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The environmental impact of beef production in the United States: 1977 compared with 2007

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ABSTRACT: Consumers often perceive that the modern beef production system has an environmental impact far greater than that of historical systems, with improved efficiency being achieved at the expense of greenhouse gas emissions. The objective of this study was to compare the environmental impact of modern (2007) US beef production with production practices characteristic of the US beef system in 1977. A deterministic model based on the metabolism and nutrient requirements of the beef population was used to quantify resource inputs and waste outputs per billion kilograms of beef. Both the modern and historical production systems were modeled using characteristic management practices, population dynamics, and production data from US beef systems. Modern beef production requires considerably fewer resources than the equivalent system in 1977, with 69.9% of animals, 81.4% of feedstuffs, 87.9% of the water, and only 67.0% of the land required to produce 1 billion kg of beef. Waste outputs were similarly reduced, with modern beef systems producing 81.9% of the manure, 82.3% CH_4, and 88.0% N_2O per billion kilograms of beef compared with production systems in 1977. The C footprint per billion kilograms of beef produced in 2007 was reduced by 16.3% compared with equivalent beef production in 1977. As the US population increases, it is crucial to continue the improvements in efficiency demonstrated over the past 30 yr to supply the market demand for safe, affordable beef while reducing resource use and mitigating environmental impact.

Key words: beef, carbon footprint, dilution of maintenance, environmental impact, greenhouse gas, productivity

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INTRODUCTION

The global population is predicted to grow to 9.5 billion people in the year 2050 (US Census Bureau, 2008), with a widespread increase in milk and meat requirements per capita conferred by increased affluence (Keyzer et al., 2005). The Food and Agriculture Organization of the United Nations (**FAO**, 2009) suggests that food production will have to increase by 70% to fulfill the caloric and nutritional needs associated with this population increase. Existing competition for energy, land, and water supplies is likely to continue as urban development encroaches upon agricultural land. United States livestock producers therefore face the challenge of producing sufficient safe, affordable beef to meet consumer demand, using a finite resource base.

An environmentally sustainable food supply can only be achieved through the adoption of systems and practices that make the most efficient use of available resources and reduce environmental impact per unit of food (Capper et al., 2008, 2009). However, understanding the relationship between environmental sustainability and efficiency requires a certain amount of conceptual change to occur. The role of efficiency in improving US beef system sustainability has been called into question by individuals and agencies promoting a social or political agenda opposed to animal agriculture (Nierenberg, 2005; Koneswaran and Nierenberg, 2008). Nonetheless, improved productive efficiency (resource use per unit of food output) considerably reduced the environmental impact of a unit of milk produced by the US dairy industry between 1944 and 2007 (Capper et al., 2009). To analyze the effects of efficiency changes in the US beef industry over the past 30 yr, a deterministic whole system model based on ruminant nutrition and metabolism was used to evaluate the comparative environmental impact [defined in this paper as resource use, waste outputs, and greenhouse gas (**GHG**) emissions] of the US beef industry in 1977 and 2007.

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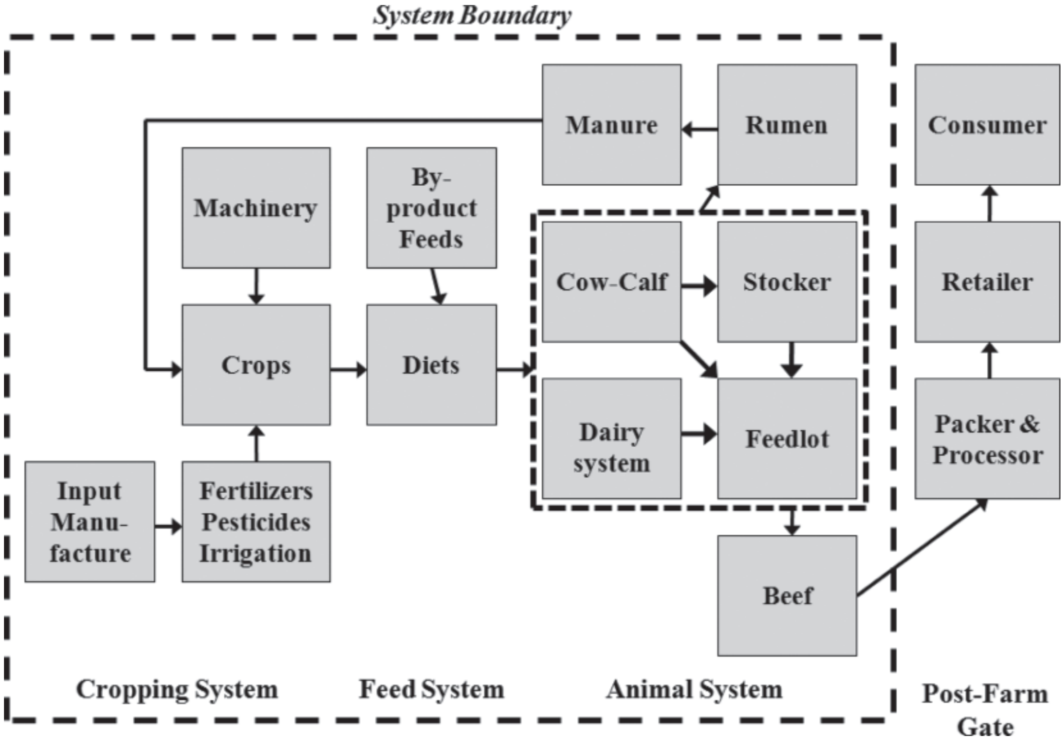

Figure 1. Summary of the model system used within the current paper. All systems and components within the dashed line (system boundary) were included in the analysis.

MATERIALS AND METHODS

This study used data from existing reports and databases and required no Animal Care and Use Committee approval.

A deterministic model based on the nutrient requirements and metabolism of animals within all sectors of the beef production system was used to quantify the environmental impact (defined as resource use and waste output per unit of beef) of the US beef industries in 1977 and 2007. The model employed a whole system approach founded on life cycle assessment principles whereby all relevant inputs and outputs from the beef production system were included, with the system boundaries set as shown in Figure 1.

Conventional beef production systems within the United States consisted of 3 major animal-based subsystems. The cow-calf unit contained animals that served to support population dynamics (cows, calves, replacement heifers, adolescent bulls, yearling bulls, and mature bulls). The stocker/backgrounder operation contained weaned steers and heifers fed until they reached sufficient BW to be placed into the feedlot. The feedlot contains both calf-fed (beef and dairy animals that enter at weaning) and yearling-fed (beef animals that enter after the stocker stage) animals that were fed until the desired BW and slaughter finish was achieved. It is acknowledged that small niche markets exist within the US beef production whereby animals are finished in pasture-based or organic systems; however, these systems comprise only 3% of beef produced in modern systems (USDA/ERS, 2010b) and equivalent data were not available for 1977. Given the preponderance of the aforementioned conventional production system within the beef industry, this was considered to provide a representative example of the difference between the 2 time points.

Primary inputs into these subsystems included animal feed and drinking water, unit electricity, and fuel for animal transport between subsystems and feed transport to farm. Secondary inputs included chemicals (fertilizer, pesticides) applied to feed crops, irrigation water, and fuel for cropping practices and agrochemical manufacture. Nutrient requirements of individual animals were calculated using AMTS Cattle Pro (2006), a commercial cattle diet formulation software based on the Cornell Net Carbohydrate and Protein System. Animal diets were formulated to fulfill the requirements of animals within each subsystem according to age, sex, breed, BW, and production level. Environmental impact was assessed by comparing annual resource inputs and waste output of the US beef production systems in 1977 and 2007 and expressed per billion kilogram of HCW beef produced in 365 d.

The US beef industry includes animal inputs from the US dairy industry in terms of cull cows (both 1977 and 2007), plus male and female calves at 3 d of age (2007 only). Resource inputs and waste output between the dairy and beef systems were calculated based upon a biological allocation method. A deterministic model of resource use and environmental impact within dairy production was previously developed by Capper et al. (2009), based upon the same nutrition and metabolism principles as the current beef model. Employing the model described by Capper et al. (2009) ensured that resource input data for both models were sourced from similar data, thus minimizing conflict between the models. The dairy model was used to determine the proportion of total resource inputs and waste output attributable to growth in Holstein heifers from birth up to 544 kg (the BW at which they would be sold as beef animals if they did not enter the dairy herd). These totals represented the environmental cost attributed to dairy cull cows entering the beef market and were applied to the appropriate beef production according to the number of cull cows within each system. The additional cost of producing male and female dairy calves for calf-fed rearing within the 2007 beef production system was calculated by partitioning out the proportion of total resource inputs and waste output attributable to pregnancy in lactating and dry dairy cows. This cost was adjusted for the number of dairy calves in the beef system, and thus the number of cows required, before application to the beef production system.

2007 Beef Production System Characteristics

The 2007 beef production system was modeled according to characteristic US production practices (USDA, 2000a,b, 2009a,b) with the total environmental impact based on national beef production and animal numbers (USDA/NASS, 2008). Total beef production in 2007 equaled 11.9 billion kilograms from 33.7 million animals slaughtered. The slaughter population was made up of 17.3 million steers, 10.2 million heifers, 2.5 million dairy cows, 3.2 million beef cows, and 554 thousand bulls.

Data from USDA (2009b) indicated that the majority of beef animals in the United States consisted of British breeds; thus beef cows and replacement heifers were assumed to be pure-bred Angus, bulls were pure-bred Hereford, and beef steers and heifers destined for slaughter were Angus × Hereford cross-bred animals. Relative proportions of cows, heifers, and bulls within the support population were based on USDA/NASS (2007b) data, with 89% of cows and heifers calving, of which 96.5% bore a live calf (USDA, 2009b). Animal numbers were prorated to a 365-d total according to the amount of time spent within each subsystem.

Lactating cows grazed pasture ad libitum with a DMI based on 567 kg of BW, an annual lactation length of 207 d (USDA, 2009a), a milk yield of 1,625 kg/lactation (Miller and Wilton, 1999; Miller et al., 1999), and milk composition of 4.03% fat and 3.38% protein (NRC, 2000). Dry cow DMI was calculated for a pasture, straw, and grass hay diet adjusted for a 42-kg average calf birth BW and 158-d dry period. Nutrient requirements for dry cows were based on an average of 201 d of gestation. The average dry cow in the analysis was at d 201 of gestation (83 d into the 158-d dry period). The assumed calving interval was 12 mo (365 d).

Replacement heifers were included in the population at a rate of 0.27 heifers per cow with an annual replacement rate of 12.9% and a 24 mo age at first calving. Heifers were fed a pasture, grass hay, and straw diet adjusted for a predominantly pasture-based diet during the spring and summer, with conserved forage supplementation during fall and winter. Heifer growth rates averaged 0.54 kg/d from birth to 454 kg at first calving (BW minus calf BW).

Diets for bulls were formulated on the same basis as the replacement heifer diets, with DMI based on median BW of 907 kg (mature), 714 kg (yearling), and 339 kg (adolescent). Adolescent bulls were considered to transfer to the yearling group at 24 mo of age and 635 kg of BW; yearling bulls were considered mature at 36 mo and 794 kg of BW. Artificial insemination is only used in 2.9% of animals within the US beef herd (USDA, 2009b); therefore, the maintenance requirement for mature and yearling bulls was adjusted for the activity required to service cows at a ratios of 23.7 cows:mature bull and 16.3 cows:yearling bull (USDA, 2009b).

Before weaning at 207 d (USDA, 2009a), beef calves suckled from the dam and consumed pasture and starter feed (flaked corn and soybean meal) at intakes calculated according to the Agricultural Modeling and Training Systems (**AMTS**) Cattle Pro (AMTS, 2006) nutrient requirements for calves with median BW of 148 kg (steers) and 137 kg (heifers) growing at 0.98 and 0.89 kg/d, respectively. Postweaning, 83.5% of calves (personal communication, Tom Field, National Cattlemen's Beef Association, Denver, CO) entered the stocker subsystem where they were fed diets that consisted of pasture, grass hay, corn silage, flaked corn, and soybean meal according to seasonal pasture availability. Intakes were calculated and diets balanced for median BW of 320 and 290 kg, and growth rates of 0.80 and 0.69 kg/d for steers and heifers, respectively. At 12 mo of age and a median BW of 370 kg, the stockers entered the feedlot as yearling-fed finishing animals. Diets for yearling-fed feedlot steers and heifers were balanced for median BW and growth rates (510 kg and 1.59 kg/d for steers; 446 kg and 1.42 kg/d for heifers, respectively), based on DMI for a finishing diet consisting of corn grain, soybean meal, alfalfa hay, and vitamin/mineral supplements. Yearling-fed steers spent 151 d on feed, whereas yearling-fed heifers spent 138 d on feed before slaughter at 635 and 544 kg, respectively. Approximately 16.5% (personal communication, Tom Field, National Cattlemen's Beef Association, Denver, CO) of weaned beef calves enter the feedlot directly as calf-fed finishing animals. Calf-fed feedlot animals were fed a diet containing the same base ingredients as the yearling-fed animals, but formulated for overall weaning to slaughter growth rates of 1.37 kg/d (steers) and 1.22 kg/d (heifers). Intakes were calculated for median BW of 445 and 389 kg for steers and heifers, respectively. Calf-fed animals were slaughtered after 268 d on feed at 635 kg (steers) or 244 d on feed at 544 kg (heifers).

According to USDA (2000a), 12.9% of animals placed in feedlots originated from dairy operations. Given the ratio of male:female dairy animals placed in finishing operations, 11.5% of all feedlot animals are dairy steers and 1.4% of all feedlot animals are dairy heifers. Given that the current US dairy herd contains ~90% Holstein animals (USDA, 2007), all dairy animals entering the beef system were assumed to be pure-bred Holsteins. Within the current model, dairy calves were fed surplus milk and a calf starter ration (flaked corn and soybean meal) from 3 d of age until weaning at 56 d. Dairy calves entered the feedlot on a calf-fed basis at 93 kg (steers) and 86 kg (heifers) and were finished on a standard feedlot diet similar to that fed to the calf-fed beef animals, balanced for overall growth rates of 1.41 and 1.24 kg/d for steers and heifers, respectively. Calf-fed dairy animals spent an average of 307 d on feed and were slaughtered at 544 kg (steers) or 499 kg (heifers). Growth rates predicted by AMTS (2006) throughout the entire beef production system allowed animals to finish at an average of 16 mo of age. Productivity-enhancing technologies including hormone implants, ionophores, β-adrenergic agonists, and in-feed hormones were available for use by the beef industry in both 2007 and 1977; however, diets were formulated without the use of productivity-enhancing technologies because of a lack of reliable adoption data for different technology categories and time points. The slaughter population for 2007 consisted of calf-fed and yearling-fed beef steers and heifers; calf-fed dairy animals (both steers and heifers) and cull animals from the beef and dairy sectors (cows and bulls). The average BW at slaughter was 607 kg.

1977 Beef Production System Characteristics

The year 1977 was chosen as a suitable time point for comparison because the ratio of growing beef animals (steers and heifers) to cull animals (cows and bulls) was representative of the average of all annual time points between 1970 and 1980 at 0.76 growing animals:0.24 cull animals (USDA/NASS, 2010). The 1977 beef production system was largely similar to the 2007 system; the majority of animals were produced within the conventional cow-calf/stocker/feedlot structure. Nonetheless, some notable exceptions exist: the practice of weaned calves proceeding directly to the feedlot for finishing was not practiced, and surplus dairy calves were directed into the US veal market. In 1977, 10.6 billion kilograms of beef was produced from 38.7 million animals slaughtered. The slaughter population was made up of 17.9 million steers, 10.9 million heifers, 1.9 million dairy cows, 7.2 million beef cows, and 832 thousand bulls.

Literature from the time-period indicated that the traditional British beef breeds predominated in 1977 (Kratz et al., 1977); thus for modeling purposes, beef cows and replacement heifers were assumed to be pure-bred Angus, bulls were pure-bred Hereford and beef steers and heifers destined for slaughter were Angus × Hereford cross-bred animals. Relative proportions of cows, heifers, and bulls within the support population were based on data from Wiltbank (1970, 1974). Animal numbers were prorated to a 365-d total according to the amount of time spent within each subsystem.

Within the cow-calf subsystem, lactating cows grazed pasture ad libitum with DMI based on 454 kg of BW and an annual lactation length of 205 d (Sellers et al., 1970). In the absence of time point-specific data, and because milk yield has not been a major selection goal for beef cattle over the past decades, a milk yield of 1,625 kg/lactation (Miller and Wilton, 1999) and milk composition of 4.03% fat and 3.38% protein (NRC, 2000) were assumed to be representative of 1977. Nutrient requirements for dry cows were based on an average of 201 d of gestation. The average dry cow in the analysis was at d 201 of gestation (83 d into the 158-d dry period). The assumed calving interval was 12 mo (365 d) Dry cow diets were formulated based on pasture, straw, and grass hay, with DMI adjusted for a 33-kg average calf birth BW and 160-d dry period.

Replacement heifers were included in the population at rates according to USDA data for 1977 heifer numbers (USDA, 1977), with an annual replacement rate of 12.9% and a 24-mo age at first calving. Heifer diets were formulated based on a predominantly pasture-based diet during the spring and summer, with conserved forage (grass hay, straw) supplementation during fall and winter. Heifer growth rates averaged 0.44 kg/d from birth to 363 kg at first calving (BW minus calf BW).

To agree with USDA (1977) data, beef bulls were included in the population at a rate of 23.3 cows:mature bull and 16 cows:yearling bull. Bull diets for bulls were formulated upon the same basis as the replacement heifer diets, with DMI based on median BW of 726 kg (mature), 572 kg (yearling), and 271 kg (adolescent). Adolescent bulls transferred to the yearling group at 24 mo of age and 508 kg of BW, yearling bulls were considered mature at 36 mo and 635 kg of BW. Maintenance requirements for mature and yearling bulls were adjusted for the activity required to service cows at the aforementioned ratios.

Within the 1977 cow-calf subsystem, calves suckled from the dam, with daily intakes predicted by AMTS Cattle Pro (2006) according to average cow milk component yield, with supplemental nutrients provided by grazed pasture. Nutrient requirements were based upon steer calves with median BW of 108 kg and a growth rate of 0.69 kg/d, and heifer calves at 96 kg of median BW growing at 0.59 kg/d. Calves were weaned at 205 d (Sellers et al., 1970) and entered the stocker subsystem. Diets within this system consisted of pasture, grass hay, corn silage, flaked corn, and soybean meal according to seasonal pasture availability. Steers within the stocker subsystem had a median BW of 238 kg and a growth rate of 0.48 kg/d, whereas heifers weighed 215 kg at the mid-point and grew at 0.42 kg/d. Steer stockers entered the feedlot as yearling-fed finishing animals at 14 mo of age with a median BW of 295 kg. Heifers entered this system at 15 mo of age, at 272 kg. Yearling-fed feedlot animals were fed finishing diets for ad libitum intake consisting of corn grain, soybean meal, alfalfa hay, and vitamin/mineral supplements, formulated to allow 1.40 kg/d growth rate in steers (median BW 397 kg) and 1.21 kg/d growth in heifers (median BW 340 kg). Yearling-fed steers and heifers remained in the feedlot for 173 and 149 d, respectively, before slaughter at 499 kg (steers) and 408 kg (heifers). Growth rates predicted by AMTS (2006) throughout the entire beef production system allowed animals to finish at an average of 20 mo of age. The slaughter population for 1977 consisted of yearling-fed beef steers and heifers and cull animals from the beef and dairy sectors (cows and bulls). The average BW at slaughter was 468 kg.

Resource Inputs and Waste Outputs

Manure production, N excretion, and P excretion for animals within each subsystem were calculated according to the animal and diet-specific output values from AMTS (2006). Dietary soluble residue, hemicellulose, and cellulose intakes were used to calculate enteric CH_4 production from all animals within each subsystem, including preweaned calves (Moe and Tyrrell, 1979). The fraction of N emitted as enteric N_2O was modeled using data reported by Kaspar and Tiedje (1981) and Kirchgessner et al. (1991). Emissions of CH_4 from manure were estimated using methodology prescribed by the US Environmental Protection Agency (**US EPA**, 2010) based on the quantity of volatile solids excreted, maximum CH_4-producing potential (0.24 m^3 per kilogram of volatile solids), and a conversion factor for pasture-based or feedlot systems. Intergovernmental Panel on Climate Change (**IPCC**, 2006) emission factors were used to calculate N_2O emissions from manure. Biogenic C, which rotates continuously through the relatively short-term cycle between the atmosphere, into crops and animals, and back to the atmosphere through animal respiration, was considered to be neutral with respect to GHG emissions. Carbon sequestration into soil and CO_2 produced through animal respiration were considered to balance and were not specifically accounted for.

The time point-specific population beef data gathered for 1977 and 2007 was based on animal numbers from January 1 to December 31 for each year. The majority of supplemental feed supplied to animals within this data set would have been harvested in 1976 and 2006; therefore, total land use was derived from a function of the annual whole population feed requirement and published crop yields for these years according to USDA/NASS (2010; http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/#top). Fertilizer application rates for crop production during 2006 were taken from the most recently published US data for corn (USDA/NASS, 2006) and soybeans (USDA/NASS, 2007a). Equivalent data for 1976 crop production was sourced from USDA/ERS (USDA/ERS, 2010a). Data for alfalfa and grass hay inputs were according to Pimentel and Pimentel (2007) and Barnhart et al. (2008). Wheat straw was considered to be a by-product of wheat production, and all fertilizer inputs were allocated to the grain portion of the wheat crop. Emissions of N_2O from fertilizer application, manure application to crops, and manure applied while grazing were estimated from the factors published by the IPCC (2006). Emissions of CO_2 from fertilizer and pesticide manufacture were derived from West and Marland (2002), and similar emissions from fossil fuel combustion for crop production were calculated from US EPA (2010). Pasture-based US beef production systems originally served to use land that was unsuitable for crop production because of characteristics such as unfavorable topography or soil type (Cardon et al., 1939). For the purposes of this study, all pasture was considered to be permanent (i.e., present as pasture and undisturbed by tillage for >25 yr). Mature temperate pasture subject to biomass removal by grazing/haying (Skinner, 2008) or burning (Sukyer and Verma, 2001) is considered to have a net C balance close to zero. Sequestration occurring as a result of land use change is a dynamic process following a logarithmic decay curve. Because of a lack of reliable data and the number of assumptions involved in applying a land use factor to cropland, C sequestered into soil was not included in the model calculations for either time point.

Voluntary water intake for mature cows was modeled according to Beckett and Oltjen (1993), with water intakes for all other classes of animal calculated from the equation derived by Meyer et al. (2006). Data relating to irrigation water application rate and usage was sourced from Census of Agriculture Ranch and Irrigation Surveys from 1979 and 2007 (USDA/NASS, 1979, 2007c).

Annual electricity use for cattle feedlots was 326 kWh per animal, prorated according to BW (Ludington and Peterson, 2005). Data from the Energy Information Administration (2001) provided the data from which to calculate a nationwide factor for CO_2 emissions from electricity generation, which was applied to electricity use within the model. There is a paucity of information available on the distances traveled by animals between subsystems within either the 1977 and 2007 production system. As noted by Forde et al. (1998), improving the quality of data available would have benefits in terms of tracking animal movements and disease. From examining the major states involved with cow-calf, stocker, and feedlot production at both time points, it seems unlikely that, for reasons of animal welfare and economic cost, animals would be moved between the furthest points. A value of 483 km was therefore adopted as the average distance for animal movements between the cow-calf, stocker, and feedlot operations for both 1977 and 2007. According to Shields and Mathews (2003), few animals traveled more than 161 km between the feedlot and slaughter plant; therefore, this distance was adopted for the final transportation stage in both years. Energy use for corn transportation was generated by comparing the major corn-producing states with those containing the greatest number of feedlot animals for each year. Assuming that moving corn for the shortest distance was the most economically favorable solution within both 1977 and 2007, weighted averages for in-state transport (set at 161 km) and out-of-state transport (distance from the center of 1 feedlot state to the center of the nearest corn-producing state) based on the proportion of total beef produced within each state were calculated. The final average transport distances for corn were 420 km (1977) and 558 km (2007). Energy use and CO_2 emissions from transport were based on the average fuel efficiency and carrying capacity of transport vehicles representative of those used for animals or grain in 1977 and 2007 (USDA/ERS, 1975; Grandin, 2001; Davis et al., 2009). The total C footprint was calculated by applying CO_2-equivalent factors from IPCC (2007) to CH_4 (25) and N_2O (298) to calculate the total C footprint as the sum of all CH_4, N_2O, and CO_2 emissions expressed in CO_2-equivalents.

RESULTS AND DISCUSSION

The Relationship Between Efficiency and Environmental Impact

Livestock industries face an ongoing challenge in producing sufficient food to fulfill consumer demand while reducing resource use and GHG emissions per unit of food. A recent FAO (2006) report concluded that livestock production contributes 18% of total global GHG. Despite a subsequent public admission that comparisons between GHG emissions from livestock production and transport were flawed after in-depth scientific review by independent scientists (Pitesky et al., 2009), the report is often used to support claims that animal agriculture should be abolished (Deutsch, 2007; Humane Society of the United States, 2009), despite the obvious inadmissibility of using global data to represent the environmental impact of regional production systems. Improved productive efficiency (resource input per unit of food output) is a major factor affecting variability in GHG emissions per unit of food. Global data are not yet available for the beef industry; however, a FAO (2010) report detailing GHG emissions from the worldwide dairy industry demonstrated the inverse relationship between efficiency and CO_2-equivalents per kilogram of milk produced. Gains in productive efficiency allow increases in food production to be achieved concurrently with reductions in environmental impact. A case-in-point is the US dairy industry, which produced 59% more milk, using 64% fewer cows in 2007 than in 1944, with a consequent 41% decrease in GHG emissions from the dairy industry (Capper et al., 2009). Nonetheless, improved efficiency is often perceived by the consumer as being achieved at the expense of animal health and welfare (Singer and Mason, 2006).

The reduction in the environmental impact of livestock conferred by an improvement in productive efficiency is achieved through the "dilution of maintenance" effect (Capper et al., 2008, 2009). Within the beef industry, this may be better defined as a population-wide "reduction and dilution of maintenance," which encompasses the individual effects and interaction between meat yield per animal, daily maintenance requirement, and time period from birth to slaughter. On a single animal basis, this concept is exemplified by Figure 2, which shows the difference in maintenance and growth requirements on a daily basis between 2 steers, representative of these classes of animals within the 1977 and 2007 beef finishing systems. Although the total daily energy requirement is increased in the 2007 animal, a combination of reduced time from birth to slaughter and increased BW at slaughter decreases total energy use per kilogram of beef produced. As shown in Figure 3, average beef yield per animal has increased from 274 kg in 1977 to 351 kg in 2007. Although total beef production was increased in 2007 (11.9 billion kg) compared with 1977 (10.6 billion kg), it is noticeable that the slaughter population was reduced by 825×10^3 animals per billion kg of beef over the same time period, a direct consequence of the increase in yield per animal.

When assessing the environmental impact of livestock production, it is not sufficient to simply consider the animals directly associated with food output (i.e., the slaughter animal), but also the supporting population. In a homogenous beef market such as that seen in 1977, where all animals reared specifically for beef originate from the beef supporting population, slaughter population size is the major driver for the magnitude of the supporting population. However, over the 30-yr period between 1977 and 2007, a growing number of dairy calves entered the beef system and were finished as "calf-fed" animals, reaching approximately 12.9% of the feedlot population in 2007 (USDA, 2000a). Provision of surplus calves from the dairy industry allows more beef to be produced without a concurrent increase in the supporting population. Through a combination of the reduced slaughter population size, calf input from the dairy industry and reduced mortality rates conferred by a better understanding of nutrition, health, and animal management over the past 30 yr, the total population (support beef animals plus slaughter animals) required to produce 1 billion kg of beef was reduced by 30.1% ($4{,}446 \times 10^3$ animals) in 2007 compared with 1977. It is also worth noting that the proportion of cull animals within the slaughter population was considerably less in the 2007 system (18.5%) than in the 1977 population (25.7%). A proportional reduction in cull animals entering the slaughter system shifts pressure up the chain, necessitating an increase in feedlot beef production to maintain supply. This serves

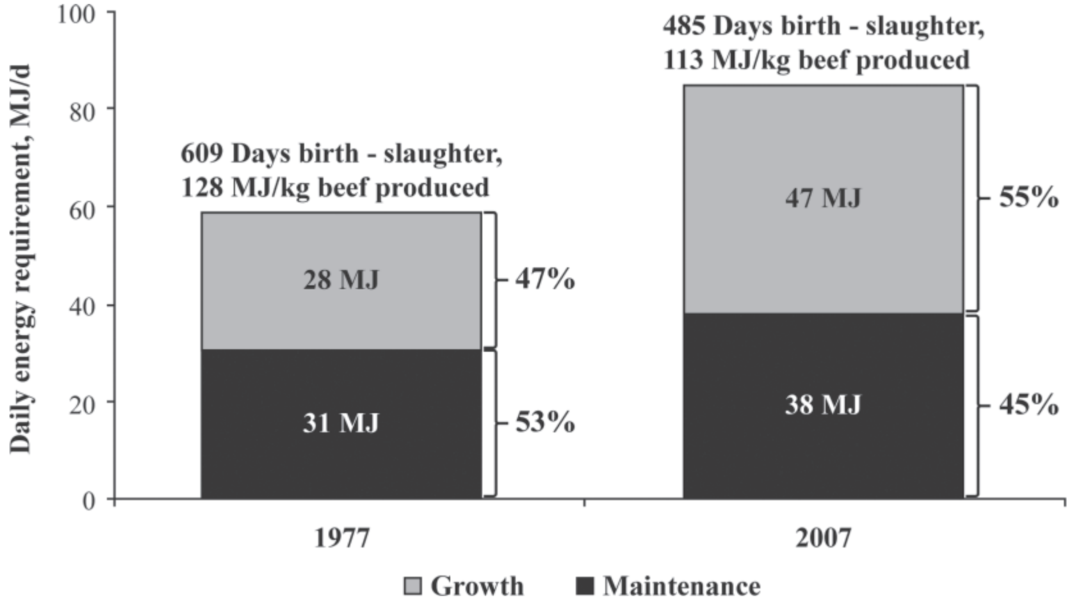

Figure 2. The "dilution of maintenance" effect conferred by increasing growth rate in steers within the 2007 US beef production system when compared with the 1977 US beef system. Energy values represent the average maintenance and growth requirements for steers destined for slaughter within the beef system. Requirements were weighted according to the number of days spent within the cow-calf, stocker, and feedlot system, and in the case of the 2007 system, to account for the proportion of yearling-fed beef, calf-fed beef, and calf-fed dairy steers within the slaughter population.

to further highlight the improvements in efficiency that allow the modern production system to use fewer animals to produce 1 billion kg of beef.

The hierarchy of nutrient partitioning dictates that the maintenance requirement of an animal must be satisfied before productivity (pregnancy, lactation, or growth) can occur. The daily maintenance nutrient requirement can therefore be considered to be a fixed cost of beef production, both on an individual animal and herd basis. Management practices that improve animal and herd productivity and reduce the nonproductive proportion of the lifetime of an animal will reduce the total maintenance cost per unit of beef produced. Within the supporting population, the major factors that improve productivity are reproductive efficiency (number of live births per cow, calving interval), age at first calving (heifers) or service (bulls), replacement rate, and mortality rate. In terms of nutrient requirements, pregnancy, lactation, and growth are classified as a production process, requiring extra nutrients above basal daily maintenance. However, in contrast to pregnancy or lactation in which a product (calf, milk) is harvested from the live animal, the time period between growth and slaughter in growing and finishing animals may essentially be considered a nonproductive period because animal protein is only collected after the point of slaughter. The total daily maintenance cost was increased in both growing animals and in the supporting herd as a consequence of genetic selection for mature BW and growth rate. Nonetheless, a considerable portion of the total maintenance requirement associated with beef production may therefore be reduced by improving growth rate through nutrition, genetics, and productivity-enhancing technologies, the combination of which reduce the time taken to reach slaughter BW. The previously defined "reduction and dilution of maintenance" interaction is therefore demonstrated by the reduction in total feed energy [nutrients required for maintenance (all animals), pregnancy (dry cows), and growth (all growing, replacement, and finishing animals)] per billion kilograms of beef from 251,090 × 10^6 MJ in 1977 to 230,898 × 10^6 MJ in 2007. It is notable that the average number of days on feed was increased in the 2007 population compared with the 1977 population (Table 1), which seems counter to the earlier argument regarding improved productivity. However, this is simply a question of semantics; days on feed accounts for the time within the feedlot, hence the increase in the 2007 population, which contained a greater proportion of calf-fed animals. Simply accounting for days on feed may be misleading in systems that contain a stocker stage as in the 1977 example; thus total time to slaughter should be the metric under consideration.

Carbon is the fundamental unit of energy within animal systems; thus differences in total maintenance energy can be considered to be a proxy for both resource use and GHG emissions. It is biochemically impossible to maintain a system with a greater net C output than input, for example, forage-based extensive systems with characteristically low growth rates have increased land, energy, and water use and GHG output per unit of beef produced (Capper, 2010). In contrast to previous studies examining the environmental impact of production systems separated by both time and typical management practices (Rydberg and Jansen, 2002; Capper et al., 2009), the current study was designed to compare similar systems, separated on a temporal basis, to allow identification of opportunities for environmental

Table 1. Characteristics of the 1977 and 2007 beef production systems[1]

Variable	1977	2007
Predominant beef breeds	Angus, Hereford,	Angus × Hereford
Calf birth BW, kg	33	42
Average slaughter BW, kg	468	607
Average beef yield per animal,[2] kg	274	351
Average age at slaughter, d	609	485
Overall growth rate (birth to slaughter), kg/d	0.75	1.08
Average days on feed	164	183
Proportion of yearling-fed beef breeds in feedlot,[3] %	100.0	72.7
Proportion of calf-fed beef breeds in feedlot,[4] %	—	14.4
Proportion of calf-fed dairy breeds in feedlot,[5] %	—	12.9
Proportion of cull beef/dairy animals in slaughter population,[6] %	25.7	18.5

[1]Further details of system characteristics are given in the Materials and Methods section.
[2]From USDA (2011).
[3]Derived from the proportions of calf-fed beef and dairy animals within the feedlot finishing system.
[4]Personal communication, Tom Field, National Cattlemen's Beef Association (Denver, CO).
[5]USDA (2000a).
[6]USDA/NASS (2008).

impact reduction in future years. The infrastructure similarities between the 1977 and 2007 production systems mean that the former cannot be classified as an extensive production system, yet efficiency gains within the 2007 system reduced resource use per unit of beef (Table 2). For example, it is acknowledged that, despite

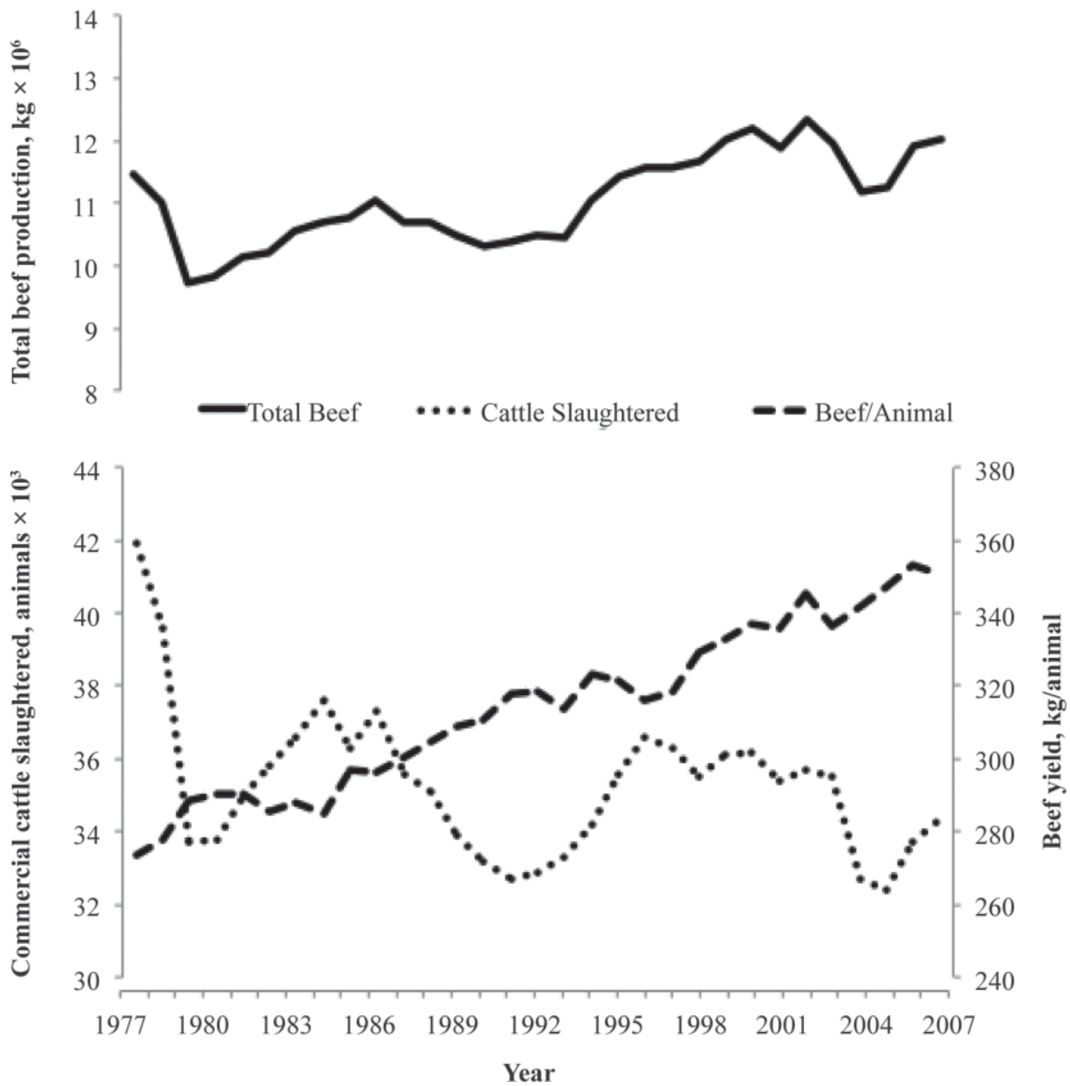

Figure 3. Changes in total US beef production, number of commercial cattle slaughtered, and beef yield per animal from 1977 to 2007.

Table 2. Comparison of resource inputs, waste output, and greenhouse gas emissions associated with producing 1 billion kg of beef in US production systems characteristic of the years 1977 and 2007

Variable	1977	2007
Beef produced, billion kg	10.6	11.9
Animals[1]		
Supporting population[2] ($\times 10^3$)	9,106	6,243
Stockers ($\times 10^3$)	2,896	1,767
Feedlot animals ($\times 10^3$)	2,776	2,322
Cull animals ($\times 10^3$)	941	523
Total animals slaughtered ($\times 10^3$)	3,656	2,831
Total population[3] ($\times 10^3$)	14,778	10,332
Nutrition resources		
Total energy requirement,[4] MJ $\times 10^6$	251,090	230,898
Feedstuffs, kg $\times 10^6$	72,883	59,320
Land, ha $\times 10^3$	9,116	6,106
Water, L $\times 10^9$	2,006	1,763
Fossil fuel energy, BTU $\times 10^9$	9,996	9,139
Waste output		
Manure, kg $\times 10^6$	50,636	41,076
N excretion, kg $\times 10^3$	500,162	438,858
P excretion, kg $\times 10^3$	48,055	43,088
Greenhouse gas emissions		
CH_4, kg $\times 10^3$	680,995	553,978
N_2O,[5] kg $\times 10^3$	9,157	8,153
C footprint,[6] kg of $CO_2 \times 10^6$	21,445	17,945

[1]Animal numbers not adjusted for the length of time spent within each subsystem.

[2]Includes cows (lactating and dry), preweaning calves, heifers (<12 mo and >12 mo of age), and bulls (adolescent, yearling, and mature).

[3]Includes all beef breed animals within the beef production system and calf-fed dairy animals but excludes cull animals.

[4]Refers to nutrients required for maintenance (all animals), pregnancy (dry cows), and growth (all growing, replacement, and finishing animals).

[5]Includes N_2O emissions from manure and inorganic fertilizer application.

[6]Includes CO_2 emissions from manufacture of cropping inputs, crop production and harvest, fuel combustion, electricity generation, and CO_2 equivalents from CH_4 and N_2O.

the low adoption rate of AI in the beef industry (USDA, 2009b), genetic advances between 1977 and 2007 have resulted in modern-day beef animals that differ phenotypically from the Angus and Hereford breeds of 1977.

Feedstuff and Land Use

Improvements in efficiency between 1977 and 2007 reduced total feedstuff use within the beef production system by 18.6% (13,563 $\times 10^6$ kg) per billion kilograms of beef. The magnitude of this difference compared with the difference in total energy use can be attributed to the increase in nutrient concentration of total feedstuffs in 2007 vs. 1997, resulting from an increase in concentrate feed use and reduced reliance on pasture as a greater proportion of animals entered the feedlot as calf-fed dairy and beef animals. It should be noted that the quantity of harvested feed (i.e., feed produced on cropland or as hay/straw rather than pasture) used within the beef production system does not necessarily represent total feed use because estimates of the amount of feed wasted range from 5 to 25% within production systems (Bolsen and Bolsen, 2006). Because of a paucity of comparative data for 1977, feed wastage is not included in the current analysis. If feed wastage were included, the difference between the 2 systems would be expected to increase slightly because there is no reason to expect that wastage was proportionally less in 1977 than in 2007. An intrinsic link exists between the quantity and quality of feed required for beef production and the area of land required to support this system. As the global population continues to increase, the land area devoted to animal agriculture, specifically ruminant livestock, is likely to continue to be an issue of major debate. The previously discussed effects of improved productivity upon population size and time to slaughter, in combination with increased cropping yields within the time period covered by this study, reduced land use per billion kilograms of beef from 9,116 $\times 10^3$ ha in 1977 to 6,106 $\times 10^3$ ha in 2007, a 33.0% decrease. The quantity of land required per unit of US beef produced in 2007 is greater than the upper limit of 43 m^2/kg of beef reported for European beef production systems by Nguyen et al. (2010). The reason for this difference is not immediately clear but may be attributed to the underlying assumption that highly productive pasture was used for grazing and silage production in the European model.

Several authors claim that world hunger could be abrogated if meat consumption decreased considerably (Pimentel and Pimentel, 2003; Millward and Garnett, 2010) because the quantity of land currently used to raise livestock could instead be used for human food crop production. There are several implicit flaws contained within this theory, including the assumption that a vegetarian or vegan diet would be acceptable to the global population, which is negated by the predictions of increased global milk and meat requirements by the FAO (2009), and the false assumption that crop production could be maintained for a wholly vegan population without an increasing reliance on fossil fuel-based fertilizers (Fairlie, 2010). Aside from these issues, the major point of contention is the supposition that land currently used to graze livestock could equally be used to grow corn, soybeans, or other human food crops. Partitioning out the quantity of land used for cropping (corn, soya, alfalfa) vs. pasture land in the current study shows that between 1977 and 2007, cropland use was reduced by 1,208 $\times 10^3$ ha/billion kg of beef and pasture land by 1,803 $\times 10^3$ ha/billion kg of beef, the proportionally greater decrease in pasture land resulting from the smaller number of beef cows (for whom pastureland is the main dietary component) required for beef production in 2007. The quantity of both cropland and pasture land available for agricultural use in the United States has continually decreased since 1945 (Lubowski et al., 2006), and it is not possible to determine whether the land released from beef production by improved animal efficiency would have been used for other animal production systems, human crop production, recreation, or urbanization. The cropping land released from the beef system could be used to grow other human food, yet pastureland used for ranching operations is generally unsuited for growing other crops due to climatic, topographic, or soil limitations. Indeed, data from the Economic Research Service of the USDA (Lubowski et al., 2006) indicates that only 8% of US grazed land is sufficiently productive to be classified as cropland pasture, yet it may remain marginal for crop use and be used for pasture for long periods of time. Given that forage is the major dietary component for animals within the cow-calf and stocker system and that 50 to 70% of the lifespan of a beef animal finished in a feedlot is spent grazing forage crops, the supposition that ruminants compete with humans for nutrient resources is unfounded. Nonetheless, increasing competition for land resources between food production, industrial, and social uses is an inevitable consequence of population growth.

As the body of knowledge relating to the nutrient requirements and ration formulation for ruminant livestock has become more advanced, the beef industry has served as an invaluable receptacle for by-products from the human food and fiber industries. Incorporation of nutrient-rich by-products such as distillers grains, potatoes, and citrus pulp into cattle rations has allowed for further reductions in land use and the conversion of unwanted vegetable material into high-quality animal protein (Fadel, 1999). By-product use within cattle rations is inherently region-specific and was therefore not accounted for within the current study; however, this omission overestimates the amount of land required for beef production in 2007. The importance of by-product feed utilization as a tool to reduce resource use in beef production should be noted.

Water Use

At a superficial level, water appears to be an entirely renewable resource within the beef production system, with an ongoing cycle of water use from the atmosphere, through plant material into the animal, and then back into the atmosphere. Although 110,000 km^3 of precipitation falls onto the surface of the earth annually (Food and Agriculture Organization of the United Nations, 2006), fresh water supplies are increasingly scarce due to a combination of excessive withdrawals, contamination, and loss of wetlands. All food production has an embedded water cost, but livestock production is often cited as a major consumer. Estimates of water use for beef production range from 3,682 L per kilogram of boneless beef (Beckett and Oltjen, 1993) to 20,555 L per kilogram of beef originating from the animal rights group People for the Ethical Treatment of Animals (PETA), the greatest values often being used to promote the suggestion that livestock production is too resource intensive to be environmentally sustainable. The Water Footprint Network (http://www.waterfootprint.org/) has published the most often-quoted figure for water consumption per kilogram of beef (15,500 L), which is used as a means to compare beef with other food products. However, the authors used global averages to calculate water usage, which were then assumed to be representative of individual beef production systems, regardless of region or productivity. By contrast, the thorough analysis of water consumption within beef production published by Beckett and Oltjen (1993) with system boundaries extending from feed production to processing reports the aforementioned water-use figure of 3,682 L per kilogram of boneless beef. Furthermore, the analysis of the Water Footprint Network included estimates of "green" water (i.e., supplied by precipitation to crops, rivers) and "grey" water (i.e., polluted or rendered unfit for other use by the production process) in addition to the more commonly used "blue" water (i.e., withdrawn from aquifers or other sources for direct production purposes), thus inflating the estimated consumption per unit of beef. The results shown in Table 2 demonstrate that water use as modeled within the current study is equivalent to 1,763 L per kilogram of beef in 2007, a decrease of 12.1% compared with the corresponding resource use in 1977. System boundaries within the current study were extended as far as the slaughterhouse door, thus processing was excluded and the functional unit was based on HCW rather than boneless weight. However, it is predicted that values similar to those obtained by Beckett and Oltjen (1993) would be reported if the system boundaries were extended to include the processing stage. As demonstrated by the other resource use metrics within the current study, improved animal productivity was the main factor affecting the reduced water use per kilogram of beef in 2007 compared with 1977, yet crop productivity (yield per hectare) also played an important role. The proportion of irrigated cropland (corn for silage and grain, soybeans, pasture) increased between 1977 and 2007 for all crops within the current study, with changes in irrigation water use per hectare varying between crops. Average US precipitation and temperature data from the National Climatic Data Center (2011) for the 2 yr in question demonstrate that the 2 time points were climatically similar; thus differences in irrigation use may have been skewed by region-specific weather. Nonetheless, increased crop yields per hectare resulted in reduction in water use per kilogram of feed of 19% for corn silage, 65% for corn grain, 89% for soybeans, and 14% for pasture in 2007 compared with 1977.

Nutrient Excretion

Livestock production industries within the United States have undergone considerable consolidation since the end of WWII, and the number of operations within all subsystems of the beef industry have declined over the past 30 yr as production has become increasingly specialized and region-specific. The quality of knowledge and modern computational resources relating to animal nutrient requirements and ration formulation are far superior to those available in 1977. In combination with the previously discussed improvements in productivity that have reduced manure output per unit of beef by 9,560 × 10^6 kg, N excretion has decreased by 12.3% (438,858 × 10^3 kg vs. 500,162 × 10^3 kg), and P excretion by 10.3% (43,088 × 10^3 kg vs. 48,055 × 10^3 kg) between 1977 and 2007. This represents a critical move forward in US beef industry sustainability, which must continue to improve in the future. Nonetheless, it is acknowledged that an industry-wide reduction in nutrient excretion does not imply a concurrent reduction in point-source water pollution incidents.

GHG Emissions and Fossil Fuel Use

The C footprint of livestock production is one of the most widely discussed environmental issues within the current agricultural arena because of its association with nonrenewable resource consumption and climate change. Historical analyses always carry a certain burden of uncertainty based on the data available; however, the current study suggests that the shift toward agricultural intensification between 1977 and 2007 reduced fossil fuel use per billion kilograms of beef from 9,996 × 10^9 BTU to 9,139 × 10^9 BTU. This is energetically equivalent to 25,991 × 10^3 L of gasoline. This is notable given that corn production is one of the major contributors to fossil fuel use within beef production and the average time period on a corn-based diet was increased in the 2007 production system.

It is difficult to assess the C footprint of any production process in isolation. Without reference to a baseline number, the final result lacks context and is of limited value save for as a marker comparison for future studies. A paucity of data are available on the changes in C footprint of other animal protein sources within the US livestock industry over time, with published literature to date being confined to dairy production (Capper et al., 2009). The C footprint per billion kilograms of beef within the current study was 17,945 × 10^6 kg CO_2-equivalents in 2007 compared with 21,445 × 10^6 kg CO_2-equivalents in 1977, the 16.3% reduction resulting from improved efficiency and productivity that reduced C emissions from crop production, enteric fermentation, manure, and fossil fuel combustion. Variations in methodology and system boundaries make interstudy comparisons difficult to validate; however, it is worth noting that the C footprint of the 2007 system was at the lower end of the range of values for beef reported by de Vries and de Boer (2010) and was within the limits reported by Nguyen et al. (2010) for European beef systems. Life cycle analyses of 3 beef-finishing scenarios (calf-fed, yearling-fed, and grass-finished) in the upper Midwestern United States were undertaken by Pelletier et al. (2010), who reported GHG emissions of 23.9 kg of CO_2-equivalents/kg of beef and 26.1 kg of CO_2-equivalents/kg of beef for calf-fed and yearling-fed scenarios, respectively, when corrected for a predicted dressing percentage of 62%. Although these scenarios were undertaken as whole-system analyses, it is difficult to make a direct comparison or validation of the results as the finishing systems within each scenario in Pelletier et al. (2010) that contained animals from beef breeds (i.e., calf-fed or yearling-fed only) and did not contain any input from the dairy sector. Nonetheless, the trend for improved productivity and efficiency to reduce environmental impact was consistent with the calf-fed system in Pelletier et al. (2010; with increased growth rates and reduced days to finish because of the greater nutrient density of the diet) compared with the yearling-fed system, as it is in the current study comparing 1977 and 2007.

Recent studies evaluating the C footprint of beef production practices characteristic of Brazil (Cederberg et al., 2009a), Sweden (Cederberg et al., 2009b), and Japan (Ogino et al., 2004) have reported greater total GHG emissions than those from the current study, ranging from 19.8 kg of CO_2-equivalents/kg of beef (Sweden) to 32.3 kg of CO_2-equivalents/kg of beef (Japan) per retail kilogram of beef at a 40% yield. By contrast, Peters et al. (2010) calculated that Australian grain-finished beef production emits 9.9 kg of CO_2-equivalents/kg of beef. The time point and methodology-specific nature of these studies means that conclusions cannot be drawn as to the relative environmental ranking of different global regions; however, it underlines the effect of system and efficiency variation upon environmental impact.

The US beef and dairy production systems are connected by the movement of dairy calves into the growing/finishing beef system and cull dairy cows into the beef processing chain. Because all surplus dairy calves were diverted into veal rather than beef production in 1977, it is not surprising that the proportion of the total C footprint per unit of beef attributable to dairy production was less in 1977 (2.6%) compared with 2007 (4.0%). The extent to which resource use and waste output can be attributed to either system depends entirely on the allocation method used; thus further research is recommended to gather an indication of the environmental impact of the entire US large ruminant system.

Reduced GHG emissions resulting from a decrease in feed and animal transportation is often claimed as an environmental advantage of "local" or extensive production systems (Nicholson et al., 2011). Whole-system sustainability can only be achieved by making improvements within each individual component of the beef system; however, within the current study, the contribution of transportation to the total C footprint of a billion kilogram of beef constituted less than 1% (0.71% in 1977, 0.75% in 2007), with the majority of GHG emissions resulting from enteric fermentation and manure. Due to the lack of published data for animal and feedstuff transport for either year, the distances used within the current study had to be derived from crop and animal production site data and transport information from Foster et al. (2006) and were therefore assumed rather than verified distances. Nonetheless, reliable data for vehicle carrying capacity and fuel efficiency were used to calculate fuel use and GHG emissions from transport; thus the proportional contribution of transportation to the total C footprint of beef production is unlikely to vary considerably from the results obtained. These data suggest that the potential opportunity to mitigate the environmental impact of beef production through transportation efficiency is limited.

The rationale behind the current study was not to definitively define the C footprint or environmental impact of US beef production, but rather to assess the effects of efficiency gains within the system between 1977 and 2007. It should be noted that the time point-specific nature of this data and the continuing evolution of the science behind environmental impact assessment means that definition of a single number to represent beef production is dangerous, if not impossible. Given the uncertainties involved with gathering historical data relating to resource use, the data presented are not intended to represent the exact quantities of resource use or waste output within this study; however, the environmental impact differences between systems are important indicators of the effects of improved efficiency.

Conclusions

As conversations relative to sustainability continue, it is crucial to identify areas for future improvement within all sections of the chain, with the results of this paper and others within the literature used as benchmarks. It is clear that improving productivity is key to reducing the environmental impact of beef production, yet anecdotal evidence from the current beef industry suggests that beef yield per animal has reached a plateau. The processing/packing industry infrastructure is not currently equipped to deal with animals weighing considerably more than 600 kg, and consumers are unlikely to demand greater portion sizes in the future. Further investigation into the contributions made by improved growth rates, fertility, morbidity, mortality, and forage management are therefore essential to better understand and apply the management practices by which the industry can continue to provide sufficient animal protein to satisfy the market while continuing to reduce resource use and waste output per unit of beef.

LITERATURE CITED

AMTS. 2006. Cattle Pro. Cornell Research Foundation, Ithaca, NY.

Barnhart, S., M. Duffy, and D. Smith. 2008. Estimated Costs of Pasture and Hay Production. Iowa State University, Ames.

Beckett, J. L., and J. W. Oltjen. 1993. Estimation of the water requirement for beef production in the United States. J. Anim. Sci. 71:818–826.

Bolsen, K., and R. Bolsen. 2006. A trouble-shooter for common silage problems. In Southwest Nutrition and Management Conference, February 24, 2006, Tempe, AZ. University of Arizona, Tempe.

Capper, J. L. 2010. The environmental impact of conventional, natural and grass-fed beef production systems Proc. Greenhouse Gases and Anim. Agric. Conf. 2010, Banff, Canada.

Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87:2160–2167.

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

Cardon, P. V., W. R. Chapline, T. E. Woodward, E. W. McComas, and C. R. Enlow. 1939. Pasture and Range in Livestock Feeding. Page 925 in USDA Yearbook of Agriculture, 1939. USDA, Washington, DC.

Cederberg, C., D. Meyer, and A. Flysjo. 2009a. Life Cycle Inventory of Greenhouse Gas Emissions and Use of Land and Energy in Brazilian Beef Production. The Swedish Institute for Food and Biotechnology, Gothenburg, Sweden.

Cederberg, C., U. Sonesson, M. Henriksson, V. Sund, and J. Davis. 2009b. Greenhouse Gas Emissions from Swedish Production of Meat, Milk and Eggs: 1990 and 2005. The Swedish Institute for Food and Biotechnology, Gothenburg, Sweden.

Davis, S. C., S. W. Diegel, and R. G. Boundy. 2009. Transportation Energy Data Book: Edition 28. Oak Ridge National Laboratory, Oak Ridge, TN.

Deutsch, C. H. 2007 Aug. 29. Eating meat worse for planet than driving, animal rights groups say. New York Times, New York, NY.

de Vries, A., and I. J. M. de Boer. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest. Sci. 128:1–11.

Energy Information Administration. 2001. Updated State-level Greenhouse Gas Emission Factors for Electricity Generation. US Department of Energy, Washington, DC.

Fadel, J. G. 1999. Quantitative analyses of selected plant by-product feedstuffs, a global perspective. Anim. Feed Sci. Technol. 79:255–268.

Fairlie, S. 2010. Meat—A Benign Extravagance. Chelsea Green Publishing, White River Junction, VT.

FAO. 2006. Livestock's Long Shadow—Environmental Issues and Options. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2009. How to Feed the World in 2050. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. Food and Agriculture Organization of the United Nations, Rome, Italy.

Forde, K., A. Hillberg-Seitzinger, D. Dargatz, and N. Wineland. 1998. The availability of state-level data on interstate cattle movements in the United States. Prev. Vet. Med. 37:209–217.

Foster, C., K. Green, M. Bleda, P. Dewick, B. Evans, A. Flynn, and J. Mylan. 2006. Environmental Impacts of Food Production and Consumption: A Report to the Department for Environment, Food and Rural Affairs. Manchester Business School, DEFRA, London, UK.

Grandin, T. 2001. Livestock Trucking Guide. Natl. Inst. Anim. Agric., Bowling Green, KY.

Humane Society of the United States. 2009. AN HSUS Report: The Impact of Industrialized Animal Agriculture on World Hunger. HSUS, Washington, DC.

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES) for the IPCC, Kanagawa, Japan.

IPCC. 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report

of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva.
Kaspar, H. F., and J. M. Tiedje. 1981. Dissimilatory reduction of nitrate and nitrite in the bovine rumen: Nitrous oxide production and effect of acetylene. Appl. Environ. Microbiol. 41:705–709.
Keyzer, M. A., M. D. Merbis, I. F. P. W. Pavel, and C. F. A. van Wesenbeeck. 2005. Diet shifts towards meat and the effects on cereal use: Can we feed the animals in 2030? Ecol. Econ. 55:187–202.
Kirchgessner, M., W. Windisch, H. L. Müller, and M. Kreuzer. 1991. Release of methane and of carbon dioxide by dairy cattle. Agribiol. Res. 44:2–9.
Koneswaran, G., and D. Nierenberg. 2008. Global farm animal production and global warming: Impacting and mitigating climate change. Environ. Health Perspect. 116:578–582.
Kratz, J. L., C. J. Wilcox, F. G. Martin, D. E. Franke, and R. B. Becker. 1977. Vital statistics of U.S. and Canadian AI beef sires. J. Anim. Sci. 45:43–47.
Lubowski, R. N., M. Vesterby, S. Bucholtz, A. Baez, and M. J. Roberts. 2006. Major Uses of Land in The United States, 2002. Economic Information Bulletin Number 14, USDA/ERS, Washington, DC.
Ludington, D., and R. C. Peterson. 2005. How much energy does your dairy use? Northeast Dairy Business September:20–21.
Meyer, U., W. Stahl, and G. Flachowsky. 2006. Investigations on the water intake of growing bulls. Livest. Sci. 103:186–191.
Miller, S. P., and J. W. Wilton. 1999. Genetic relationships among direct and maternal components of milk yield and maternal weaning gain in a multibreed beef herd. J. Anim. Sci. 77:1155–1161.
Miller, S. P., J. W. Wilton, and W. C. Pfeiffer. 1999. Effects of milk yield on biological efficiency and profit of beef production from birth to slaughter. J. Anim. Sci. 77:344–352.
Millward, D. J., and T. Garnett. 2010. Food and the planet: Nutritional dilemmas of greenhouse gas emission reductions through reduced intakes of meat and dairy foods. Proc. Nutr. Soc. 69:103–118.
Moe, P. W., and H. F. Tyrrell. 1979. Methane production in dairy cows. J. Dairy Sci. 62:1583–1586.
National Climatic Data Center. 2011. NNDC Climatic Data Online. National Climatic Data Center, Asheville, NC.
Nguyen, T. L. T., J. E. Hermansen, and L. Mogensen. 2010. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18:756–766.
Nicholson, C. F., M. I. Gómez, and O. H. Gao. 2011. The costs of increased localization for a multiple-product food supply chain: Dairy in the United States. Food Policy 36:300–310.
Nierenberg, D. 2005. Happier Meals: Rethinking the Global Meat Industry. Worldwatch Paper 171, Worldwatch, Washington, DC.
NRC. 2000. Nutrient Requirements of Beef Cattle. Natl. Acad. Press, Washington, DC.
Ogino, A., K. Kaku, T. Osada, and K. Shimada. 2004. Environmental impacts of the Japanese beef-fattening system with different feeding lengths as evaluated by a life-cycle assessment method. J. Anim. Sci. 82:2115–2122.
Pelletier, N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agric. Sys. 103:380–389.
Peters, G. M., H. V. Rowley, S. Wiedemann, R. Tucker, M. D. Short, and M. Schulz. 2010. Red meat production in Australia: Life cycle assessment and comparison with overseas studies. Environ. Sci. Technol. 44:1327–1332.
Pimentel, D., and M. Pimentel. 2003. Sustainability of meat-based and plant-based diets and the environment. Am. J. Clin. Nutr. 78:660S–663S.
Pimentel, D., and M. Pimentel. 2007. Food Energy and Society. 3rd ed. CRC Press, Boca Raton, FL.
Pitesky, M. E., K. R. Stackhouse, and F. M. Mitloehner. 2009. Clearing the air: Livestock's contribution to climate change. Adv. Agron. 103:3–40.
Rydberg, T., and J. Jansen. 2002. Comparison of horse and tractor traction using energy analysis. Ecol. Eng. 19:13–28.
Sellers, H. I., R. L. Willhelm, and R. C. DeBaca. 1970. Effect of certain factors on weaning weight of beef calves. J. Anim. Sci. 31:5–12.
Shields, D. A., and K. A. Mathews. 2003. Interstate Livestock Movements. USDA/ERS, Washington, DC.
Singer, P., and J. Mason. 2006. The Way We Eat: Why Our Food Choices Matter. 1st ed. Rodale Books, Emmaus, PA.
Skinner, R. H. 2008. High biomass removal limits carbon sequestration potential of mature temperate plants. J. Environ. Qual. 37:1319–1326.
Sukyer, A. E., and S. B. Verma. 2001. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. Glob. Change Biol. 7:279–289.
US Census Bureau. 2008. Total Midyear Population for the World: 1950–2050. US Census Bureau, Washington, DC.
USDA. 1977. Cattle. USDA, Washington, DC.
USDA. 2000a. Part I: Baseline Reference of Feedlot Management Practices, 1999. USDA-APHIS-VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO.
USDA. 2000b. Part II: Baseline Reference of Feedlot Health and Health Management, 1999. USDA-APHIS-VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO.
USDA. 2007. Dairy 2007, Part I: Reference of Dairy Cattle Health and Management Practices in the United States, 2007. USDA-APHIS-VS, Fort Collins, CO.
USDA. 2009a. Beef 2007–08 Part I: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA-APHIS-VS, Fort Collins, CO.
USDA. 2009b. Beef 2007–08 Part II: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA-APHIS-VS, Fort Collins, CO.
USDA. 2011. Data and Statistics. Accessed May 2011. http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp.
USDA/ERS. 1975. Livestock Trucking Services: Quality, Adequacy and Shipment Patterns. USDA/ERS, Washington, DC.
USDA/ERS. 2010a. Data Sets: Fertilizer Use and Price. USDA/ERS, Washington, DC.
USDA/ERS. 2010b. Livestock and Poultry Outlook LDP-M-192. USDA/ERS, Washington, DC.
USDA/NASS. 1979. 1979 Census of Agriculture: Farm and Ranch Irrigation Survey. USDA, Washington, DC.
USDA/NASS. 2006. Agricultural Chemical Usage 2005 Field Crops Summary. USDA-NASS, Washington, DC.
USDA/NASS. 2007a. Agricultural Chemical Usage 2006 Field Crops Summary. USDA-NASS, Washington, DC.
USDA/NASS. 2007b. Cattle Report. USDA, Washington, DC.
USDA/NASS. 2007c. 2007 Census of Agriculture: Farm and Ranch Irrigation Survey. USDA-NASS, Washington, DC.
USDA/NASS. 2008. Livestock Slaughter 2007 Summary. USDA, Washington, DC.
USDA/NASS. 2010. Livestock Slaughter Annual Summary. USDA, Washington, DC.
US EPA. 2010. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008. US EPA, Washington, DC.
West, T. O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91:217–232.
Wiltbank, J. N. 1970. Research needs in beef cattle production. J. Anim. Sci. 31:755–762.
Wiltbank, J. N. 1974. Management programs to increase reproductive efficiency of beef herds. J. Anim. Sci. 38:58–67.