Agricultural Systems 169 (2019) 1–13

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Environmental footprints of beef cattle production in the United States

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ARTICLE INFO

Keywords:
Beef sustainability
Carbon footprint
Energy use
Life cycle assessment
Nitrogen footprint
Water consumption

ABSTRACT

The environmental impacts of beef cattle production and their effects on the overall sustainability of beef have become a national and international concern. Our objective was to quantify important environmental impacts of beef cattle production in the United States. Surveys and visits of farms, ranches and feedlots were conducted throughout seven regions (Northeast, Southeast, Midwest, Northern Plains, Southern Plains, Northwest and Southwest) to determine common practices and characteristics of cattle production. These data along with other information sources were used to create about 150 representative production systems throughout the country, which were simulated with the Integrated Farm System Model using local soil and climate data. The simulations quantified the performance and environmental impacts of beef cattle production systems for each region. A farm-gate life cycle assessment was used to quantify resource use and emissions for all production systems including traditional beef breeds and cull animals from the dairy industry. Regional and national totals were determined as the sum of the production system outputs multiplied by the number of cattle represented by each simulated system. The average annual greenhouse gas and reactive N emissions associated with beef cattle production over the past five years were determined to be 243 ± 26 Tg carbon dioxide equivalents (CO_2e) and 1760 ± 136 Gg N, respectively. Total fossil energy use was found to be 569 ± 53 PJ and blue water consumption was 23.2 ± 3.5 TL. Environmental intensities expressed per kg of carcass weight produced were 21.3 ± 2.3 kg CO_2e, 155 ± 12 g N, 50.0 ± 4.7 MJ, and 2034 ± 309 L, respectively. These farm-gate values are being combined with post farm-gate sources of packing, processing, distribution, retail, consumption and waste handling to produce a full life cycle assessment of U.S. beef. This study is the most detailed, yet comprehensive, study conducted to date to provide baseline measures for the sustainability of U.S. beef.

1. Introduction

The U.S. beef industry is a major contributor to the national and global food system and economy. Per capita domestic annual consumption was estimated at 25 kg with 20% of global supplies produced in the U.S. in 2015 (USDA-FAS, 2015; USDA-ERS, 2012). In addition to growing populations, increases in per capita meat consumption worldwide have been predicted (Alexandratos and Bruinsma, 2012). For the U.S. beef industry, this provides the potential for increased production to feed the growing domestic population while meeting expanding export markets.

Increasing productivity in an environmentally, economically, and socially sustainable manner in our complex U.S. beef production system is of concern to both producers and consumers. Quantifying the sustainability of beef is challenging, as the supply chain is one of the most multifaceted food systems in the world. A methodology has been developed to characterize beef production systems and to assess their performance and environmental impacts (Rotz et al., 2013; Asem-Hiablie et al., 2018a). Based upon regional cattle production data and national data for processing, packaging, transportation, retail and consumption, a comprehensive life cycle assessment is being conducted to quantify the sustainability of U.S. beef.

Our objective in this work was to quantify important environmental impacts of beef cattle production systems for each of seven regions of the U.S. and to use those regional assessments to determine national impacts of cattle production. This assessment is not intended to promote specific production practices or regional preferences over others, but rather to study the diverse management practices that have evolved in response to prevailing climate, available resources and culture of various regions of the country. Region-specific production data collection and footprint analysis, while necessary for ensuring representativeness at the national level, also helps identify unique opportunities

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https://doi.org/10.1016/j.agsy.2018.11.005
Received 31 May 2018; Received in revised form 8 November 2018; Accepted 11 November 2018
Available online 27 November 2018

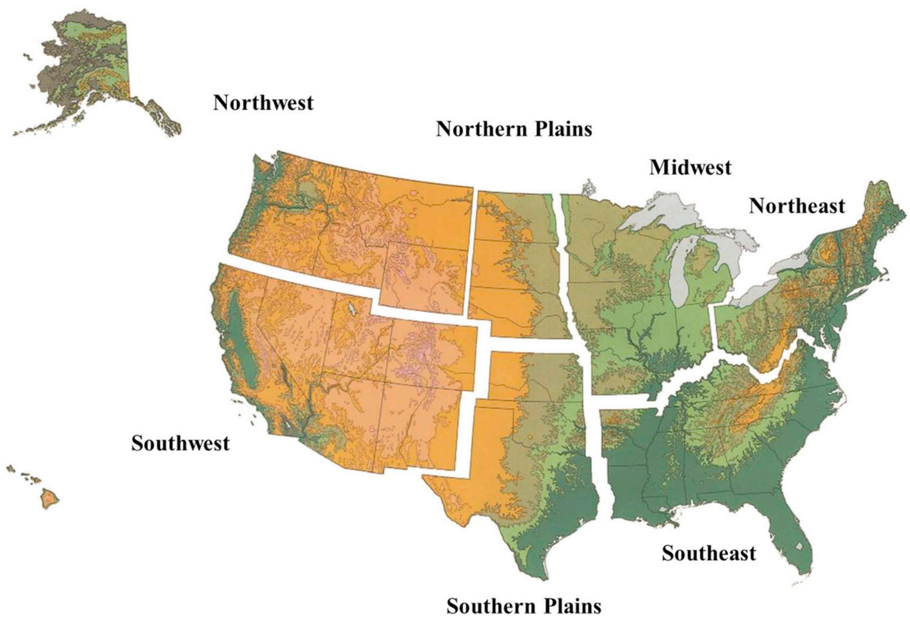

Fig. 1. Seven regions of the United States where surveys, visits, and simulation analyses were conducted to evaluate the environmental footprints of beef cattle production.

for improving sustainability in each region. By combining these cattle production data with post-harvest data, a full life cycle assessment can be completed.

2. Materials and methods

Beef production and management data were obtained for seven regions of the U.S. (Northeast, Southeast, Midwest, Northern Plains, Southern Plains, Northwest and Southwest; Fig. 1) through online surveys and site visits to farms, ranches, and feedlots (Asem-Hiablie et al., 2015, 2016, 2017, 2018b) and from the national agricultural statistics database (NASS, 2018). These regions were defined, primarily based upon climate and how the climate and resources (natural and man-made) affect the culture and management practices across the country. Survey and visit data from 2270 responding cattle operations included ranches and farms with various combinations of cow-calf, stocker and finishing cattle ranging in size from 1 to 28,500 cows and feedlots with capacities up to 115,000 cattle. Characteristics of operations varied widely across regions, with smaller operations and higher stocking rates in the wetter climate of the east to very large operations and low stocking rates in the more arid conditions of the west. Other important differences were in animal housing, on-farm feed production, and fertilizer and lime use.

For the purposes of this study, ranches are defined as any operation that predominantly included cattle on pasture or rangeland. This included cow-calf – to – finish operations where calves were weaned, raised and finished on the same operation. In some regions, these operations are referred to as farms, with a substantial amount of feed produced on site. For purposes of discussion here, we are including farms within the category of ranches. Feedlots are defined as operations where cattle were predominantly fed in confinement (open lot or barn) either for backgrounding on a high forage diet or finishing on a high concentrate diet. Although the terminology for operations varies, for consistency, we are using these terms to define our production systems.

2.1. Modeling procedure

To represent the wide range of operations found, representative beef cattle production systems were modeled using the Integrated Farm System Model (IFSM; USDA-ARS, University Park, PA). The IFSM is a process-level simulation tool used to assess the performance, environmental impacts and economics of cattle and feed production systems (Rotz et al., 2013, 2016). Feed production and intake, animal growth and performance, and the cycling of nutrients within the cattle production system are simulated for many years of weather. Nutrient movements are tracked to predict soil accumulation or attenuation and losses to the environment. Common paths of nitrogen (N) loss include ammonia (NH_3) volatilization, nitrous oxide (N_2O) emission through nitrification and denitrification processes, and leaching and runoff of nitrate (NO_3^-). Process-based simulation predicts volatilization on an hourly time step and nitrification, denitrification, leaching and runoff on a daily basis as influenced by temperature, wind speed, precipitation and soil and management characteristics (Rotz et al., 2014, 2016; Bonifacio et al., 2015).

Previous studies have evaluated and verified IFSM's accuracy in representing beef and dairy operations. Comparing IFSM simulations of feed production and intake, fossil energy use and production costs with actual records for the U.S. Meat Animal Research Center showed differences of < 1% during the study year of 2011 (Rotz et al., 2013). Numerous other studies have verified the model's ability to represent feed crop production, animal performance, emissions, and other components of the model (examples are Bonifacio et al., 2015; Waldrip et al., 2014; Rotz et al., 2014; Stackhouse-Lawson et al., 2012). To ensure that simulated operations in the current study were representative of their respective regions, further verification of IFSM's predictions of feed intake, resource inputs including fossil energy use, and animal performance were made through comparisons with survey and ranch visit data (Asem-Hiablie et al., 2015, 2016, 2017, 2018b).

Following guidelines of the Livestock Environmental Assessment and Performance partnership (LEAP, 2016), a cradle-to-farm gate partial LCA is performed to determine the annual carbon [net greenhouse gas (GHG)] emission, fossil energy use, blue (non-precipitation) water use, and reactive N loss. Carbon or GHG is the sum of all important emissions of methane (CH_4), N_2O and carbon dioxide (CO_2) converted to carbon dioxide equivalents (CO_2e). These include both the direct emissions coming from the production system as well as the indirect N_2O emissions that occur elsewhere in the environment resulting from a transformation of NH_3 and NO_3^- lost from the production system (IPCC, 2006a). Fossil energy use includes that of fuels and electricity used in farm and ranch operations, transport vehicles, irrigation and

Table 1
Emission or use factors for production of purchased resources and feeds, including transport and upstream sources, used in IFSM to determine cradle-to-farm gate footprints of beef cattle production systems.

Resource	Unit	Greenhouse gas emission, kg CO_2e	Fossil energy use, MJ	Blue water use, L	Reactive N loss, g N
Energy[a]					
Fuel	/L	0.522	4.01	–	0.48
Natural gas	/m^3	0.668	2.46	–	0.26
Electricity	/kWh	0.629	5.00	–	0.27
Fertilizer[a]					
Nitrogen	/kg N	3.11	62.4	–	0.91
Phosphate	/kg P_2O_5	1.84	32.5	–	1.87
Potash	/kg K_2O	1.30	18.4	–	0.53
Lime[a]	/t	14	190	–	9.0
Machinery[b]	/kg mass	3.54	42.6	–	1.22
Seed[c]	/kg	0.30	85.0	2.0	3.0
Pesticide[b]	/kg a.i.	22.0	275	–	11
Plastic wrap[d]	/kg	2.0	50.0	–	–
Purchased feed					
Corn[c]	/kg DM	0.30–0.35	3.58–3.7	3–280	4.5–2.06
Alfalfa hay[c]	/kg DM	0.18–0.23	1.2–2.30	1–900	0.38–0.93
Grass hay[c]	/kg DM	0.15	2.00	0–300	0.2
Dry distiller's grain[e]	/kg DM	0.41	4.40	180	2.6
Corn gluten[e]	/kg DM	0.33–0.35	3.99	3.0	2.06
Soybean meal[e]	/kg DM	0.41–0.43	4.39–4.97	36–616	1.2–3.3
Protein mix[f]	/kg DM	1.02	10.2	300	1.0
Byproduct waste[g]	/kg DM	0.0	0.0	0.0	0.0
Fat[f]	/kg DM	1.52	12.2	50	1.0
Mineral and vitamin mix[f]	/kg DM	1.62	16.2	60	0.0
Milk replacer[h]	/kg DM	12.1	58.1	1450	45.0

[a] Obtained from BASF's Eco-efficiency analysis tool representative of U.S. national values (BASF, Ludwigshafen, Germany).
[b] Obtained from the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne National Laboratory, Argonne, IL).
[c] Obtained from simulated crop farms in each region using the Integrated Farm System Model (USDA/ARS, 2018).
[d] Rotz et al. (2010).
[e] Derived from simulations of corn and soybean crop farms in each region using the Integrated Farm System Model (USDA/ARS, 2018) and processing resource use with an economic allocation among the coproducts of the grains produced.
[f] Unpublished data (Greg Thoma, University of Arkansas, Fayetteville, AR).
[g] Use of a waste material has no environmental burden.
[h] Derived from Kim et al. (2013).

feed processing. Blue water is primarily that used for irrigating crops and includes that for drinking and sprinkling for dust control on feedlots. Reactive N is the sum of all N leaving the production system in the forms of NH_3, N_2O, NO_3^- and NOx. These environmental impacts are presented as an intensity metric expressed per unit of carcass weight produced. Emissions associated with the production of resources used on cattle operations (upstream sources) are included in the LCA. Upstream sources include the production of fuel, natural gas, electricity, fertilizer, purchased feed, machinery, seed and pesticide. Emission or use values used for these upstream sources are listed in Table 1. Estimates of upstream impact contributions for purchased corn and forage were obtained using IFSM simulations of crop farms in each region where the environmental impacts were divided by the feed produced and added to that associated with transport of the feeds.

Emission and resource use factors for commonly used by-product feeds were determined using IFSM simulations of cropping systems in each region with allocation among coproducts of grains produced (Table 1). Economic (or revenue) allocation for the partitioning of upstream contributions of these products was based on prevailing market prices and the mass ratio of each produced. For example, as dry distillers grains (DDG) is a by-product of ethanol production from corn, the allocation factor was 78.5% for ethanol and 21.5% for DDG. Corn milling products and their respective economic allocations were starch (75.4%), corn oil (5.3%), corn gluten feed (11.6%), and corn gluten meal (7.6%). Soybean products were partitioned between soy hulls, soybean meal, and soy oil with allocations of 1.8%, 60.4%, and 37.9%, respectively. Environmental factors assumed for milk replacer, whose primary ingredient is whey, were estimated based upon the work of Kim et al. (2013). To determine reactive N loss, economic allocation was used to attribute 25% of whole milk's footprint to the whey by-product, which provided a value of 45 g N/kg dry matter of whey powder.

Compared to most previous studies, an important change was made in calculating GHG emissions. The global warming potential (GWP) values for CH_4 and N_2O were updated to the latest 100-year values recommended by the Intergovernmental Panel on Climate Change (IPCC; Myhre et al., 2013). The GWP for CH_4 was increased to 28, and this value considered the removal of carbon dioxide (CO_2) from the atmosphere to create CH_4. The GWP for N_2O was decreased to 265. The net effect was about a 9% increase in our calculated carbon dioxide equivalent (CO_2e) for beef cattle production compared to our previous studies.

The analysis of beef cattle production was conducted in three major steps. First, individual operations, which represented farm, ranch and finishing operations across each region, were developed and simulated. Next, those individual operations were linked to form full production systems for each region. Finally, the regional data were integrated to determine the environmental impacts of all cattle production in the U.S.

2.1.1. Representative cattle operations

Ranch, farm and feedlot operations were modeled to represent the wide range in size and production practices found across the country. These included 150 beef operations consisting of cow-calf, cow-calf and stocker, cow-calf – to – finish, stocker, backgrounding feedlot and finishing operations. An all grass cow-calf – to – finish operation was included as a minor component in the eastern and northwestern regions. At least 20 and no > 28 cattle operations were modeled in each region along with 1–2 dairy farms and a dairy-breed calf-rearing facility. Eighteen crop farms were also modeled throughout regions to produce the alfalfa, corn, soybeans and small grain feeds purchased by the cattle operations. This number represented a balance between getting a good representation of the production systems used in each region and maintaining a reasonable number of simulations.

All important cattle producing states were represented. In the Northern and Southern Plains, the states (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma and Texas) were divided into eastern, central and western areas with operations in each, primarily because of the large decrease in annual precipitation found moving from east to west and the resulting effects on management (Asem-Hiablie et al., 2015, 2016). These were also among the most important cattle producing states, and this provided better representation of these regions. The modeled ranches and feedlots were distributed across states and these areas to assure representation of climatic, edaphic and management differences.

The modeled operations were not intended to be actual operations; they were developed to represent the practices found in each region. These representative operations were created considering data and information collected through our regional surveys and visits of cattle operations (Asem-Hiablie et al., 2015, 2016, 2017, 2018b) and other available information. The survey and visit data provided information on the distribution and size of operations for the region along with other information such as feed crops grown, cropping practices, grazing strategies, hay making, tillage and manure handling practices, and supplemental feeding. Modeled operations were developed to represent the range in size and management practices observed in the survey and visit data. The number of each type of operation (cow-calf, stocker, finish and various combinations) modeled were generally set in proportion to that found through the survey of the region. Other practices were also set in relation to that found in the region as much as possible, considering the limited number of operations simulated. Brief descriptions of each modeled beef and dairy operation are provided in Tables S1, S2 and S3 of the supplementary information.

A major difference across the regions was a decrease in stocking rate or increase in grazing area allotted per animal moving from east to west. The greater precipitation in the eastern and Midwestern regions enabled greater forage and feed production per unit of land. Fertilizer and lime use also varied with greater use of both in the east and Midwest with little fertilizer and essentially no lime used in the western regions. More on-farm supplemental feed production was found across the northern regions.

Surveys reported that hay was made from harvested pasture forage for feeding during non-grazing seasons in most regions, but not on all operations. Therefore, haymaking was used in most ranch simulations (Tables S1). Hay area was set to provide the amount of forage needed to complete the forage required by the herd on the simulated ranch, i.e. land areas were set to avoid long-term sale of hay. Energy and protein supplement feeds were fed as needed to meet cattle requirements. Simulated quantities used were compared to those reported (Asem-Hiablie et al., 2015, 2016, 2017, 2018b) to ensure proper representation of feed use. When corn or alfalfa were produced on the ranch or farm, the amount produced often exceeded that needed to feed the cattle. In our simulations, the cultivated area of each crop was set to meet long-term average needs of the herd to provide separation between feed production for on-farm use and that for cash crop sales.

Equipment types and numbers used on ranches were based on herd sizes and the feed crops grown on the operation (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). One pickup or utility truck was adequate for smaller ranches while up to 3 were used on larger operations. Each ranch normally included 2 tractors, but one was used on the smallest operations and 3 or 4 were used on the largest. Hay equipment was included on ranches where hay was produced. On operations that produced corn, small grains or alfalfa, appropriately sized tillage, planting and harvesting equipment were included. Hours of machinery use were predicted by IFSM based on the size of the ranch and the types of machinery operations performed. No custom hired operations were used to assure that the model included all machinery and energy use required by the production system. Horses were often found on cattle operations, but the number of horses used was small compared to the cattle produced (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). Thus, their emissions were ignored as contributing < 1% of total impacts.

Feedlots varied in size, finishing 100 to 100,000 cattle per year with the largest operations located in the Southern Plains. For each location, sizes were set to reflect reported industry survey numbers (Asem-Hiablie et al., 2015, 2016, 2017, 2018b) as well as published agricultural statistics data (NASS, 2018). The operations included backgrounding-only feedlots (primarily in the northern regions), feedlots that only finished cattle, and feedlots where cattle were backgrounded and finished. Backgrounding and finishing periods each varied from 4 to 6 months among feedlots. Operations that finished only Holstein cattle from the dairy industry were included in most regions. Prior to the feedlot, these Holstein calves were maintained on a calf ranch where they were weaned from an all-milk replacer diet to a forage and concentrate diet over a 4-month period. After transfer to the feedlot, the cattle were backgrounded and finished over a 13-month period.

Open lot housing was normally used in most regions, but barns were often used in the Midwest and Northeast (Table S2). Average finish weights (including heifers and steers) varied between 600 and 632 kg. Cattle were treated with growth implants and ionophores on operations in proportion to the number of treated cattle found through our survey and visit data (Asem-Hiablie et al., 2015, 2016, 2017, 2018b).

Corn, alfalfa and grass areas were set to meet herd needs on operations where they were produced. Most of the cattle manure was applied to cropland producing feed, but some was exported, particularly on the large operations. Manure use was set following the information gathered through our survey and visit data (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). Inorganic fertilizer was used to meet crop needs beyond that supplied by manure nutrients. This allowed the cattle production systems to benefit from the manure nutrients recycled in feed production.

Based upon the information gathered through site visits, equipment used on feedlots included feed wagons or trucks, loaders, tractors, pickups and cattle trucks, and an array of tillage, planting and harvest equipment where feed crops were produced (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). Feeding normally used 1 mixer wagon to feed up to 10,000 cattle or feed truck for up to 25,000 cattle. Feed handling was done with 1 or 2 skid-steer loaders on smaller lots with up to 3 payloaders on the largest lots. Two or three tractors were used on smaller lots with 4 or more on larger lots, particularly those producing feed crops. Pickup and/or cattle truck use varied from 1 on the smaller operations up to 5 on the largest. Appropriately sized tillage, planting and harvest equipment were used to produce the feed crops grown on each operation. No-till systems were primarily used in most regions with minimum tillage systems most often used in the Midwest (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). Irrigation equipment was often used on operations in the western regions.

The impacts of transporting animals between production phases was estimated independent of IFSM simulations (Rotz et al., 2015). The estimated round trip fuel use of 0.000033 l/(km kg BW) and associated carbon emission of 0.088 g CO_2e/(km-kg BW) were based on assumptions of a semi-trailer truck with a capacity of 24,000 kg BW and fuel efficiency of 2.6 km/l. Average round trip hauling distances (generally varying from 200 to 500 km) were assumed for cattle produced in each state. Previous studies showed that transportation contributed < 1% to the total fossil energy use and other environmental footprints, implying no need for more accurate calculations (Rotz et al., 2015).

Each ranch or feedlot was simulated using 25 years of local historical weather. Weather for each location consisted of daily mean, maximum, and minimum temperatures, solar radiation, precipitation and wind speed data determined as described by Rotz et al. (2015). Weather stations were selected for locations within the locale where cattle were being produced and where relatively complete weather data sets were available. Table S4 shows a summary of each location's weather. Annual precipitation decreased moving from east to west and ambient temperatures increased moving from North to South. There was also a slight trend toward greater wind speed in western regions.

Soil characteristics were set for each location based upon Web Soil Survey data (NRCS, 2018). Predominant soils were identified for each area or state. From these predominant soils, typical physical characteristics were defined (Table S5), which were used in the simulation of each ranch and feedlot in the designated area.

Twenty-five year simulations provided long-term values for the various resource inputs, emissions to water and air as well as crop and animal productivity as affected by climate. Predicted emissions or losses of N and P represented all of those coming from the land used to produce forage and feed for the cattle. Because losses would occur without cattle on the land, we estimated the additional emissions due to the animals. This was done by simulating each cattle operation with all land in permanent pasture or range without soil amendments and without cattle. These baseline emissions or losses were subtracted from those obtained by simulating each representative operation with all management practices implemented. This procedure provided consistency with that recommended by the IPCC (2006a) where only those emissions associated with the cropping practices and management of cattle were included in the analysis.

2.1.2. Representative production systems

Environmental footprints for all individually simulated ranch and feedlot operations were integrated into full production systems within their respective study regions using two methods (Rotz et al., 2015). In the first method, simulation results for individual operations, expressed per kg of carcass weight (CW) were averaged for each of the three phases of cow-calf, stocker or backgrounding, and finishing. The sum of each environmental impact across the three phases provided the production system's full footprint. This was primarily used to show the breakdown or distribution across these three major phases of cattle production. With the second method, environmental footprints were determined representing the mean and range of various production systems found within each region. Combinations of cow-calf, cow-calf and stocker, and feedlot operations were linked to form full production systems. Cow-calf – to – finish operations were also included. For this step, the emphasis was on the impacts of representative full cattle production systems in each region. This analysis included transport of cattle between operations up to cattle leaving the finish operation for harvest.

The main environmental impacts estimated and reported per unit CW for each simulated operation were net GHG emissions (CH_4, N_2O and CO_2 as direct sources and NH_3 and NO_3^- as indirect sources), fossil energy use, blue water use and reactive N loss (total NH_3, N_2O, NO_3^- and NOx). Carcass weight was the total cull and finished cattle weights produced by each system multiplied by their corresponding dressing percentages. Assumptions related to determining the annual cull animal weights were an 11% herd replacement rate (NASS, 2018), 2% mortality rate (NASS, 2018) and 50% dressing percentage (Stackhouse-Lawson et al., 2012). For calves produced, the final CW was estimated as the projected number of calves finished multiplied by their finish weights and an assumed dressing percentage of 62% (Stackhouse-Lawson et al., 2012; NASS, 2018). In estimating the number of calves exiting the cow-calf phase annually, an average annual calving percentage of 88% (NASS, 2018) was assumed and replacements retained were removed from that number. The projected number of finished cattle assumed an annual post-weaning mortality rate of 2.5% (Estimated through NASS (2018) cattle numbers and other unpublished sources).

When determining the mean environmental impacts of production systems of each region, values from all production systems were weighted in proportion to their contribution to the total cattle produced. The sum of two weighting factors was used for ranches: an operation factor and a location factor. The operation weight factor was determined as the ratio of cattle produced in a simulated production system to that reported in our industry survey as being produced in that type of system (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). Although the simulated systems were generally set in proportion to that found in the survey, some differences occurred due to the limited number of production systems modeled. This weighting helped assure that each type of production system appropriately represented those found in the region. The location factor was determined from agricultural statistics data (NASS, 2018). This factor was the total number of cows represented by the simulated operations relative to the number of cows in that area or state. For feedlots, only the location factor was used, which was based upon finished cattle numbers.

There was a substantial number of Holstein cattle from the dairy industry providing beef in most regions. Dairy farms were simulated in those regions and the total environmental impacts of each farm were allocated between milk and cattle leaving the farm using a biophysical allocation (IDF, 2010). The number of dairy cows culled for beef was estimated from the number of dairy cattle in each region, with the assumptions of 37% annual replacement and 5% mortality rate, respectively (NASS, 2018). The environmental footprints of cows exiting a dairy farm were determined by IFSM simulations of dairy operations and the biophysical allocation. To express the results per unit of CW, a dressing percentage of 50% was used (Stackhouse-Lawson et al., 2012).

The environmental impact of Holstein steers was obtained by simulating a calf ranch with IFSM where calves were mostly fed milk replacer for the first 2 months. The environmental impact of other feed and resource inputs into the production system were accounted for as well. Environmental footprints for Holstein calves were obtained from the dairy farm simulations using the same allocation method used for cows where the allocation between cows and calves was based upon the BW of each leaving the farm. The impacts for creating the calf were added to those of feedlot finishing providing values for the full production system of Holstein beef. Holstein mortality rates were 10% for calves and 2.5%/yr for weaned and growing cattle (estimated through NASS (2018) cattle numbers and other unpublished sources).

Environmental impacts of beef produced in each region were then adjusted to account for those of incoming dairy cattle. Adjustment for Holstein steers was done by applying the ratio of Holstein over total cattle finished as a weighting factor. The portion of Holsteins finished in each region was estimated from the number of Holstein calves born in a region (Tables S6 and S7) and our industry survey data for the portion of Holstein cattle found on feedlots (Asem-Hiablie et al., 2015, 2016, 2017, 2018b). The CW for Holstein steers was 59% of finished BW (Stackhouse-Lawson et al., 2012). Adjustments to account for cull dairy cows were based on the ratio of cull dairy cows slaughtered (32% of dairy cow inventory) and cattle finished annually in each region (NASS, 2018).

2.1.3. National cattle production

A national analysis was done using NASS (2018) animal and production data and the environmental footprints of cattle production determined through the regional analyses. Annual cattle inventory numbers, including dairy cows, beef cows, calves (both dairy and beef) and finished cattle (cattle sold for slaughter) were obtained for each state from NASS (2018). Other annual data obtained from NASS (2018) included national values for dairy cows slaughtered, beef cows slaughtered, total cattle slaughtered, dressed slaughter weights for different cattle groups, and total carcass weight produced. Longer-term average values were used by finding the mean over the 5-yr period of 2013–2017 (Table S6).

Calves and growing cattle used for beef were estimated using national agricultural statistics and survey data. Total calves were divided between dairy breeds and traditional beef breeds by assuming that about half of the calves produced by dairy cows and 89% of those from beef breeds entered a finished cattle production system. The remaining 11% of the beef breed calves were used as replacement heifers. Values determined for each state were uniformly adjusted to provide the total national number of calves required for beef production (Tables S6 and S7). Cattle in the intermediate phase of stocker or backgrounding were estimated from our survey data (Asem-Hiablie et al., 2015, 2016, 2017, 2018b) to meet the number required for finishing. From the survey data, a ratio was determined for the number of stocker or backgrounding cattle found in each region to the number of beef cows. This regional number was multiplied by the number of cows in each state and state values were totaled for a national value. This national total provided an overestimate compared to the reported number finished, so all state values were reduced by the same proportion to give a total national number about 2% greater than those finished and 2% less than the calves produced. These 2% differences account for mortalities and other losses as the cattle move through these phases (Tables S6 and S7).

Cattle used for beef production included cull cows and bulls and finished cattle. The number of cull dairy cows entering beef production was set at 31.8% of the annual inventory and cull beef breed cows was 8.8% (Tables S6 and S7; NASS, 2018). The number of finished cattle produced in each state was set based upon 2012 census data for cattle sold for slaughter adjusted to match annual cattle numbers produced from 2013 to 2017 (NASS, 2018).

Environmental footprints of beef cattle production for each state were determined as the total of those of the representative operations in

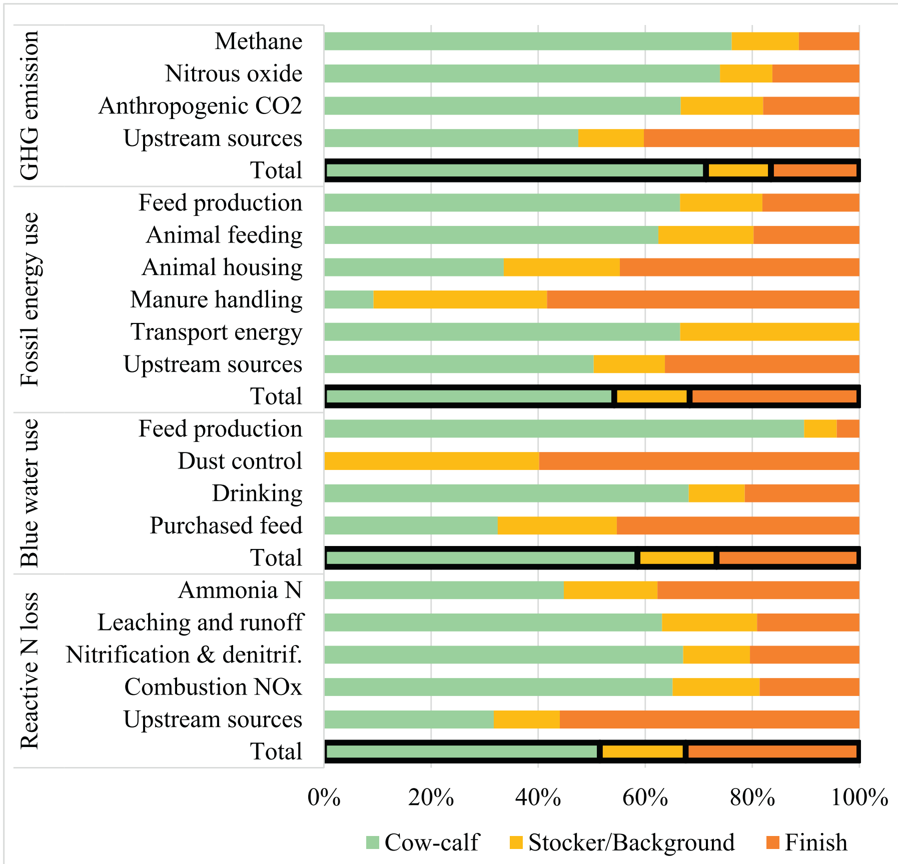

Fig. 2. Distribution of the sources of each environmental impact across the three major phases in the life cycle of beef cattle production.

the state. Representative cattle operations included cow-calf, cow-calf and stocker, cow-calf – to – finish, stocker or backgrounding, beef breed finishing, Holstein finishing, and cull dairy cows. For the northeast, southeast and northwest regions, a grass-finished cow-calf – to – finish operation was also included. Beef carcass weight produced by each of these operations was determined from the number of cull and finished cattle entering beef production from each operation and their corresponding percent dressing. The environmental footprints of each operation were set as the average of all operations of that type simulated in the regional analyses. This provided values for the total environmental footprints and total carcass weight produced for each state. Totals over all states provided regional and national totals. By dividing each national footprint by the carcass weight produced, an intensity was determined.

2.2. Sensitivity and uncertainty analyses

Sensitivity analyses were done to evaluate the relative influence of the individual components on each environmental footprint (Rotz et al., 2015). This analysis is useful for identifying components that have the greatest effect on predicted emissions or resource use and for indicating the associated error if there was an incorrect assumption affecting this component. A sensitivity index was determined as the percent change in the assessed footprint relative to a 10% change in the tested component. This procedure ignored potential interactions among components, but these interactions should be small in this analysis. A sensitivity index close to 0 indicated low sensitivity and hence, little change in the predicted output as a result of a change in the component. The converse was true for sensitivity indices close to or > 1. Sensitivity indices were determined for each of the major sources of each environmental footprint for each region. Most values were similar across regions so the average of all regions was used to illustrate the sensitivity to national predictions.

To quantify the confidence in predicted environmental impacts of the production systems, an uncertainty analysis was done following procedures previously reported (Rotz et al., 2013; Stackhouse-Lawson et al., 2012). The uncertainties of the predicted total footprints were determined from the uncertainties of each footprint's major contributing components. As characteristic of biological systems, statistical determination was limited by the unavailability of measured data. Thus, the uncertainties of the major components of each footprint were set and refined following expert opinion and recommendations of the IPCC (2006a,b) based on their Tier 2 methodologies. The square root of the sums of squares of each major source multiplied by its estimated uncertainty gave the predicted footprint's uncertainty (IPCC, 2006b). The uncertainties associated with IFSM predictions of GHG emissions were ± 10 and ± 20% for enteric and manure handling CH_4, respectively, ± 50% for N_2O and ± 20% for fuel combustion and upstream emissions (IPCC, 2006a). For fossil energy use, ± 20% was used for feed production, animal feeding, animal housing, manure handling and upstream predictions with ± 40% applied to transportation. For blue water consumption, ± 30% was used for feed production and other purchased feeds and ± 20% was used for drinking water. The uncertainty associated with the prediction of reactive N components (NH_3 emissions, leaching and runoff losses, nitrification and denitrification, fuel combustion and upstream emissions) were all assigned a value of ± 20% based on experiences with IFSM predictions versus observed values.

3. Results and discussion

Analyses of beef production systems are presented in three forms.

The first is a breakdown of the major impacts of a full production system representing typical production practices in each region. For this analysis, average values are presented for the cow-calf, stocker or background and feedlot phases of cattle production. For the second form, the weighted average footprints across all simulated production systems are presented for each region, including the contribution from Holstein steers and cull dairy cows. Finally, the regional values are used to give the national impacts.

3.1. Representative production systems

Beef cattle are normally produced through the 3 phases of cow-calf, stocker or backgrounding and finishing. To obtain a distribution of the impacts across these phases (Fig. 2), simulated values were obtained for individual cow-calf, stocker or backgrounding and finishing operations in each region. Mean values for all operations of each type were determined for each region (Table S8) with all results expressed per unit of CW. This CW included that of cull cows and bulls from cow-calf operations and finished steers and heifers. Dairy breeds were not included in this analysis.

Total feed consumed to produce 1 kg CW of beef was about 22 kg DM with the majority (74%) consumed in the cow-calf phase (Table 2). The total consumption consisted of about 82% forage, 11% grain and 7% byproduct and waste product feeds. This indicates that 10–15% of the feed consumed in beef production comes from sources that might be available for human consumption. Simulated feed consumption was relatively consistent across regions (Table 2; Table S8). Drinking water consumption varied more across regions (Table S8) as influenced by temperature (Table S4). Similar to feed consumption, about 70% of the life cycle drinking water was consumed on cow-calf operations (Fig. 2).

Fossil energy use varied across regions, primarily influenced by size of operations. Fuel use varied from 0.16 to 0.47 L/kg CW with the greatest use on the smaller operations of the eastern regions (Table S8). Over all regions, fuel use averaged 0.25 L/kg CW (Table 2). Natural gas was primarily used on large feedlots for processing grain with a relatively low consumption of 0.03 m^3/kg CW. Electricity use was greater in the western regions due to greater use of irrigation in feed production and for supplying drinking water to larger land areas. Across regions, electricity use varied from 0.26 to 0.99 kWh/kg CW. The major portions of fuel, electricity and total energy use were associated with the cow-calf phase (Table 2; Table S8; Fig. 2).

Important gaseous emissions in beef production include NH_3, CH_4, and N_2O. Ammonia is emitted from urine and fecal excretions, which occur in all phases of cattle production (Rotz, 2004). Our simulations showed about 35% of the NH_3 being emitted during the finishing phase where cattle were normally confined in feedlots or barns (Table 2; Fig. 2). About half occurred during the cow-calf phase from urine and fecal deposits on pasture or rangeland. In beef cattle production, most of the CH_4 is produced by enteric fermentation. Over the cattle production life cycle, about 77% of this emission was associated with cow-calf production (Table 2). Nitrous oxide is primarily produced by nitrification and denitrification processes in soil following urine deposition or fertilizer application and in stored manure. In the beef cattle life cycle, the major portion was again associated with cow-calf production (Fig. 2). Emissions of volatile organic compounds such as alcohols also occur, primarily from silage production and manure storage. Beef cattle production is a relatively low source of this emission and our model predicted similar amounts from each phase (Table 2).

Nitrogen and phosphorus emissions to water are also considerations in beef cattle production. Nitrogen is primarily lost in the form of NO_3^- leaching to groundwater with much smaller amounts in surface runoff. Phosphorus is primarily lost through runoff. Our model predicted a wide range in NO_3^- loss with very little occurring in the dry southwest region and the greatest losses occurring in the eastern regions. The national mean was 23 g NO_3^--N/kg CW with 63% associated with the cow-calf phase. Phosphorus losses associated with beef cattle production were found to be very low, < 1 mg P/kg CW (Table 2).

3.2. Regional production systems

Differences in climate and management practices among simulated farms, ranches and feedlots created variation in the environmental footprints of the simulated production systems within each region. For individual beef cattle production systems, total carbon footprint ranged from 17 to 40 kg CO_2e/kg CW (Table 3). Smaller cow-calf – to – finish operations had a similar range and mean footprint as systems using large feedlots for finishing (data not shown). No particular size or type of production system was found to be most efficient indicating that many parameters can impact the efficiency and environmental impact of production. Soil type (primarily clay content), precipitation patterns

Table 2
Feed consumption, fossil energy use and emissions predicted through simulations of cattle operations for the three major phases of beef cattle production.

	Unit	Cow-calf	Stocker or background	Finish	Total
Feed consumption					
Grazed forage	kg DM/kg CW	12.3	0.89	0.0	13.2
Harvested forage	kg DM/kg CW	3.2	1.30	0.62	5.1
Grain concentrate[a]	kg DM/kg CW	0.2	0.15	2.22	2.6
Other feed[b]	kg DM/kg CW	0.5	0.12	0.87	1.5
Total	kg DM/kg CW	16.2	2.36	3.72	22.3
Fossil energy use					
Fuel	liter/kg CW	0.17	0.04	0.04	0.25
Natural gas	m^3/kg CW	0.00	0.00	0.02	0.03
Electricity	kWh/kg CW	0.29	0.06	0.064	0.41
Air emissions					
Ammonia	g/kg CW	46.1	18.0	35.2	99.3
Methane	g/kg CW	370	61	51	482
Nitrous oxide	g/kg CW	14.7	1.9	3.2	19.9
VOCs[c]	g/kg CW	3.9	2.6	3.3	9.7
Water emissions					
N leaching & runoff	g/kg CW	14.7	4.1	4.4	23.2
P runoff	mg/kg CW	0.07	0.13	0.18	0.38

[a] Primarily corn, but may include other grains fed to cattle.
[b] Distillers grain, other byproduct feeds (corn gluten feed, soybean meal, cottonseed, etc.) and waste (bakery, potato, almond hulls, etc.) unsuitable for human consumption.
[c] Volatile organic compounds emitted are adjusted by their equal benefit incremental reactivity to reflect their potential contribution to ozone formation (Rotz et al., 2016).

Table 3
A summary of the farm gate environmental footprints or intensities of representative beef cattle production systems in each region excluding and including Holstein steers and cull cows.

Environmental footprint	Traditional beef cattle				With Holstein cattle		Uncertainty
	Range[a]		Mean	Weighted mean[b]	Steers[c]	Steers & cull cows[d]	%
	Min	Max					
Northeast							
GHG[e], kg CO_2e/kg CW	22.4	32.3	25.9	26.2	20.6	17.7	± 10.8
Fossil energy, MJ/kg CW	43.7	79.9	62.2	62.8	63.1	46.8	± 10.0
Blue water, L/kg CW	102	403	193	192	301	224	± 14.6
Reactive N, g N/kg CW	142	288	203	207	176	161	± 7.3
Southeast							
GHG, kg CO_2e/kg CW	18.5	39.9	28.9	28.9	28.8	27.0	± 14.0
Fossil energy, MJ/kg CW	36.1	90.2	62.9	62.8	62.7	59.7	± 9.9
Blue water, L/kg CW	109	411	214	213	214	199	± 13.9
Reactive N, g N/kg CW	126	725	272	274	272	257	± 7.5
Midwest							
GHG, kg CO_2e/kg CW	20.6	30.9	25.3	25.5	22.8	21.2	± 13.5
Fossil energy, MJ/kg CW	33.7	75.4	49.7	49.5	49.0	46.6	± 10.3
Blue water, L/kg CW	112	656	286	286	258	331	± 12.9
Reactive N, g N/kg CW	147	314	200	202	188	175	± 8.4
Northern plains							
GHG, kg CO_2e/kg CW	18.1	25.9	20.5	20.4	20.3	20.2	± 7.6
Fossil energy, MJ/kg CW	33.4	119.3	49.3	48.6	48.6	48.4	± 8.9
Blue water, L/kg CW	644	3260	1568	1533	1506	1517	± 18.6
Reactive N, g N/kg CW	98.5	445	153	153	152	152	± 8.7
Southern plains							
GHG, kg CO_2e/kg CW	16.6	30.1	23.2	23.2	22.3	22.2	± 9.6
Fossil energy, MJ/kg CW	28.9	85.4	56.0	55.6	54.3	53.8	± 11.7
Blue water, L/kg CW	1027	7091	2296	2689	2660	2638	± 18.3
Reactive N, g N/kg CW	82	246	144	149	147	147	± 8.1
Northwest							
GHG, kg CO_2e/kg CW	18.8	35.2	21.3	20.9	19.3	18.6	± 7.4
Fossil energy, MJ/kg CW	30.3	98.1	45.3	43.8	42.0	40.3	± 10.2
Blue water, L/kg CW	2074	14,527	61,116	6187	5520	5865	± 17.8
Reactive N, g N/kg CW	95.6	463	160	154	154	150	± 8.1
Southwest							
GHG, kg CO_2e/kg CW	18.2	23.8	20.2	20.2	17.6	16.8	± 6.8
Fossil energy, MJ/kg CW	33.1	95.9	50.8	51.1	47.6	44.7	± 9.3
Blue water, L/kg CW	1359	14,771	5032	5040	4230	4024	± 17.6
Reactive N, g N/kg CW	85.4	150	112	113	125	121	± 9.1

[a] Range in values found across 20+ individual production systems simulated in each region.
[b] Mean footprints weighted by operation type, regional location and animal numbers in each state.
[c] Weighted value including dairy breed steers making up a portion of the cattle finished.
[d] Weighted value including the dairy breed steers and cull dairy cows.
[e] GHG is total greenhouse gas emission expressed in CO_2 equivalents.

and N fertilizer use were important factors influencing N_2O emissions. The type of animal housing also affected direct and indirect N_2O emissions. The lifetime of cattle had some impact because the longer their life before slaughter, the more CH_4 and other emissions they produced. Producers can have some influence on the environmental impacts of their operations through improved rate of gain and manure management practices; however, the major factors of soil type and climate are beyond their control.

The mean GHG emission intensity of all traditional beef cattle production systems in each region ranged from 20.2 to 28.9 kg CO_2e/kg CW (Table 3). The highest values were found in the eastern and Midwestern regions, primarily due to greater precipitation (i.e. wetter soils) and greater use of fertilizers and lime in these regions. Little difference was found between the mean and weighted means (Table 3), which implies that our representative operations were appropriately distributed within the regions.

Mean GHG emissions for the regions decreased when Holstein cattle were included in the farm-gate assessments (Table 3). The largest differences occurred in the important dairy regions, i.e. Northeast, Midwest and Southwest. This resulted from the relatively low emissions and resource use allotted to calves born on dairy farms in comparison to calves produced on cow-calf operations (Stackhouse-Lawson et al., 2012). As shown, maintenance of the breeding stock contributes a significant portion of the environmental impact in beef cattle production systems. Since the dairy calf is a byproduct of milk production, it has a much smaller footprint. Moreover, a cull dairy cow has a lower footprint than a finished beef breed because part of her life-long environmental impacts are allocated to milk production (Rotz et al., 2010). The GHG emissions allocated to animals leaving the representative dairy farms in each region ranged from 12.0 to 17.4 kg CO_2e/kg CW. Cull dairy cows had about a third less GHG emission intensity and finished Holstein cattle had about half the intensity of finished beef breeds (data not shown).

Fossil energy use for individual production systems ranged from 29 to 119 MJ/kg CW (Table 3). The major influencing factors on this energy footprint were the amount, type and source of energy used for irrigation. The source of energy used to water cattle also had an impact since solar and wind energy were sometimes used, and this energy was not included in the footprint. Truck and all-terrain vehicle use also influenced fuel consumption. The mean fossil energy footprint of beef cattle production systems within each region ranged from 45 to 63 MJ/kg CW with very little difference between the straight means and weighted means (Table 3). For similar reasons as GHG emissions, inclusion of Holstein cattle reduced the energy footprint up to 25% across the 7 regions (Table 3).

Because of major differences in irrigation use, blue water consumption varied widely among production systems. Regional production system use ranged from 102 to 14,771 L/kg CW with most of the irrigation done in the western regions (Table 3). Inclusion of Holstein steers did not have much effect on water use per unit of CW because these cattle spent more time on feedlots consuming feed from irrigated crops. Cull dairy cows also had similar use per unit of CW produced as finished beef cattle, so their inclusion also did not have much effect on blue water use (Table 3).

Among individual production systems, reactive N loss also varied widely (Table 3), primarily because of the influences of climate, soil type and fertilizer use. These influences affect soil N leaching, runoff and denitrification processes while cattle housing and manure storage type affect NH_3 and N_2O emissions. Due to more rainfall in the East and Midwest, N in runoff and leachate were greater. Ammonia losses were relatively high in the west because of warmer temperatures and the use of feedlots where manure remains exposed for long periods. The weighted mean N loss in all regions was similar to the mean (Table 3). Regional means ranged from 112 g N/kg CW in the arid Southwest to 272 g N/kg CW in the wetter Southeast where more fertilizer was used. Including Holstein steers and cull dairy cows had little effect on N emissions per unit of CW in most regions with just a small decrease in the Northeast and a small increase in the Southwest (Table 3).

3.3. National production

National environmental footprints were determined considering the number of cattle maintained or produced in each state (Tables S6 and S7). These footprints were determined for traditional beef breeds alone and the total of beef and dairy breeds. The total carcass weight produced in each region was determined from the estimated annual production of cull animals and finished cattle. Most of the production came from the Northern and Southern Plains and Midwest regions with about 26% coming from the other four regions (Table 4). The estimated annual carcass weight produced, including dairy cattle, was 11,386 Gg, which compared very well to the average annual (2013–2017) carcass weight produced in the U.S. (11,369 Gg) reported by NASS (2018). Of this total, about 20% came from dairy breeds (Table 4).

The total GHG emission associated with beef production was found to be 243 ± 26 Tg CO_2e, with 66% associated with the Southern Plains, Southeast and Midwest regions (Table 4). About 88% of this total originated from the production of traditional beef breeds. In an earlier study, Capper (2011) determined a total GHG emission associated with beef cattle production of 214 Tg CO_2e in 2007. As noted above, a change was made in our analysis that must be considered in comparing CO_2e values to most previous studies. To align with current IPCC recommendations (Myhre et al., 2013), the GWP for CH_4 was increased and that for N_2O was decreased with the net effect of approximately a 4% increase in the CO_2e emission in beef cattle production systems. Considering this change, total GHG emission determined in the Capper study compares well with our value. The EPA (2018) estimates that, in recent years, beef cattle have produced about 132 Tg CO_2e/yr through enteric fermentation and manure management. Converted to the newer GWP values, this is 143 Tg CO_2e/yr. Because we include energy and other resource inputs including feed production, our value is greater. Considering only enteric and manure emissions from traditional beef breeds, we have a very similar national total of about 142 Tg CO_2e/yr.

As reported in other studies, the major contributor of greenhouse gas emissions was enteric CH_4 (56% of total; Fig. 3a). Various sources of N_2O contributed 24% of the total with most of this gas coming from pasture, range and crop land. Contributions of N_2O and CH_4 from manure were similar and relatively small compared to other sources. Anthropogenic CO_2 emissions from fuel combustion and lime decomposition were also a relatively small contributor (4%). Upstream sources, which included electricity, fertilizer and fuel production, represented about 13% of the total.

The fossil energy input to U.S. beef cattle production was determined as 569 ± 53 PJ with 83% for the production of traditional beef breeds and 17% for dairy breeds (Table 4). This total represents about 0.7% of total U.S. consumption of fossil fuels (EIA, 2018). In a similar national analysis, Capper (2011) determined a fossil fuel energy input of 115 PJ for 2007. With the information available, the specific cause of the difference cannot be determined. In our analysis, we found a substantial amount of fuel used on farms and ranches for utility trucks and all-terrain vehicles (Asem-Hiablie et al., 2015, 2016, 2017, 2018b), which may have been underestimated in the earlier study. Most of the

Table 4
Average annual cattle numbers (2013–2017), carcass weight produced and simulated emissions and resource use for seven regions and the total United States.

	Cattle numbers (1000)			Carcass weight, Gg	Emissions and resource use			
Region	Cows[1]	Stockers/background	Finished[2]		Greenhouse gas, Gg CO_2e	Fossil energy, TJ	Blue water, GL	Reactive N, Gg
Beef breeds								
Northeast	844	1088	351	157	6494	13,855	47.2	52.1
Southeast	6988	4871	463	358	49,429	87,408	389	383
Midwest	4102	3924	2989	1273	33,210	66,087	403	256
Northern Plains	4405	1545	5153	2078	28,821	67,628	2522	209
Southern Plains	7524	10,178	10,027	3995	64,230	174,508	6874	407
Northwest	3455	701	822	414	17,096	31,347	5393	90.1
Southwest	2600	609	2145	887	14,010	33,750	3563	79.5
National	29,917	22,908	21,950	9163	213,292	474,584	19,191	1476
Beef plus dairy breeds								
Northeast	1381	1322	588	418	10,010	23,635	111	88.4
Southeast	7149	4890	481	417	50,180	89,616	396	391
Midwest	4935	4722	3767	1851	40.885	90,776	654	328
Northern Plains	4461	1703	5307	2153	29,783	70,909	2581	219
Southern Plains	7727	11,206	11,029	4446	69,575	190,660	7881	460
Northwest	3772	870	987	580	19,543	36,996	6450	115
Southwest	3413	1655	3166	1522	22,640	66,504	5084	159
National	32,838	26,368	25,326	11,386	242,618	569,096	23,157	1760

[1] Includes all beef breed cows in the region, and dairy breed cows are those culled from dairy entering the beef value chain.
[2] Includes all beef and dairy breed cattle finished for market. This does not include cull animals processed for market.

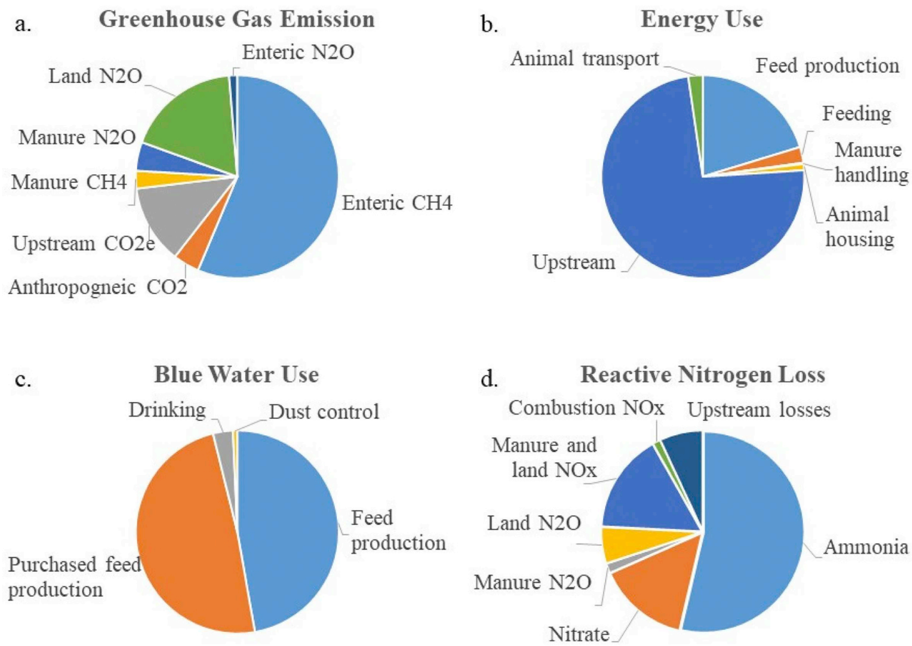

Fig. 3. Distribution of each environmental footprint among sources.

energy input was from the upstream production of resources with electricity production requiring most of this energy (Fig. 3b). Of the energy used within production systems, most was used in feed production.

Blue water consumption for U.S. beef cattle production was 23.2 ± 3.5 TL (Table 4). This compares well to a value of 21 TL found by Capper (2011). As with energy, about 83% was associated with the production of traditional beef breeds. Nearly all of the water was used to irrigate crops for feed production with about 3% consumed by cattle, and < 1% used for dust control in feedlots (Fig. 3d).

Total reactive N released to air and water through beef cattle production was 1760 ± 136 Gg (Table 4). Similar to the other environmental impacts, about 84% was related to the production of traditional beef breeds. About 67% of the total emission came from the Southern Plains, Southeast and Midwest regions. The primary source in the Southern Plains and the other dry regions of the west was NH_3 emission, while NO_3^- leaching was more important in the wetter climate of the Midwest and eastern regions (data not shown). Overall, a little over half of this emission was NH_3 with NO_3^- contributing 15% (Fig. 3c). Methods of the EPA (2004) have estimated annual NH_3 emissions from beef cattle in confinement to be about 690 Gg in 2015. Our national analysis gives an annual emission from traditional beef breeds of 939 Gg with about half of this coming from cattle in confinement and half from grazing cattle. Thus, our estimate (half of 939 Gg) is about 30% lower than the comparable EPA estimate.

Dividing the national impact values by the total CW provides environmental intensities for U.S. beef cattle production (Table 5). The GHG emission intensity was 21.3 ± 2.3 kg CO_2e/kg CW. This value can be compared to those previously found for the Southern Plains region (Rotz et al., 2015) and the analysis of a beef cattle operation in Nebraska (Rotz et al., 2013). The revised carbon footprints for the Southern Plains study using the new GWP factors (20.4 CO_2e/kg CW) and the Nebraska study using our assumed dressing percentages (19.9 CO_2e/kg CW) are slightly less than this national value but very similar to those found for the Northern and Southern Plains (Table 3). A number of other studies have quantified the carbon footprint of beef. Methodologies used have varied, which confounds direct comparison of results. In a summary of previous studies, carbon footprints of beef cattle production generally fell in the range of 10 to 15 kg CO_2e/kg BW or 16 to 24 kg CO_2e/kg CW (Rotz et al., 2013). In a more recent LCA, Roop et al. (2014) determined a value of 10.4 ± 0.48 kg CO_2e/kg BW for cattle produced in the Northwest, which is approximately 17 ± 0.8 CO_2e/kg CW. Sanders and Webber (2014) determined a farm-gate value of 27 ± 8.1 kg CO_2e/kg of packaged beef, which is approximately 20 ± 6.1 kg CO_2e/kg CW assuming 33% loss of fat, bone and shrink in processing. Thus our values fall within this range, particularly considering that previous studies used lower GWP values in converting emissions to CO_2e.

Fossil energy use expressed per unit of carcass weight (50.0 ± 4.7 MJ/kg CW) is similar to that previously reported for the Southern Plains (Rotz et al., 2015). This energy use intensity also compares well to that found for the production system in Nebraska (Rotz et al., 2013) when converted to CW (45.3 MJ/kg CW). Energy use in these previous studies was verified with data from actual operations. These values also compare well with those determined by Heitschmidt et al. (1996), but they are much greater than the fossil energy use reported by Capper (2011) (9.6 MJ/kg of beef CW).

Blue water use was about 2000 ± 300 L/kg CW with or without

Table 5
Environmental intensities for cattle production in the United States expressed per unit of carcass weight (CW) produced.

Environmental intensity	Units	Traditional beef breeds	Traditional beef breeds plus dairy culls	Uncertainty
Greenhouse gas	kg CO_2e/kg CW	23.3	21.3	± 10.6%
Fossil energy use	MJ/kg CW	51.8	50.0	± 9.4%
Blue water use	L/kg CW	2095	2034	± 15.2%
Reactive N loss	g N/kg CW	161	155	± 7.7%

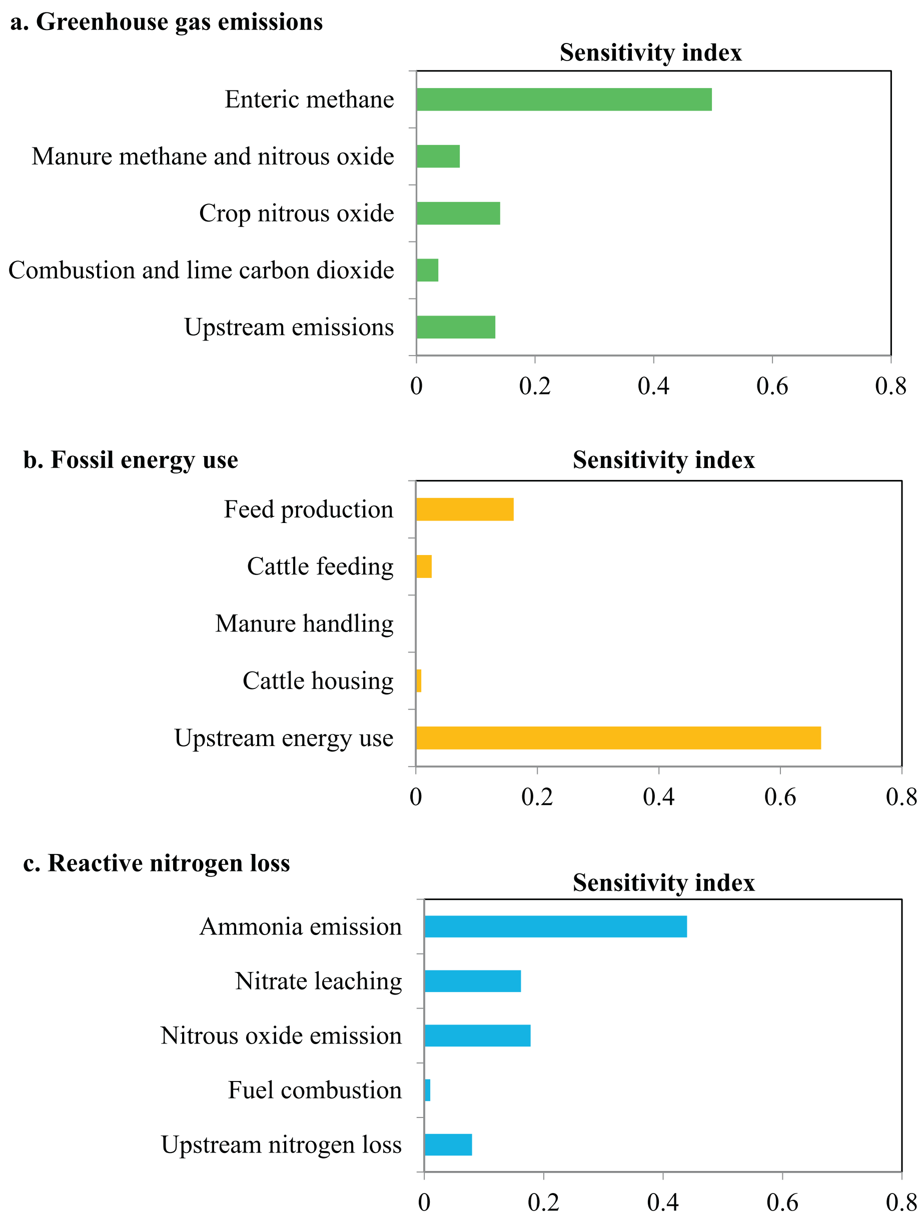

Fig. 4. Sensitivity of the environmental footprints of beef cattle production to changes in the major sources. The sensitivity index is the ratio of the percent change in output over the percent change in input.

dairy breeds included (Table 5). This national value was somewhat less than that previously reported for the Southern Plains (2470 L/kg CW; Rotz et al., 2015) and considerably less than that of the operation in Nebraska (4700 L/kg CW; Rotz et al., 2013). The operation in Nebraska relied heavily on irrigation including some irrigated pasture, which led to greater consumption. Since our national analysis includes regions where little irrigation is used, a lower intensity is expected. Our national value compares well to that determined by Capper (2011) for the year 2007 (1763 L/kg of beef CW).

Reactive N loss was found to be about 160 ± 12 g N/kg CW both with and without including dairy breeds. This emission was similar to that found for the production system in Nebraska (91.7 g N/kg BW or 154 g N/kg CW; Rotz et al., 2013) but greater than that previously reported for the Southern Plains (138 ± 12 g N/kg CW; Rotz et al., 2015). As shown above, N losses were greater in the Midwestern and eastern regions due to greater precipitation and greater use of N fertilizer. This metric of environmental impact is unique to our model, so comparisons to other work could not be made.

3.4. Sensitivity analysis

Sensitivity indices were determined for the major sources of each of the four environmental footprints in each region. Indices varied across regions due to differences in climate, soil and management practices, but in most cases, the relative magnitudes were similar among regions. Only the average sensitivity indices over all regions is presented (Fig. 4).

Emission sources contributing to the carbon footprint of beef cattle production include CH_4 from enteric fermentation and manure storage, N_2O from manure, pasture and cropland, CO_2 from liming and fuel combustion, and secondary emissions from the manufacturing of the operation's inputs. As found in our previous study of the Southern Plains region (Rotz et al., 2015), the total carbon footprint was relatively insensitive to combustion and manure sources, slightly sensitive to upstream, and pasture and cropland N_2O sources, and moderately sensitive to enteric CH_4. (Fig. 4a). Hence, no single emission source was found to greatly influence the carbon footprint of beef cattle production systems. As the carbon footprint was moderately sensitive to enteric CH_4, reducing emissions from this source would have the most impact. Many dietary changes and feeding treatments have been proposed, but few have been tested for long-term feasibility (Boadi et al., 2004; Hristov et al., 2013). Finding cost effective and socially acceptable solutions is challenging.

Production of resources used in cattle production was the major consumer of fossil energy. Therefore, assumptions related to upstream emissions were most influential in the estimated energy use in cattle production systems (Fig. 4b). Important upstream sources included purchased electricity, fertilizer and feed. Energy use was found to be slightly sensitive to the fuel and fertilizer used to produce feed within our defined production systems. Total fossil energy use was insensitive to that used in cattle feeding, housing or manure handling.

Components of the water footprint were associated with purchased feed production, irrigation of crops produced on cattle operations, animal drinking and dust control on feedlots. The majority (> 95%) of the water used in most regions for cattle production was that used for crop irrigation, either on the operation or to produce purchased feed. Consequently, the blue water footprint was highly sensitive to crop production use and very insensitive to drinking water and other uses (data not shown). This varied some across regions, with less sensitivity for feed production in the eastern regions where little irrigation is used.

Ammonia emissions from grazing land and feedlots were the main sources of reactive N loss in most cattle production systems. Therefore, the total reactive N footprint was moderately sensitive to NH_3 emissions, slightly sensitive to N_2O emissions and NO_3^- leaching from grazing land and not sensitive to upstream N loss or fuel combustion (Fig. 4c). This varied somewhat across regions, with less sensitivity to NH_3 emissions and greater sensitivity to NO_3^- losses in the wetter eastern regions, but NH_3 remained the most sensitive component in all regions. Efforts to reduce the reactive N footprints should consider reducing or capturing NH_3 emissions for use in feed production to improve N use efficiency in the system. Given that most of this emission is from grazing land and open feedlots, achieving this reduction is challenging. Economically feasible practices are not currently available that can provide a substantial reduction (Rotz, 2004).

3.5. Opportunities for improving sustainability

The wide variation in environmental footprints found among individual production systems indicates that reductions can be made to improve overall sustainability. However, much of the difference among systems is due to climate and soil factors that are beyond the control of producers. Warmer and wetter climatic conditions and higher clay content soils tend to increase both carbon and N emissions. The amount of precipitation received also greatly affects the need for irrigation of crops and to a small extent, the need for water to drink. Broad, general recommendations cannot be made at a national level for improving sustainability. Improvements must be made on an individual operation basis considering the uncontrollable factors influencing the management of the operation.

When considering individual operations, there are management factors to consider for reducing environmental impacts. A major consideration is the time needed to produce finished cattle. Generally, the longer they are alive, the more impact they have. There are trade-offs though in that the feed used to obtain the greater rate of gain may have a greater environmental impact. Optimal use of fertilizer and lime should be considered to make best use of available nutrients with less loss to the environment. Minimizing the use of trucks and all-terrain vehicles and greater use of solar and wind power for watering cattle and fencing can reduce energy consumption. In areas where irrigation is required, efficient use of that water for crop or pasture production is critical for reducing blue water consumption. These and other factors must be considered as we develop more efficient and sustainable cattle production systems.

A benefit often discussed in cattle production is that of C sequestration. On individual operations where appropriate transitions in management are made, soil organic matter can be accumulated for a period and C can be sequestered (Franzluebbers, 2005; Franzluebbers and Follett, 2005). This impact of beef cattle is likely small on a national scale. Most cattle producing operations in the U.S. have used relatively consistent management practices for many years, so soil C levels should be near a long-term equilibrium. Where opportunities exist for reducing the use of tillage in crop production or improving rotational grazing strategies, additional C can be sequestered and stored in the soil providing a short-term reduction in net greenhouse gas emissions (Franzluebbers, 2005; Rotz et al., 2009). These may provide other benefits by reducing fossil energy use and improving nutrient use efficiencies.

4. Conclusion

A national assessment of the environmental impacts of beef cattle production in the U.S. determined GHG emissions of 243 ± 26 Tg CO_2e, fossil energy use of 569 ± 53 PJ, reactive N loss of 1760 ± 136 Gg N, and blue water consumption of 23.2 ± 3.5 TL. Expressed per kg of carcass weight produced, these impacts were 21.3 ± 2.3 kg CO_2e, 50.0 ± 4.7 MJ, 155 ± 12 g N and 2034 ± 309 L, respectively. These data provide a baseline for future assessments and evaluation of the potential benefits of mitigation strategies. This also provides information to support a complete LCA of beef including packing, processing, marketing and consumption. Further work is ongoing to complete this full chain LCA, to better quantify the human edible feeds consumed in beef production, and to more fully assess opportunities for improving the sustainability of beef.

Funding

Funded in part by The Beef Checkoff and the USDA's Agricultural Research Service. The authors thank Dr. K.R. Stackhouse-Lawson for her effort in initiating this project and others of the National Cattlemen's Beef Association for their help in obtaining information supporting this analysis. USDA is an equal opportunity provider and employer.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.11.005.

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