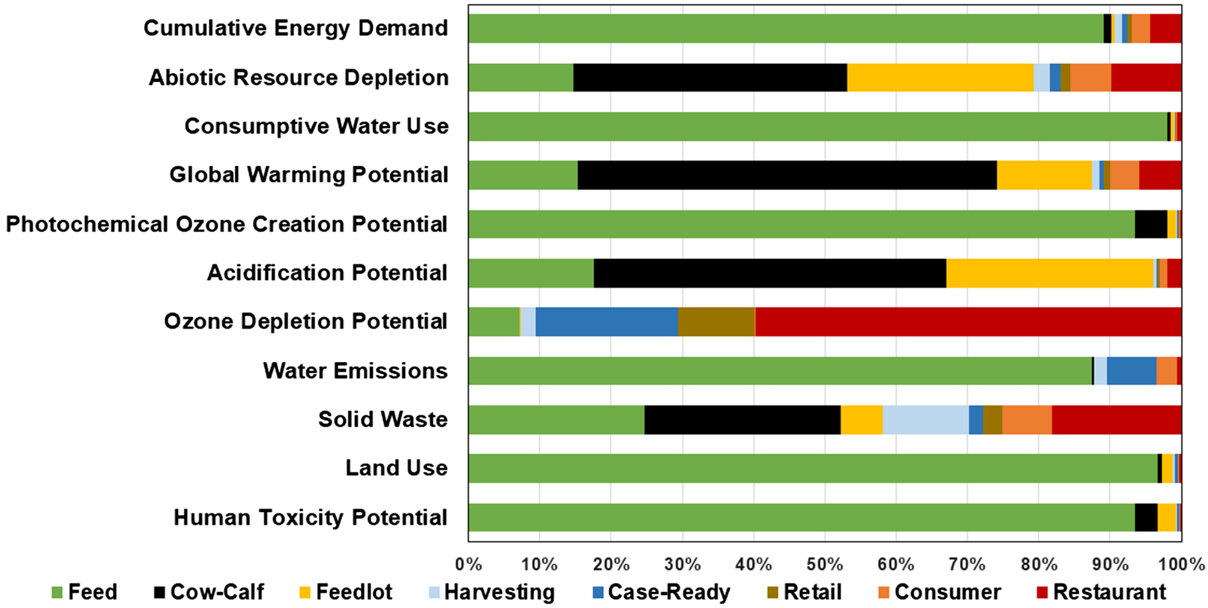

Figure 2. Percentage contribution of the various phases of beef production and consumption to each environmental impact (Asem-Hablie et al., 2018).

For chicken meat production, López-Andrés et al. (2018) conducted a comprehensive "cradle to slaughterhouse gate" LCA for production in Mexico that included 15 environmental metrics. They found that the greatest impact of most metrics was from chicken farms where the main factors responsible were feed production (use of chemicals and energy) and on-farm emissions from organic waste decomposition. A similar slaughter-gate assessment was done for chicken meat production in Iran that included 10 environmental metrics (Kalhor et al., 2016). They also found that the large majority (60%–97%) of each metric was related to farm production.

When comprehensive assessments such as these are conducted, there is still a need to integrate this information to indicate an overall impact. These assessments are usually done to compare production strategies or to follow the impact over time. With multiple metrics and those metrics having varied importance, an obvious conclusion about the change in environmental sustainability is difficult to determine. One approach is to assign a relative importance factor to each metric such that the total of all factors is 1.0. Multiplying the relative change between systems for each metric by this relative factor and totaling across all metrics gives a relative change. This approach has been applied to beef, in an extension of the work reported by Asem-Hiablie et al. (2018). Importance factors were established through a survey of consumers and other stakeholders rating the importance of various environmental concerns. With this ranking, environmental sustainability of beef improved 7% over a 6-y period from 2005 to 2011 (unpublished data).

The result of this type of integrated analysis is heavily influenced by the assumed importance factors. Therefore, the quality of such an assessment is dependent upon how well the factors represent the relative importance of the various metrics assessed. This importance may vary among studies due to influences of climate, management practices, and social concerns across regions and countries. Some metrics and their related environmental concerns are global issues such as ozone layer depletion potential and global warming potential. The importance of most metrics, though, are on a regional scale. Metrics like acidification potential and eutrophication potential primarily affect the surrounding air shed and watershed. Most air emissions such as ammonia and volatile organic compounds do not drift long distances from the source, so they primarily affect ecology in the surrounding area (Ferm, 1998). Likewise, emissions to water affect local watershed and potentially downstream discharges with little direct impact on a global scale (Boardman et al., 2019). Therefore, for example, in regions with a warm, dry climate, air emissions and water consumption are likely more important than emissions to water. Heavily populated areas may have different environmental concerns than rural areas. Thus, developing universal importance factors does not seem appropriate; they must represent the area, region, or country of the assessment.

Important Environmental Concerns

LCA and its application to the sustainability of livestock production is a relatively young science. Assessment methods and standards are rapidly developing, but concerns over methodology and appropriate assumptions remain (IPCC, 2006; FAO, 2016, 2018). Although we are developing standards and methods that give exact numbers, proper interpretation and application of that information remains difficult. Current data available give us only a clue to the real threats to long-term sustainability of livestock production.

Global warming potential

Global warming potential is an important issue, but it may not be as important as often perceived or promoted, particularly for ruminant livestock. The recent estimate for global GHG emission is 49 Gt CO_2e (IPCC, 2014). The FAO (2020) estimates recent global emissions from agriculture to be 5.4 Gt CO_2e with 3.9 Gt CO_2e from livestock and their manure. This implies that about 11% of the global emission is related to agriculture with 7.9% from livestock and their manure. Recent estimates for GHG emissions from the US indicate that 9.3% is related to agriculture with 3.9% from livestock and their manure (USEPA, 2020b). This compares to 27% for direct emissions from transportation and 76% from the combustion of all fossil fuels.

A farm-gate LCA of beef cattle production in the US has shown that beef production's global warming potential represents less than 4% of the total estimated GHG emissions from the country (Rotz et al., 2019). This type of assessment is more comprehensive than other assessments by including all resource inputs and emissions both directly and indirectly related to cattle production. Our discussion earlier on methane emissions not having a long-term impact on global warming can have a rather large effect on this number. Since cattle numbers in the US have been declining for many years, the real impact on global warming may be less. Since the majority of the carbon footprint of US beef comes from enteric fermentation (Asem-Hiablie et al., 2018; Rotz et al., 2019), removing that GHG source reduces global warming potential by about 50%. This cannot be applied globally though, where cattle numbers have increased over the past 50 y (FAO, 2020). The effect of livestock on global warming cannot be ignored, but a proper perspective must be maintained relative to other important environmental concerns and GHG sources.

Reactive nitrogen

An important threat to the long-term sustainability of livestock production is reactive nitrogen losses to the environment. Feed production for all forms of livestock is dependent upon use of inorganic fertilizer and nitrogen-fixing legumes to maximize yields and protein contents. As these feeds are consumed, most of the nitrogen is excreted and rapidly transformed to reactive forms in the manure (Rotz et al., 2014). A major form is ammonium, which readily transforms to ammonia. Ammonia is highly volatile, so much can be lost during manure handling. For example, about half of the nitrogen consumed as dietary protein can be lost through ammonia volatilization from a beef cattle feedlot (Hristov et al., 2011; Todd et al., 2011). Losses are normally less from other housing facilities, but greater loss can then occur during manure storage and field application (Rotz, 2004; Rotz et al., 2014).

Ammonia emissions can cause several environmental concerns (NRC, 2003; Paulot et al., 2014). Within poorly ventilated structures, high concentrations can occur causing health and welfare concerns for animals and workers. When emitted to ambient air, ammonia can transform to other nitrogen forms that deposit locally or longer distances from the source. Increased levels of nitrogen deposition can alter sensitive ecosystems. The greatest concern, though, is for the formation of small particles in the atmosphere, which is a human health concern. These small particulates also contribute to smog formation and its effect on visibility in some regions. For these reasons, ammonia is designated as a criteria air pollutant by the US Environmental Protection Agency (USEPA, 2019).

National estimates for the US indicate that about 80% of the ammonia emitted within the country comes from agriculture, with 58% coming from livestock manure (USEPA, 2019). A national assessment of US beef cattle production (Rotz et al., 2019) indicates that life cycle ammonia emissions from beef production represent about 34% of the estimated total emission from the country (USEPA, 2019). International estimates show about 31% of ammonia emissions coming from livestock manure (EDGAR, 2020). Paulot et al. (2014) estimate that 63% of global ammonia emission comes from agriculture, with 44% from livestock manure. Although there is much uncertainty in these numbers, they strongly indicate that livestock production is the major contributor to this criteria air pollutant. Nitrate losses to groundwater and runoff in feed production are of further concern. Their effects on water quality are at a local or regional scale, and no data are available to estimate their regional, national, or global impact.

Reactive nitrogen loss is a concern in the production of all livestock species. Although emissions vary as influenced by housing facilities and manure handling practices, from 30% to 60% of the nitrogen excreted is lost during the recycling of manure nitrogen through feed production (Rotz, 2004). In LCA, these emissions affect acidification potential, eutrophication potential, human toxicity, and over-fertilization of ecosystems sensitive to nitrogen levels. Reducing nitrogen losses and recycling more through crop production may provide economic benefit to the producer through reduced inorganic fertilizer use, but added production costs to implement these strategies normally outweigh the small benefit received.

Water

Another threat to long-term sustainability of livestock production is water consumption, primarily in feed production. Within the US, the US Geological Survey estimates that 42% of freshwater is used to irrigate crops, which includes livestock feed production (Dieter et al., 2018). Less than 1% is used in animal consumption, cooling, and other direct uses in animal production. Global estimates suggest agriculture uses about 70% of freshwater withdrawals, with about 20% used for livestock feed production (FAO, 2018).

In sustainability assessments, water use is defined by 3 categories: blue, green, and grey water (Doreau et al., 2012). Blue water is freshwater obtained from surface and groundwater sources. Green water includes all moisture lost from plants through evapotranspiration. Grey water is the amount of water needed to dilute the concentration of pollutants to a level safe for other uses. Of the 3 types, blue water competes most directly with other water needs, so it is often used in sustainability assessments. In livestock production, green water includes all water used to produce feed (precipitation and irrigation), and this is much greater than that of blue water (irrigation only). Assessments have used different categories of water use, which has contributed to large variation in reported values for water consumption in livestock production. When comparing water footprints, it is important to know the water type considered. In an international study of water use for livestock production, Gerbens-Leenes et al. (2013) concluded that beef had greater total water use intensities than pork, with chicken having the least. When considering just blue or grey water intensities, similar values were found across the 3 meat products. Greater green water use in cattle production was due to a smaller feed conversion efficiency relative to the other species (Gerbens-Leenes et al., 2013).

A national assessment indicates that about 6% of the freshwater consumption in the US is related to beef cattle production, with about 97% of this total consumption used to irrigate feed crops (Rotz et al., 2019). Most of the cattle in the US are produced in the drier, western region of the country where production often relies upon irrigated crops and sometimes irrigated pasture. The overall demand for water is increasing in many of these areas, and in some areas, the supply is decreasing. In the eastern portion of the US, water is much more available and less of a constraint on sustainability. Water quality and the eutrophication potential of production practices are of greater concern in this region, increasing the importance of grey water assessment. Similar conclusions can be drawn for pork and poultry depending upon precipitation patterns in regions where the feed is produced.

Fossil fuels

Use of fossil fuels is a concern for long-term sustainability of any product or service. Energy consumption in agriculture is generally not a major concern compared with other uses. In the US, less than 2% of total energy consumption is used in agriculture (Hitaj and Suttles, 2016). About 30% of global energy consumption is estimated to be used in the full agri-food chain with about 9% used on farms (FAO, 2012). Although values specific to livestock production were not found, less than half of that used in on-farm agricultural production would be associated with producing livestock and their feed.

Fossil energy use is often acknowledged as a major concern in livestock production, particularly for the transport of animals among production sectors. In a national assessment of US beef cattle production, the total energy used in cattle production was less than 1% of that estimated for the whole country, and the total energy used in transporting animals was less than 3% of that consumed in cattle production (Rotz et al., 2019). Most of the energy consumed in livestock production is used to produce resource inputs such as electricity and fertilizer (Hitaj and Suttles, 2016; Rotz et al., 2019).

Waste

In a full LCA of meat, and likely most any other food, the major contributor to increased intensity of environmental impact is waste, primarily with the consumer. A study in the European Union estimates that about 65% of the loss in the food chain occurs around food service and household use (Stenmarck et al., 2016). A recent study indicates the average family in the US wastes about a third of the food purchased (Yu and Jaenicke, 2020). Waste can include physical waste that normally ends in waste treatment or that from consuming more than is needed. The analysis by Yu and Jaenicke essentially includes both of these forms by comparing food energy purchased by the consumer to that required.

In quantifying losses in the food chain, the FAO (2011) has defined food losses as what occurs during production, processing, and distribution and food waste as what occurs in retail and with the consumer. Throughout all regions of the world, about a third of the food is lost or wasted. For meats, the total of losses and waste is about 20% in all regions. In Europe, North America, and Oceania, about half occurs with the consumer, whereas in Africa, Southern Asia, and Latin America, greater loss occurs in production and distribution and less waste occurs with the consumer. This indicates similar totals for most regions of the world; however, in developing regions, greater loss may occur in processing and preservation than in consumer waste. In developed regions, the consumer is the major source of loss and waste.

Not only do loss and waste affect the waste stream created, but this also increases the intensity of all metrics considered in a LCA. For example, considering 20% waste, a kilogram of meat purchased by the consumer with a carbon footprint of 20 kg CO_2e/kg has a footprint of 25 kg CO_2e/kg of consumed meat. This not only affects global warming potential but also has this same effect on all environmental, economic, and social metrics that can be considered. In light of this comprehensive effect, no other specific source has near this impact. This implies that the greatest impact on the sustainability of livestock products, as well as other foods, is from loss and waste.

Mitigation Strategies

Strategies to improve the sustainability of livestock products must start with the reduction of loss and waste. There is essentially nothing else that can be done to our livestock systems to obtain more benefit for the environment and society. As we look toward feeding an increasing global population with best use of resources and least impact on the environment, this is where improvement is needed most. Responsibility for reducing waste primarily rests with the consumer. Since this is a very large group with complete freedom in making decisions on food use, change is difficult to implement. This must be done through education of the public about effects of waste on long-term sustainability of food systems.

Looking beyond food waste, mitigation strategies are often associated with a specific emission (quantifiable metric) and its source. For example, strategies often focus on reducing global warming potential, and changes may have little effect on other metrics such as acidification or eutrophication potentials. Often though, mitigation of one metric may affect and even exacerbate another. A full LCA with sound scientific inventory must be used to weigh the costs and benefits of any strategy. A comprehensive assessment is needed to ensure that the benefits received outweigh potential adverse effects on other metrics.

For all livestock species, an important mitigation option is to use more intensive production practices to produce finished animals in a shorter period (Leinonen et al., 2012; Stackhouse-Lawson et al., 2012b; Heller, 2017). Many environmental impacts of animals are directly related to their life span. The animal is consuming resources and producing emissions every day over their life cycle. Thus, strategies that finish animals in a shorter period can potentially reduce the environmental intensities of most metrics. Given the growing demand for meat with limited resources and increasing environmental consequences, there is the need for developing and using more intensive production systems worldwide (Herrero et al., 2013). Strategies to increase the rate of gain are of most benefit as long as those alternative practices do not use substances or treatments that have adverse effects on animal and human health, among other potential concerns. Harvest of animals at an optimal age is also important for meat quality. This supports the need for comprehensive LCA to properly evaluate and compare production options.

Intensification should begin through improved feeding practices. For ruminants, feeding higher-quality forage can improve feed intake and animal rate of gain. Forage with lower fiber content or greater fiber digestibility improves intake and the nutrition obtained. Forages with greater energy content increases energy intake providing more energy for growth. Substantial increases in growth rate can be obtained by supplementing forage with grain and other concentrate feeds to increase the energy content of diets. For all livestock, meeting nutrient needs through balanced diets normally provides optimal growth and resource use with a minimum environmental impact per unit of meat produced. This is best done by feeding animals total mixed rations in confined housing facilities where diets can be controlled. Legesse et al. (2015) found a significant reduction in GHG intensity from Canadian beef production between 1981 and 2011 as a result of increased average daily gain and slaughter weight, improved reproductive efficiency, reduced time to slaughter, increased crop yields, and a shift toward high-grain diets that enabled cattle to be marketed at an earlier age.

Use of growth-promoting technologies and their effect on sustainability can be controversial, but studies support that their use reduces the intensity of resource use, emissions, and other environmental concerns. For beef cattle production in the US, the combined use of ionophore, implant (estrogen/trenbolone acetate-based), and ß2-adrenergic agonist (zilpaterol) treatments was found to reduce GHG emission intensity by 9% with a 13% decrease in ammonia emission over the full life cycle of cattle (Stackhouse-Lawson et al., 2012b). These reductions occurred through an increase in rate of gain resulting in greater finish weight and less time on feed. Feed protein utilization was also improved, which further reduced nitrogen excretion and ammonia emission.

In beef production, an important mitigation strategy can be the use of culled dairy animals, particularly male calves (Stackhouse-Lawson et al., 2012a). In traditional beef cattle production, a major portion of resource use and emissions to the environment occur in maintaining breeding stock. Calves received from the dairy sector come into beef production with a relatively low environmental footprint because maintenance of their breeding stock is mostly associated with dairy production. The carbon footprint of Holstein beef was found to be about half that of traditional beef breeds (Stackhouse-Lawson et al., 2012a), but not all environmental metrics had this benefit. Holstein calves were maintained on feedlots throughout their life cycle, which created greater ammonia emissions. In a national assessment of US beef production, use of culled animals from the dairy industry reduced national intensities of GHG emission, fossil energy use, and reactive nitrogen loss by 9%, 4%, and 4%, respectively (Rotz et al., 2019).

Global warming potential

Most evaluations of mitigation strategies in livestock production have focused on global warming potential. Through a comprehensive literature review, Hristov et al. (2013) compared a wide range of potential strategies for reducing GHG emissions from livestock production. These included qualitative assessments of feeding, manure handling, and animal management practices. They concluded that improving forage quality and the overall efficiency of dietary nutrient use can reduce emissions. Feed supplements may also be used to reduce enteric methane production in ruminants, but long-term studies are needed to confirm performance and feasibility. Of the many additives investigated, one of the more promising is 3-nitrooxypropanol, shown to decrease enteric methane up to 30% without negative effects on feed intake or animal production (Hristov et al., 2015; Jayanegara et al., 2018).

Many manure handling strategies can be used in livestock production, and the methods used vary across the species of cattle, swine, and poultry (Rotz, 2004; Montes et al., 2013). For GHG emissions, the major sources are the housing facility and manure storage, but field application of manure also affects nitrous oxide emissions from field crops. Therefore, mitigation from manure sources requires elimination or reduction of manure storage in the housing facility and emission reduction in subsequent storage and handling.

Housing facilities and mitigation options vary considerably across livestock species. Cattle spend most of their life cycle on pasture or rangeland, where mitigation is difficult. Under these aerobic conditions, little methane is produced from excreted manure (Rotz et al., 2019). The major GHG emission from pasture is nitrous oxide, for which improved management may provide small reductions (Rotz, 2004). Use of urease and nitrification inhibitors has provided substantial reductions in nitrogen losses and increased forage production in pastures (Zaman et al., 2009), but practical application of these treatments remains a challenge. Cattle are often finished on open lots. The aerobic conditions on lots again lead to low methane production, but nitrification and denitrification processes produce nitrous oxide (Rotz and Thoma, 2017). As with pasture, few options exist for reducing this GHG source. However, GHG emissions from pasture and open lot manure are relatively small compared with enteric emissions (Rotz et al., 2019), so reducing these emissions has not received priority.

For swine, poultry, and sometimes cattle production, barns or enclosed housing is used. When manure is removed from the facility daily or at some other short-time interval, little GHG emission occurs. Methanogenic, nitrification, and denitrification processes in manure occur through time under the right anaerobic, aerobic, or fluctuating conditions. By shortening the time for these conditions to occur, emissions are suppressed. Manure stored long term within the facility leads to greater GHG emission. A slatted floor with under-floor storage is a common practice for swine and sometimes cattle production. Use of this design increases housing emissions compared with systems using daily manure removal (Montes et al., 2013). Compared with daily removal and long-term outdoor liquid storage, the total system emission may be similar or less with the slatted floor system. Poultry facilities include high-rise, deep litter, cage and belt, and aviary systems. Rapid removal of manure using the cage and belt system provides a strategy for reducing gaseous emissions, but rapid disposal or proper storage is needed to avoid greater loss in manure handling (Malomo et al., 2018).

Intensive production systems for swine and poultry normally require long-term storage of manure. Storage facilities are often tanks or earthen basins for liquid handling. Dry or solid manure such as that from open lots of cattle and bedded pack or deep litter facilities for cattle, pigs, or chickens can be stored in stacks. Methane and nitrous oxide gases are formed and released during long-term storage of the manure. Aerating the stacks to improve composting can reduce methane emissions, but this processing increases ammonia and nitrous oxide emissions (Montes et al., 2013).

A mitigation option for slurry or liquid storage is to use a cover or enclosed tank to reduce the escape of gases formed. Bottom filling of a slurry storage tank can allow a crust to form on the surface, which reduces methane emissions by up to 40% (IPCC, 2006), but nitrous oxide formation and emission may occur in the crust, offsetting some of the benefit of reduced methane loss (Chianese et al., 2009). Within an enclosed storage facility, some ventilation is required to release the gases formed, particularly methane. A flare can be used to combust the escaping methane to reduce global warming potential. To obtain further benefit, anaerobic digestion can be used to greatly increase methane production for use as a natural gas replacement or for generating electricity. Use of anaerobic digestion systems can provide substantial benefit as a mitigation strategy, but care must be taken to minimize methane leakage (Montes et al., 2013). With large amounts of methane being produced through digestion of the manure, leaks can cause the system to become a net emitter, increasing global warming potential.

Reactive nitrogen

As pointed out earlier, reactive nitrogen losses may be a greater threat to the long-term sustainability of livestock production than GHG emissions. The major nitrogen emission of concern is ammonia, with emissions affecting acidification potential, eutrophication potential, human toxicity, and other potential impacts. Ammonia emissions occur throughout all stages of manure handling (Rotz et al., 2014) leading to a wide range of potential mitigation practices. Mitigation can occur through alternative feeding, housing, and manure handling practices (Rotz, 2004; Ndegwa et al., 2008).

Strategies and technologies are available to reduce emissions, but economically feasible solutions are often difficult to find. This is particularly true for cattle production in which animals spend most or all of their lives on pasture, rangeland, and open lots. Under these conditions, capture of the nitrogen being lost through volatilization, leaching, denitrification, and runoff is essentially impossible. Producing cattle using housing facilities where nutrient losses can be controlled or captured is often not feasible while maintaining reasonable production costs and value for the meat sold. In pork and poultry production in which animals are normally produced within enclosed facilities, more options are available for mitigating and capturing nitrogen losses (Rotz, 2004; Ndegwa et al., 2008).

Often the most economical method for reducing reactive nitrogen losses is through more efficient feeding of protein (Nahm, 2007; Sajeev et al., 2018). Meeting protein requirements while feeding the least amount of total protein leads to less nitrogen excretion. With less excretion, less loss will occur from all manure sources and through all pathways (Rotz, 2004; Ndegwa et al., 2008). For grazing cattle, protein intake may not be controllable, particularly on high-quality pastures where consumption of high-protein forage leads to greater excretion. Much of this nitrogen is excreted on small urine spots where the nitrogen deposited is much greater than that taken up by the growing forage (Rotz, 2004). This excess can lead to greater losses through leaching and denitrification processes. Use of lower-quality pastures or rangeland with the right amount and form of protein supplement may help mitigate reactive nitrogen losses in some regions.

Poultry and swine production has an advantage over cattle for optimal nitrogen intake. By designing rations for optimal protein intake through the use of individual amino acids, animal needs can be more accurately met (Nahm, 2007; Madrid et al., 2012). This technology is widely used in intensive pork and chicken production, but it has limited value in beef production. Meeting specific amino acid needs of ruminant livestock is more difficult, particularly for grazing animals. For animals fed in confinement, more optimal feeding of protein can be maintained through feeding in groups established by age, weight, and breed. Rations can then be designed to better meet the needs of the group, and more optimal diets will reduce nitrogen excretion and the losses that follow. Byproduct feeds are often fed for more efficient use of available resources and to reduce waste streams. Feeding products with high concentrations of protein (such as distiller's grain) to meet energy requirements can lead to overfeeding of protein, greater nitrogen excretion, and thus greater ammonia emission (Todd et al., 2011). This creates a tradeoff between different environmental impacts whereby one benefits while another suffers. Decisions toward sustainability must be made considering the importance of local, regional, and global needs.

Following excretion, many strategies and technologies have been considered to reduce ammonia emissions in manure storage and handling (Ndegwa et al., 2008; Groenestein et al., 2011). Potential practices include changes in housing design, manure treatments, covered storages, and alternatives in field application. Various floor designs have been tested for fecal and urine separation to reduce hydrolysis or the conversion of urea to volatile nitrogen forms. Manure treatments include acidification of manure to reduce conversion of ammonium to ammonia, urease inhibitors to slow hydrolysis, and ammonium binding agents and treatments to convert manure nitrogen to more stable forms. Use of covers or enclosures for manure storage can reduce emissions during long-term storage. When manure is applied to fields to recycle nutrients in feed production, ammonia emissions can be greatly reduced through immediate incorporation or subsurface injection, which traps the nitrogen in the soil where it is converted to more stable forms such as nitrate. Subsurface injection also reduces nitrogen and phosphorus runoff, providing further benefit by reducing eutrophication potential (Rotz et al., 2011).

When steps are taken to reduce nitrogen losses, a full systems perspective must be followed. Reducing ammonia volatilization in a housing facility is of limited value if that ammonia is lost through poor management in manure storage and field application. Combining fecal and urine separation in the housing facility, covered manure storage, and subsurface application can greatly reduce ammonia emissions (Rotz et al., 2006). The saved nitrogen must then be applied to cropland at the right time and at the right rate to maximize crop uptake or that nitrogen will just be lost through nitrification, denitrification, leaching, and runoff processes. Only by addressing mitigation from all sources can reactive nitrogen losses be minimized.

Water

Because the large majority of water consumed in livestock production is used to irrigate feed crops, mitigating or reducing consumption must focus on more efficient irrigation practices. Recommended improvements may vary between developed and developing countries. In the developing region of South Asia, low irrigation water use efficiency and the resulting overuse of water for crop production is noted as a leading cause of water scarcity (Mitra et al., 2017). Flood irrigation is commonly used in these regions. Low efficiency results from the use of water-intensive cropping systems, use of un-optimized irrigation supply systems, and uneven water distribution within fields. Under these conditions, large opportunities are available for improving water use efficiency, but this improvement must be weighed against greater energy and other resource inputs required to implement more efficient technology.

In developed regions such as North America and Australia, improvement in water use efficiency is a continuing goal. Improvements have been made through more timely and uniform placement of water through sprinkler irrigation systems, and technologies are being developed for further improvement (Greenwood et al., 2010; Koech and Langat, 2018). Remote sensors and wireless communication can be used to monitor soil moisture throughout a field for more timely application. Variable rate application can then be used to apply water more efficiently to meet crop needs. In-field monitoring may also be combined with process-level soil, crop, and weather modeling to project crop needs for more timely and appropriate amounts of application.

Another approach to improving water use efficiency is to develop or use crops that are less sensitive to soil moisture availability (Doreau et al., 2012). Maize harvested as either grain or whole-plant silage has become an important crop for livestock production in many regions of the world, and maize production requires relatively large amounts of water. Use of a shorter season variety may be beneficial to better align with seasonal moisture availability, but any sacrifice in yield must be considered. A potential loss in yield will require greater land use and other resources to produce the same amount of feed. Alternative crops can be an option, but yield is again an important consideration. As an example, sorghum is a crop known to be more tolerant to moisture stress then maize, and it also provides both forage and grain feeds suitable for livestock. Under dry land production, sorghum grain yields, on average, are about half that of maize (NASS, 2020). Silage yields may be similar or reduced depending upon available soil moisture.

Another possible option for the future is breeding or genetic modification of a crop such as maize to be more efficient in water use (Hatfield and Dold, 2019). Many confounding factors affect evapotranspiration of a crop, which makes genetic improvements challenging. Increases in yield obtained through plant breeding have generally increased water use efficiency as greater yield is obtained with less or no increase in evapotranspiration (Hatfield and Dold, 2019). This implies water use efficiency can continue to improve as crop productivity is improved.

A practical solution to reduce blue water consumption is to grow feed crops in regions where precipitation is adequate to maintain production without irrigation. Tradeoffs must be considered, though, for optimal use of land and transportation resources. To maintain or improve environmental sustainability, manure nutrients from livestock should be recycled through crop production for feed. Due to the difficulty and cost in transporting manure, this requires an integrated crop and livestock system in which animals and feed are produced together at or near the same location. Demand for land in more temperate regions may reduce the feasibility of expansion of integrated crop livestock systems. Meeting the growing demand for food requires development of more efficient production systems that improve the productivity of marginal land.

Fossil fuels

Although livestock production does not appear to be a major consumer of fossil fuels relative to other uses, practices to reduce consumption should always be considered. Since most of the use is in the production of resources used to produce livestock, mitigation must focus on reducing the use of these resources. A major input is electricity, for which the use of new technologies in lighting and other improvements in efficiency are providing reductions in use. Use of fluorescent and light-emitting diode lighting can provide up to an 80% reduction in electricity use compared with traditional incandescent lighting, but dust and humidity conditions must be considered for their use in livestock facilities (Harmon and Petersen, 2011).

Fertilizer production is another important consumer of fossil energy. An important first step in reducing fertilizer use is to utilize manure nutrients, reducing the need for inorganic fertilizers (FAO, 2012). Use of manure must be combined with improved manure management strategies and technologies to reduce losses and retain nutrients for timely application to meet crop needs (Montes et al., 2013). As discussed earlier, use of anaerobic digestion systems to produce biofuels can offset energy inputs while retaining most nutrients for use in feed production. This technology can be applied from very small-scale systems in developing countries to very large systems used in industrial-scale livestock production (FAO, 2012). When inorganic fertilizers are used, precision application methods provide more efficient use, saving energy and reducing GHG emissions (Balafoutis et al., 2017).

Grain crops such as maize provide a major feed source for livestock production. These annual crops require greater energy use in crop establishment. Reducing the number of tillage operations through conservation and no-till practices reduces on-farm fuel use but may increase the use of pesticides and the energy used to create these chemicals (Musser et al., 2006). Use of natural drying in the field can reduce energy used in post-harvest drying and preservation. Efficient use of irrigation not only reduces water consumption but also reduces the energy required for pumping and distributing water.

New technologies show promise for further reducing energy use in the future. Feed production requires various machinery operations, in which use of GPS guidance and autosteering systems can reduce fuel consumption (Bora et al., 2012). Truck and all-terrain vehicle use in monitoring cattle on large ranches is a direct user of fossil fuels. Use of unmanned aircraft (drones) to monitor animals and grazing conditions may provide a method for reducing this source of energy use. Wireless sensor networks also provide an opportunity for monitoring crop-growing conditions and tracking the location and health of cattle (Jawad et al., 2017). These technologies not only save energy and labor but also provide more accurate and timely data for improving management (Berckmans, 2017).

Conclusions

Sustainability assessments of livestock production require a comprehensive analysis that considers all important components and their interactions across all important measures of sustainability. LCA tools are used for these evaluations, but variations in system boundaries, assumed inventory data, and functional units make comparisons across studies difficult. GHG emissions from livestock production is of concern, but because of the relatively short time methane remains in the atmosphere, livestock's long-term influence on climate change may be overemphasized as a sustainability concern. The greatest threat to the sustainability of livestock products—and essentially all foods—is loss and waste, for which all measures of sustainability expressed per unit consumed are increased. Specific to livestock, an important threat to long-term sustainability is ammonia emission from manure along with other reactive nitrogen emissions during feed production. Livestock are estimated to contribute over 40% of global ammonia emissions; these emissions affect smog and small particulate formation and have related effects of toxicity to human health, eutrophication of surface waters, and acidification of sensitive ecosystems. Freshwater consumption is another important consideration for livestock sustainability, with an estimated 20% of global consumption used to produce livestock feed. Diminishing supply and increasing demand for freshwater may constrain livestock production in some regions of the world. Management strategies and technologies are available or under development that mitigate the environmental impacts of livestock production, but finding economical solutions that maintain product value is challenging. Environmental concerns vary across local, regional, and global interests, preventing general formation and recommendation of sustainable production practices.

Literature Cited

AAFC. 2020. Holos software program. Agriculture and Agri Food Canada. Lethbridge, Alberta, CA. http://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/holos-software-program/?id=1349181297838. (Accessed 15 June 2020).

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey. 2018. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. Nature. 1:16. https://doi.org/10.1038/s41612-018-0026-8

Asem-Hiablie, S., T. Battagliese, K. R. Stackhouse-Lawson, and C. A. Rotz. 2018. A life cycle assessment of the environmental impacts of a beef system in the United States. Int. J. Life Cycle Ass. 24:441–455. https://doi.org/10.1007/s11367-018-1464-6.

Balafoutis, A, B. Beck, S. Fountas, J. Vangeyte, T. van der Wal, I. Soto, M. Gómez-Barbero, A. Barnes, and V. Eory. 2017. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability-Basel. 9:1339. https://doi.org/10.3390/su9081339.

Barkley, Z. R., K. J. Davis, S. Feng, N. Balashov, A. Fried, J. DiGangi, Y. Choi, and H. S. Halliday. 2019. Forward modeling and optimization of methane emissions in the South Central United States using aircraft transects across frontal boundaries. Geophys. Res. Lett. 46:13564–13573. https://doi.org/10.1029/2019GL084495.

Basiago, A. 1995. Methods of defining 'sustainability'. Sustainable Dev. 3:109–119. https://doi.org/10.1002/sd.3460030302.

Beauchemin, K. A., H. H. Janzen, S. M. Little, T. A. McAllister, and S. M. McGinn. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. Agr. Syst. 103:371–379. https://doi.org/10.1016/j.agsy.2010.03.008.

Berckmans, D. 2017. General introduction to precision livestock farming. Animal Frontiers. 7:6–11. https://doi.org/10.2527/af.2017.0102.

Boardman, E., M. Danesh-Yazdi, E. Foufoula-Georgiou, C. L. Dolph, and J. C. Finlay. 2019. Fertilizer, landscape features and climate regulate phosphorus retention and river export in diverse Midwestern watersheds. Biogeochemistry. 146:293–309. https://doi.org/10.1007/s10533-019-00623-z.

Bora, G. C., J. F. Nowatzki, and D. C. Roberts. 2012. Energy savings by adopting precision agriculture in rural USA. Energy, Sustainability and Society. 2:22. https://doi.org/10.1186/2192-0567-2-22.

Chianese, D. S., C. A. Rotz, and T. L. Richard. 2009. Whole-farm greenhouse gas emissions: a review with application to a Pennsylvania dairy farm. Appl. Eng. Agric. 25:431–442. https://doi.org/10.13031/2013.26895.

Dieter, C. A., M. A. Maupin, R. R. Caldwell, M. A. Harris, T. I. Ivahnenko, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2018. Estimated use of water in the United States in 2015. US Geological Survey Report, USGS Numbered Series 1441. Reston, VA. https://pubs.er.usgs.gov/publication/cir1441. (Accessed 15 June 2020).

Doreau, M., M. S. Corson, and S. G. Wiedemann. 2012. Water use by livestock: A global perspective for a regional issue? Animal Frontiers. 2:9–16. https://doi.org/10.2527/af.2012-0036.

Ecoinvent Centre. 2020. Ecoinvent database. Version 3.6. Ecoinvent Centre, Zurich, Switzerland. https://www.ecoinvent.org/database/database.html

EDGAR. 2020. Emissions database for global atmospheric research. Joint Research Center, EU Science Hub. https://edgar.jrc.ec.europa.eu/overview.php?v=432_AP. (Accessed 29 March 2020).

FAO. 2011. Global food losses and food waste: Extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/a-i2697e.pdf. (Accessed 15 June 2020).

FAO. 2012. Energy-smart food at FAO: An overview. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/an913e/an913e00.htm. (Accessed 15 June 2020).

FAO. 2016. Environmental performance of large ruminant supply chains: Guidelines for assessment. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/a-i6494e.pdf. (Accessed 15 June 2020).

FAO. 2018. Water use of livestock production systems and supply chains: Guidelines for assessment. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/I9692EN/i9692en.pdf. (Accessed 15 June 2020).

FAO. 2020. FAOSTAT [corporate statistical database]. Food and Agriculture Organization of the United Nations, Rome, Italy.

Ferm, M. 1998. Atmospheric ammonia and ammonium transport in Europe and critical loads: A review. Nutr. Cycl. Agroecosys. 51:5–17. https://doi.org/10.1023/A:1009780030477.

Gerbens-Leenes, P. W., M. M. Mekonnen, and A. Y. Hoekstra. 2013. The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. Water Resources and Industry. 1–2:25–36. https://doi.org/10.1016/j.wri.2013.03.001.

Gerber, P. J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio. 2013. Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Greenwood, D., K. Zhang, H. Hilton, and A. Thompson. 2010. Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology. J. Agr. Sci. 148:1–16. https://doi.org/10.1017/S0021859609990487.

Groenestein, C. M., M. C. J. Smits, J. F. M. Huijsmans, and O. Oenema. 2011. Measures to reduce ammonia emissions from livestock manures; now, soon and later. Report 488. Livestock Research, Wageningen UR. https://core.ac.uk/reader/29232320. (Accessed 15 June 2020).

Harmon, J. D., and D. Petersen. 2011. Farm energy: Indoor lighting for livestock, poultry, and farm shop facilities. Agriculture and Environment Extension Publications. 32. Iowa State University Extension and Outreach, Ames, IA. http://lib.dr.iastate.edu/extension_ag_pubs/32. (Accessed 15 June 2020).

Hatfield, J. L., and C. Dold. 2019. Water use efficiency: Advances and challenges in a changing climate. Front. Plant Sci. 10:103. https://doi.org/10.3389/fpls.2019.00103.

Heller, M. 2017. Food product environmental footprint literature summary: Pork. Report by: Center for Sustainable Systems, University of Michigan. Oregon Dept. of Environmental Quality. https://www.oregon.gov/deq/FilterDocs/PEF-Pork-FullReport.pdf. (Accessed 15 June 2020).

Herrero, M., P. Havlík, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Blümmel, F. Weiss, D. Grace, and M. Obersteiner. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. P. Natl. Acad. Sci.-Biol. 110:20888–20893. https://doi.org/10.1073/pnas.1308149110.

Hitaj, C., and S. Suttles. 2016. Trends in U.S. agriculture's consumption and production of energy: Renewable Power, Shale Energy, and Cellulosic Biomass. EIB-159, U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/74658/60128_eib159.pdf?v=0. (Accessed 15 June 2020).

Hristov, A. N., M. Hanigan, A. Cole, R. Todd, T. A. McAllister, P. M. Ndegwa, and A. Rotz. 2011. Review: Ammonia emissions from dairy farms and beef feedlots. Can. J. Anim. Sci. 91:1–35. https://doi.org/10.4141/CJAS10034.

Hristov, A. N., J. Oh, F. Giallongo, T. W. Frederick, M. T. Harper, H. L. Weeks, A. F. Branco, P. J. Moate, M. H. Deighton, S. R. O. William, M. Kindermann, and S. Duval. 2015. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. P. Natl. Acad. Sci. USA. 112:10663–10668. https://doi.org/10.1073/pnas.1504124112.

Hristov, A. N., T. Ott, J. Tricarico, A. Rotz, G. Waghorn, A. Adesogan, J. Dijkstra, F. Montes, J. Oh, E. Kebreab, S. Oosting, P. J. Gerber, B. Henderson, H. P. S. Makkar, and J. Firkins. 2013. Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. J. Anim. Sci. 91:5095–5113. https://doi.org/10.2527/jas.2013-6585.

Hsu, K., J. Kazer, and T. Cumberlege. 2018. Quorn footprint comparison report. Carbon Trust Advisory Limited, London. https://www.quorn.se/files/content/Carbon-Trust-Comparison%20Report-2018.pdf. (Accessed 15 June 2020).

IPCC. 2006. Guidelines for national greenhouse inventories. Vol. 4: Agriculture, forestry and other land use. Task Force on National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html. (Accessed 15 June 2020).

IPCC. 2014. Summary for policymakers. In: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S.

ISO. 2006. International Standard 14044, Environmental management—Life cycle assessment—Requirements and guidelines. International Organization for Standardization. https://www.iso.org/standard/38498.html. (Accessed 15 June 2020).

Jawad, H. M., R. Nordin, S. K. Gharghan, A. M. Jawad, and M. Ismail. 2017. Energy-efficient wireless sensor networks for precision agriculture: A review. Sensors-Basel. 17:1781. https://doi.org/10.3390/s17081781.

Jayanegara, A., K. A. Sarwono, M. Kondo, H. Matsui, M. Ridla, E. B. Laconi, and Nahrowi. 2018. Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: A meta-analysis. Ital. J. Anim. Sci. 17:650–656. https://doi.org/10.1080/1828051X.2017.1404945.

Kalhor, T., A. Rajabipour, A. Akram, M. Sharifi. 2016. Environmental impact assessment of chicken meat production using life cycle assessment. Information Processing in Agriculture. 3:262–271. https://doi.org/10.1016/j.inpa.2016.10.002.

Kim, D., N. Stoddart, C. A. Rotz, K. Veltman, L. Chase, J. Cooper, P. Ingraham, R. C. Izaurralde, C. D. Jones, R. Gaillard, H. A. Aguirre-Villegas, R. A. Larson, M. Ruark, W. Salas, O. Jolliet, G. J. Thoma. 2019. Analysis of beneficial management practices to mitigate environmental impacts in dairy production systems around the Great Lakes. Agr. Syst. 176:1–12. https://doi.org/10.1016/j.agsy.2019.102660.

Koech, R., and P. Langat. 2018. Improving irrigation water use efficiency: A review of advances, challenges and opportunities in the Australian context. Water-Sui. 10:1771. https://doi.org/10.3390/w10121771.

Legesse, G., K. A. Beauchemin, K. H. Ominski, E. J. McGeough, R. Kroebel, D. MacDonald, S. M. Little, and T. A. McAllister. 2015. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Anim. Prod. Sci. 56:153–168. https://doi.org/10.1071/AN15386.

Leinonen, I., A. G. Williams, J. Wiseman, J. Guy, and I. Kyriazakis. 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Egg production systems. Poultry Sci. 91:26–40. https://doi.org/10.3382/ps.2011-01635.

López-Andrés, J., A. Aguilar-Lasserre, L. Morales-Mendoza, C. Azzaro-Pantel, J. Pérez-Gallardo, and J. Rico-Contreras. 2018. Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms. J. Clean. Prod. 174:477–491. https://doi.org/10.1016/j.jclepro.2017.10.307.

Lynch, J. 2019a. Agricultural methane and its role as a greenhouse gas. Food Climate Research Network, University of Oxford. https://foodsource.org.uk/building-blocks/agricultural-methane-and-its-role-greenhouse-gas. (Accessed 15 June 2020).

Lynch, J. 2019b. Availability of disaggregated greenhouse gas emissions from beef cattle production: A systematic review. Environ. Impact Asses. 76:69–78. https://doi.org/10.1016/j.eiar.2019.02.003.

MacLeod, M., P. Gerber, A. Mottet, G. Tempio, A. Falcucci, C. Opio, T. Vellinga, B. Henderson, and H. Steinfeld. 2013. Greenhouse gas emissions from pig and chicken supply chains: A global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/3/i3460e/i3460e.pdf. (Accessed 15 June 2020).

Madrid, J., S. Martínez, C. López, J. Orengo, M. J. López, and F. Hernández. 2012. Effects of low protein diets on growth performance, carcass traits and ammonia emission of barrows and gilts. Anim. Prod. Sci. 53:146–153. https://doi.org/10.1071/AN12067.

Malomo, G. A., S. A. Bolu, A. S. Madugu, and Z. S. Usman. 2018. Nitrogen emissions and mitigation strategies in chicken production. In: B. Yücel, and T. Ta kin, editors, Animal husbandry and nutrition. Intech Open. p. 43–61.

Mitra, B. K., S. Sahin, A. Markandya, and N. Pham. 2017. Improving irrigation water use efficiency holds the key to tackling water scarcity in South Asia: Technical potential and financing options. Institute for Global Environmental Strategies (IGES) Policy Brief. p. 1–12.

Mogensen, L., J. Hermansen, N. Halberg, R. Dalgaard, J. C. Vis, and B. G. Smith. 2009. Life cycle assessment across the food supply chain, Chapter 5. In: Baldwin, C. J., editor, Sustainability in the food industry. IFT Press. Wiley-Blackwell. p. 115–144.

Montes, F, R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, G. Waghorn, P. J. Gerber, B. Henderson, H. P. S. Makkar, and J. Dijkstra. 2013. SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. J. Anim. Sci. 91:5070–5094. https://doi.org/10.2527/jas.2013-6584.

Musser, W. N., D. M. Lambert, and S. G. Daberkow. 2006. Factors affecting direct and indirect energy use in U.S. corn production, 2006 Annual Meeting of the American Agricultural Economics Association, July 23–26, Long Beach, CA.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, B. Robock, G. Stephens, T. Takemura, and H. Zhang. 2013. Anthropogenic and natural radiative forcing. In: T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, eds, Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Nahm, K. H. 2007. Feed formulations to reduce N excretion and ammonia emission from poultry manure. Bioresource Technol. 98:2282–2300. https://doi.org/10.1016/j.biortech.2006.07.039.

NASA. 2019. The carbon cycle. National Aeronautics and Space Administration, Earth Observatory. https://earthobservatory.nasa.gov/features/CarbonCycle. (Accessed 15 June 2020).

NASS. 2020. Quick Stats 2.0. National Agricultural Statistics Service, US Department of Agriculture. http://quickstats.nass.usda.gov. (Accessed 15 June 2020).

Ndegwa, P. M., A. N. Hristov, J. Arogo, and R. E. Sheffield. 2008. A review of ammonia emissions mitigation techniques for concentrated animal feeding operations. In: E. Muhlbauer, L. Moody, and R. Burns, eds, Mitigating air emissions from animal feeding operations. Iowa State University. p. 266–283. https://store.extension.iastate.edu/Product/Mitigating-Air-Emissions-Conference-Proceedings-pdf#page=275. (Accessed 15 June 2020).

NOAA. 2020. Trends in atmospheric methane. Earth Systems Research Laboratory, National Oceanic & Atmospheric Administration. https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/#global_growth. (Accessed 15 June 2020).

NRC. 2003. Air emissions from animal feeding operations: Current knowledge, future needs. Ad Hoc Committee on Air Emissions from Animal Feeding Operations, National Research Council, Washington, DC.

OECD/FAO. 2018. OECD-FAO Agricultural Outlook 2018–2027. OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/I9166EN/I9166EN.pdf. (Accessed 15 June 2020).

OpenLCA. 2020. Open LCA software. Version 1.10. GreenDelta GmbH, Berlin, Germany. http://www.openlca.org/.

Paulot, F., D. J. Jacob, J. O. Bash, K. Travis, and D. K. Henze. 2014. Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH3). U.S. Environmental Protection Agency Papers. 229. http://digitalcommons.unl.edu/usepapapers/229. (Accessed 15 June 2020).

Pelletier, N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agr. Syst. 103:380–389. https://doi.org/10.1016/j.agsy.2010.03.009.

Putman, B., J. Hickman, P. Bandekar, M. Matlock, and G. Thoma. 2018. A retrospective assessment of US pork production: 1960 to 2015, Final Report. University of Arkansas, Fayetteville, AR.

Rotz, C. A. 2004. Management to reduce nitrogen losses in animal production. J. Anim. Sci. 82:E119–E137. https://doi.org/10.2527/2004.8213_supplE119x.

Rotz, C. A., S. Asem-Hiablie, S. Place, and G. Thoma. 2019. Environmental footprints of beef cattle production in the United States. Agr. Syst. 169:1–13. https://doi.org/10.1016/j.agsy.2018.11.005.

Rotz, C. A., B. J. Isenberg, K. R. Stackhouse-Lawson, and J. Pollak. 2013. A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. J. Anim. Sci. 91:5427–5437. https://doi.org/10.2527/jas.2013-6506.

Rotz, C. A., P. J. A. Kleinman, C. J. Dell, T. L. Veith, and D. B. Beegle. 2011. Environmental and economic comparisons of manure application methods in farming systems. J. Environ. Qual. 40:438–448. https://doi.org/10.2134/jeq2010.0063.

Rotz, C. A., F. Montes, S. D. Hafner, A. J. Heber, and R. H. Grant. 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43:1143–1158. https://doi.org/10.2134/jeq2013.04.0121.

Rotz, C. A., J. Oenema, and H. van Keulen. 2006. Whole farm management to reduce nitrogen losses from dairy farms: A simulation study. Appl. Eng. Agric. 22:773–784. https://doi.org/10.13031/2013.21992.

Rotz, C. A., and G. Thoma. 2017. Assessing the carbon footprint of dairy production systems. In: D. K. Beede, editor, Large dairy herd management, 3rd edition. Am. Dairy Sci. Assoc., Champaign, IL. p. 19–31.

Rotz, C. A., and T. L. Veith. 2013. Integration of air and water quality issues, Chapter 10. In: Kebreab, E., editor, Sustainable animal agriculture. CAB International, Oxfordshire, UK. p. 137–156.

Saarinen, M., M. Fogelholm, R. Tahvonen, and S. Kurppa. 2017. Taking nutrition into account within the life cycle assessment of food products. J. Cleaner Prod. 149:828–844.

Sajeev, E. P. M., B. Amon, C. Ammon, W. Zollitsch, and W. Winiwarter. 2018. Evaluating the potential of dietary crude protein manipulation in reducing ammonia emissions from cattle and pig manure: A meta-analysis. Nutr. Cycl. Agroecosys. 110:161–175.

Saling, P., A. Kicherer, B. Dittrich-Krämer, R. Wittlinger, W. Zombik, I Schmidt, W. Schrott, and S. Schmidt. 2002. Eco-efficiency analysis by BASF: The method. Int. J. Life Cycle Ass. 7:203–218.

Schlömer, C. von Stechow, T. Zwickel, and J. C. Minx, eds., Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, US.

SimaPro. 2020. SimaPro [software]. PRé Consultants, Amersfoort, the Netherlands.

Skunca, D., I. Tomasevic, I. Nastasijevic, V. Tomovic, and I. Djekic. 2018. Life cycle assessment of the chicken meat chain. J. Clean. Prod. 184:440–450. https://doi.org/10.1016/j.jclepro.2018.02.274.

Stackhouse-Lawson, K. R., C. A. Rotz, J. W. Oltjen, and F. M. Mitloehner. 2012a. Carbon footprint and ammonia emissions of California beef production systems. J. Anim. Sci. 90:4641–4655. https://doi.org/10.2527/jas.2011-4653.

Stackhouse-Lawson, K. R., C. A. Rotz, J. W. Oltjen, and F. M. Mitloehner. 2012b. Growth-promoting technologies decrease the carbon footprint, ammonia emissions, and costs of California beef production systems. J. Anim. Sci. 90:4656–4665. https://doi.org/10.2527/jas.2011-4654.

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. http://www.fao.org/3/a0701e/a0701e.pdf. (Accessed 15 June 2020).

Stenmarck, A., C. Jensen, T. Quested, and G. Moates. 2016. Estimates of European food waste levels. FUSIONS EU. https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf. (Accessed 15 June 2020).

Thoma, G., D. Nutter, R. Ulrich, C. Maxwell, J. Frank, and C. East. 2011. National lifecycle carbon footprint study for production of US swine. University of Arkansas, Fayetteville, AR. https://porkcdn.s3.amazonaws.com/sites/all/files/documents/NPB%20Scan%20Final%20-%20May%202011.pdf. (Accessed 15 June 2020).

Todd, R. W., N. A. Cole, M. B. Rhoades, D. B. Parker, and K. D. Casey. 2011. Daily, monthly, seasonal, and annual ammonia emissions from Southern High Plains cattle feedyards. J. Environ. Qual. 40:1090–1995. https://doi.org/10.2134/jeq2010.0307.

USDA-ARS. 2020. Integrated farm system model. Pasture Systems and Watershed Mgt. Research Unit, US Department of Agriculture Agricultural Research Service, University Park, PA. https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model/. (Accessed 15 June 2020).

USEPA. 2019. 2014 national emissions inventory report. U.S. Environmental Protection Agency, Washington, D.C. https://gispub.epa.gov/neireport/2014/. (Accessed 15 June 2020).

USEPA. 2020a. Greenhouse gas emissions from a typical passenger vehicle. U.S. Environmental Protection Agency, Washington, D.C. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle. (Accessed 15 June 2020).

USEPA. 2020b. U.S. greenhouse gas emissions and sinks: 1990–2018. EPA 430-P-20-001. U.S.Environmental Protection Agency, Washington, D.C. https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf. (Accessed 15 June 2020).

Weidema, B. P., and K. S. Stylianou. 2019. Nutrition in the life cycle assessment of foods—Function or impact? Int. J. Life Cycle Ass. https://doi.org/10.1007/s11367-019-01658-y.

WHO. 2020. Global and regional food consumption patterns and trends. World Health Organization, Geneva. https://www.

who.int/nutrition/topics/3_foodconsumption/en/. (Accessed 15 June 2020).

Winkler, T, K. Schopf, R. Aschemann, and W. Winiwarter. 2016. From farm to fork—A life cycle assessment of fresh Austrian pork. J. Clean. Prod. 116:80–89. https://doi.org/10.1016/j.jclepro.2016.01.005.

Wuebbles, D. J., and K. Hayhoe. 2002. Atmospheric methane and global change. Earth-Sci. Rev. 57:177–210. https://doi.org/10.1016/S0012-8252(01)00062-9.

Yu, Y., and E. C. Jaenicke. 2020. Estimating food waste as household production inefficiency. Am. J. Agr. Econ. 102:525–547. https://doi.org/10.1002/ajae.12036.

Zaman, M., S. Saggar, J. D. Blennerhassett, and J. Singh. 2009. Effect of urease and nitrification inhibitors on N transformation, gaseous emissions of ammonia and nitrous oxide, pasture yield and N uptake in grazed pasture system. Soil Biol. Biochem. 41:1270–1280. https://doi.org/10.1016/j.soilbio.2009.03.011.