



SUSTAINABLE ANIMAL SCIENCE AND PRACTICES

The effects of improved performance in the U.S. dairy cattle industry on environmental impacts between 2007 and 2017

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Abstract

The U.S. dairy industry considerably reduced environmental impacts between 1944 and 2007, primarily through improved dairy cow productivity. However, although milk yield per cow has increased over the past decade, whole-system environmental impact analyses have not been conducted over this time period, during which environmental modeling science has improved considerably. The objective of this study was to compare the environmental impact of U.S. dairy cattle production in 2007–2017. A deterministic model based on population demographics, metabolism, and nutrient requirements of dairy cattle was used to estimate resource inputs, nutrient excretion, and greenhouse gas (GHG) emissions per 1.0×10^6 t (one million metric t or MMT) of energy-corrected milk (ECM) produced in 2007 and 2017. System boundaries extended from the manufacture and transport of cropping inputs to milk at the farm gate. Milk transport, processing, and retail were not included. Dairy systems were modeled using typical management practices, herd population dynamics, and production data from U.S. dairy farms. Cropping data were sourced from national databases. The resources required to produce 1.0 MMT ECM in 2017 were considerably reduced relative to those required in 2007, with 2017 production systems using 74.8% of the cattle, 82.7% of the feedstuffs, 79.2% of the land, and 69.5% of the water as compared to 2007. Waste outputs were similarly reduced, with the 2017 U.S. dairy industry producing 79.4%, 82.5%, and 85.7% of the manure, N, and P excretion, respectively. Dairy production in 2017 emitted 80.9% of the CH_4 and 81.5% of the N_2O per 1.0 MMT ECM compared to 2007. Enteric and manure emissions contributed the major proportion (80%) of GHG emissions per unit of milk, with lesser contributions from cropping (7.6%) and fertilizer application (5.3%). The GHG emissions per 1.0 MMT ECM produced in 2017 were 80.8% of equivalent milk production in 2007. Consequently, although total U.S. ECM production increased by 24.9% between 2007 and 2017, total GHG emissions from this milk production increased by only 1.0%. In line with previous historical analyses, the U.S. dairy industry has made remarkable productivity gains and environmental progress over time. To maintain this culture of continuous improvement, the dairy industry must build on gains made to date and demonstrate its commitment to reducing environmental impacts while improving both economic viability and social acceptability.

Key words: carbon footprint, dairy, dilution of maintenance, environmental impact, greenhouse gas, productive efficiency

Introduction

The environmental impact of producing animal source foods is a critical topic of policy discussion in domestic and international governments, social media, the popular press, and the consumer marketplace. In 2006, the U.S. dairy industry, in conjunction with other livestock industries worldwide, was rocked by an [Food and Agricultural Organization of the United Nations \(FAO\) \(2006\)](#) assertion that livestock contributed more to global greenhouse gas (GHG) emissions than transportation. This claim was withdrawn after critical review ([Pitesky et al., 2009](#)) and has since been revised, with current estimates suggesting that global livestock production accounts for 14.5% and dairy, specifically, for 2.9% of GHG emissions ([FAO, 2013](#)). Nonetheless, livestock's contribution to the environmental impacts associated with food production are significant concerns for all food chain stakeholders, including livestock producers who play a major role in reducing environmental impacts per unit of food. The environmental impacts of improving livestock productivity have been demonstrated in multiple studies, ranging from historical analyses of the impacts of improving dairy cattle productivity between 1944 and 2007 ([Capper et al., 2009](#)) to comparisons between specific dairy breeds ([Capper and Cady, 2012](#)), livestock production systems ([Olesen et al., 2006](#); [Weiske et al., 2006](#); [Capper et al., 2008](#); [Bartl et al., 2011](#); [Christie et al., 2011](#); [Gerber et al., 2011](#)), regions ([FAO, 2010](#)), or key performance indicators (KPI) and associated traits ([Garnsworthy, 2004](#); [Casey and Holden, 2005](#); [Bell et al., 2011](#); [Zehetmeier et al., 2011](#); [Wall et al., 2012](#); [Bell et al., 2013](#); [White, 2016](#); [Mostert et al., 2018](#); [Özkan Gülzaria et al., 2018](#)). As dairy systems become more productive, efficiency improves via the dilution of maintenance effect ([Bauman et al., 1985](#); [VandeHaar and St-Pierre, 2006](#)) and both resource use and GHG emissions are reduced per unit of milk, yet monitoring changes in food production processes, yields, and environmental impacts is a time-consuming and expensive undertaking. Therefore, point-in-time estimates become dated very quickly yet continue to be widely cited, often leading to incorrect conclusions regarding progress to reduce environmental impacts of food production. Despite the Memorandum of Understanding between the U.S. Department of Agriculture (USDA) and the Innovation Center for U.S. Dairy ([USDA, 2018](#)), with the goal of reducing GHG emissions from the U.S. dairy cattle industry by 25% by 2020 (compared to a 2007 baseline), there is little information available on the gains conferred by improved nutrition, genetics, technology, and management over the past decade. Additionally, from 2007 to 2017, U.S. milk production increased from 14.7% of global cattle milk market share to 15.6%, while the U.S. milking cow population declined slightly from 3.7% to 3.4% of the global dairy cattle population in spite of a slight numerical increase ([FAO, 2019](#)). The last in-depth quantifications of the environmental impact of U.S. milk production were based on data from the middle of the last decade ([Capper et al., 2009](#); [Thoma et al., 2013](#)). Milk yield has continued to increase in U.S. dairy cows since the 1950s, increasing by an average of 1.4% compounded annually between 1980 and 2017, while annual milk yield per cow has increased linearly, with a regressed mean of 141 kg/yr ([USDA, 2019](#)). Furthermore, other animal and herd performance factors have changed (e.g., milk composition, age at first calving, and calving interval), which are important for quantifying dairy's environmental footprint ([Capper and Cady, 2012](#)). We used a more detailed, updated deterministic model based on cattle nutrition, metabolism, and herd population parameters to update the information previously published by [Capper](#)

[et al. \(2009\)](#) to estimate the changes in environmental impacts (resource use, nutrient excretion, and GHG emissions) resulting from improvements in U.S. dairy herd performance, milk yield, and crop production over the decade from 2007 to 2017.

Materials and Methods

Environmental impact was assessed using a deterministic model based on animal nutrition, metabolism, and herd population parameters founded on life cycle assessment (LCA) principles. Given that this study used data from existing published reports and databases, approval from an animal care and use committee was not required. The evaluation was designed to compare the environmental impact (resource use, nutrient excretion, and GHG emissions) of U.S. milk production from dairy cattle over the decade between 2007 and 2017. Cropping and dairy systems were modeled according to typical characteristic practices and performance metrics for the two time points according to published production data, with system inputs, cattle demographic dynamics, and basic procedures as first described by [Capper et al. \(2008\)](#) and later updated in [Capper et al. \(2009\)](#) and [Capper and Cady \(2012\)](#).

System boundaries extended from the production of feed and forage crops (including manufacture of cropping inputs, e.g., herbicides, pesticides, and fertilizers, plus water used for irrigation) through to and including milk harvest. The impacts of milk transportation, off-farm processing, packaging, and consumption were not included, neither were specific on-farm technologies and practices (e.g., manure processing and application) not directly related to animal feeding, care, and handling. A number of coproducts and byproducts originate from dairy cattle production, including (but not limited to) beef, veal, leather, pharmaceuticals, and bone meal. Ideally, the total environmental impact would be allocated between the principal product (milk) and all coproducts and byproducts; however, this was beyond the scope of the current investigation. To provide consistency with the [Capper et al. \(2009\)](#) paper and to ensure that the results were as conservative as possible, the decision was, therefore, made not to apply allocation within this analysis. The functional unit by which environmental impact was assessed was the production of 1.0×10^6 t (one million metric tons or MMT) of salable energy-corrected milk (ECM) calculated from the [Tyrrell and Reid \(1965\)](#) formula: $ECM = (0.327 \times M) + (12.95 \times MF) + (7.2 \times MP)$, where M is kg of milk, MF is kg of milk fat, and MP is kg of milk protein. The fundamental unit of evaluation was one animal day (AD; impact of a single animal in 1 d) for various age by gender groups within the U.S. dairy cattle population. Because annual averages were the source of input data, annual impact was based on an animal year (AY: $365 \times$ number of required AD). An AY is equivalent to one animal per year. There was no accounting for seasonality effects and herd size and the rate of passage of animals through the population was assumed constant within a single year. This analysis was an extension of the previous [Capper et al. \(2009\)](#) report, yet a new 2007 baseline was established for several reasons, including: the fundamental unit of milk production being more accurately expressed as ECM, whereas, in the 2009 report, it was simply quantified on the basis of milk yield (not accounting for component composition); greater detail in the evaluation model and processes; original data inputs for 2007 being updated or no longer available; and revision of global warming constants by the Intergovernmental Panel on Climate Change ([IPCC, 2013](#)). Upgrades to the model since the previous reports include a more

detailed heifer demographic model based on monthly growth and mortality data, interpolating data published by [USDA \(2007b\)](#) from birth to first calving, and accounting for culling by parity number; thus, having a population distribution by lactation number more representative of the population. Fitting all performance data within the model started with describing lactation curves for each year \times lactation based on [Keown et al. \(1986\)](#) and shown in [Figures 1a and b](#). An iterative process was employed to accurately estimate the required number of AD for each lactation while preserving the proportion of the population in each lactation. Due to these updates, results within this report cannot be directly appended to results reported in [Capper et al. \(2009\)](#) to obtain a precise delta across the entire time frame of 1944–2017 and, therefore, must be confined to the time period 2007–2017.

Milk production, composition, and cow performance data varied in availability, accuracy, and national coverage according to the data source; however, given that the USDA tracks all milk sales across the United States, a USDA–NASS database ([USDA, 2019](#)) was considered to be the most appropriate source for production statistics; whereas sourcing milk composition data from the DairyMetrics subscription database ([Dairy Records Management Systems \[DRMS\], 2018](#)), which is based on individual cow data rather than data from pooled tanker loads of milk across multiple farms, was considered to be more relevant. Documentation of the extent of the U.S. dairy cow population and milk production was, therefore, extracted from the USDA–NASS database using the Quick Stats Tool ([USDA, 2019](#)). Average national performance data were captured from the DairyMetrics database, with performance data for 2007 based on weighted averages of preserved historical queries made on November 1, 2004, March 14, 2005, and September 29, 2010. This procedure

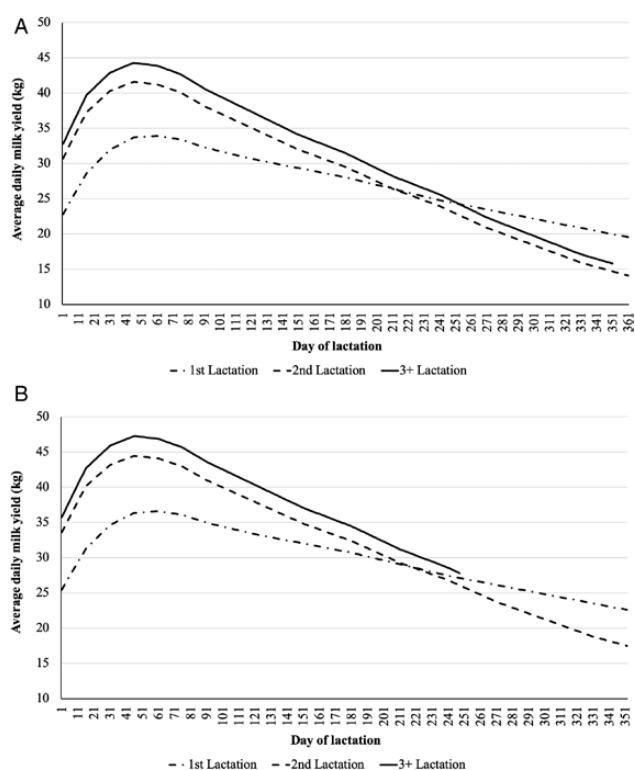


Figure 1 (a) Estimated lactation curves for cows in first, second, and third parity in 2007, derived from [Keown et al. \(1986\)](#). (b) Estimated lactation curves for cows in first, second, and third parity in 2017, derived from [Keown et al. \(1986\)](#).

was used because the DairyMetrics database is updated daily and it was not possible using standard consultant queries to retrieve historical averages at a specific time point and because the historical data records from the original 1944–2007 report were no longer available. Performance metrics for 2017 were based on an average of DairyMetrics queries performed on February 3 and February 27, 2018. Average performance metrics from DRMS were based on an average of 1.96 million cows from 14,232 herds and 2.19 million cows from 11,387 herds of all breeds from all major dairy regions of the United States for 2007 and 2017, respectively.

Baseline population and performance metrics for both years are summarized in [Table 1](#). In the intervening decade between 2007 and 2017, total milk production increased by 16.0% (84.2×10^6 t to 97.7×10^6 t) with a modest 2.2% increase in cow numbers from 9.19 to 9.39 million. Annual milk yield per cow increased from 9,164 kg/yr to 10,406 kg/yr (+13.6%). Contrary to longstanding expectations of an inverse relationship between milk yield and component concentrations, milk fat and protein percentages increased by 12.1% and 10.3%, respectively, resulting in a 22.3% increase in annual ECM yield per cow from 9,150 kg/yr (2007) to 11,195 kg/yr (2017). Dividing expected lifetime yield by average days of life from birth to end of life in the herd (whether by death or removal) resulted in an average daily milk yield per day of life of 19.1 kg ECM/d in 2007 compared to 22.6 kg ECM/d in 2017, an 18.7% increase.

Various cattle performance factors were included in the model to account for changes in management over time. Somatic cell count (SCC) was added to the model as a proxy to estimate milk loss resulting from both increases in SCC and mastitis incidence. Average SCC decreased from 350,000 to 250,000 between 2007 and 2017, indicating reduced losses of salable milk. Calving interval decreased from 14.0 mo to 13.6 mo between 2007 and 2017 and, when combined with a slightly shorter dry period (60 d in 2007 compared to 57 d in 2017), increased the percentage of productive days during an individual cow's life within the milking herd. The overall replacement rate of mature cows by heifers increased from 33.7% to 36.9%, despite the death rate being virtually unchanged from 5.3% to 5.2%. This increase in replacement rate may be due to the increased availability of heifers from the use of sexed semen, which was not accounted for in this analysis. The increased replacement rate and shorter calving intervals in 2017 combined to shorten the average days of life in the herd by 138 d (4.5 mo), yet cattle produced an additional 2,705 kg total lifetime ECM. The average calving percentage increased from 102% annually to 108%, a further indication that more heifers were available for replacement in 2017, which again may have been due to increased use of sexed semen. A 9-d reduction in age at first calving in 2017 (25.7 mo compared to 26.0 mo in 2007) also contributed to the increased calving percentage. No national summary of dairy heifer replacement mortality and morbidity has been published since the [USDA \(2007b\)](#) report; therefore, heifer mortality was considered unchanged. However, because heifers were calving earlier, it was assumed that they were growing somewhat faster in order to achieve the same weight at first calving.

The dairy cattle population for each time point (2007 or 2017) contained both productive animals (lactating cows) and supporting nonmilk-yielding animals (dry cows, replacement heifers, and young and mature bulls) as shown in [Table 2](#). The average primiparous dairy cow weighed 612 kg in 2007 and 635 kg in 2017, and the average multiparous cow weighed 726 kg and 748 kg in 2007 and 2017, respectively. Calves not destined as herd replacement animals (e.g., bull calves,

Table 1. Key data input metrics for the 2007 and 2017 U.S. dairy cattle populations

Production parameter	2007	2017
Total U.S. production ¹ , kg/yr	8.42 × 10 ¹⁰	9.77 × 10 ¹⁰
Lactation-age females in national herd ¹ , head	9.19 × 10 ⁶	9.39 × 10 ⁶
Milk yield per cow ¹ , kg/yr	9,164	10,406
Milk fat content (all parities) ² , %	3.56	3.99
Milk protein content (all parities) ² , %	2.92	3.22
Total U.S. ECM production ³ , kg/yr	8.41 × 10 ¹⁰	10.51 × 10 ¹⁰
Energy-corrected milk yield (ECM) ³ , kg/yr	9,150	11,195
ECM lifetime milk yield ³ , kg	31,184	33,889
ECM daily yield per lactating cow ⁴ , kg/d	28.6	36.1
ECM yield per day of life (birth to cull/death) ⁴ , kg	19.1	22.6
Somatic cell count ⁵ , '000 cells/ml	350	250
Calving interval ⁶ , d	426	414
Dry period length ² , d	60	57
Lactation length ² , d	366	357
Cow mortality ² , %	5.3	5.2
Expected number of lifetime lactations ²	2.97	2.71
Average days of life (birth to cull/death) ² , d	1,634	1,496
Overall replacement rate ² , %	33.7	36.9
Cows conceiving to natural service ⁷ , %	30	30
Cows conceiving to artificial insemination ⁷ , %	70	70
Bull:cow ratio (natural service) ⁸	1:25	1:25
Calving rate ² , %	102.1	108.0
Bull:heifer calf sex ratio ⁹	51:49	51:49
Twinning rate ¹⁰ , %	5.0	5.0
Mixed sex twins ¹⁰ , %	50	50
Stillborn calves ¹¹ , %	5.6	5.6
Heifer calf mortality (live birth—weaning) ⁶ , %	6.8	6.8
Heifer mortality (weaning—breeding) ⁶ , %	1.9	1.9
Heifer reproductive failure ⁶ , %	4.0	4.0
Overall heifer loss (birth to milking herd entry) ⁶ , %	19.1	19.1
Age at first calving ² , mo	26.0	25.7
Diet forage ingredients ¹²	Alfalfa hay Corn silage Grass hay Wheat straw	Alfalfa hay Corn silage Grass hay Wheat straw
Diet concentrate ingredients ¹²	Corn grain Soybean meal	Corn grain Soybean meal
Diet type ¹²	Total mixed ration	Total mixed ration

¹USDA (2019).²Calculated as a function of data from DRMS DairyMetrics database (DRMS, 2018) with 2007 data as a weighted average of data accessed on November 1, 2004, March 14, 2005, and September 29, 2010; and 2017 averaged from data accessed on February 3 and 27, 2018.³Estimated using formula from Tyrrell and Reid (1965).⁴Calculated from ECM yield and average days of life.⁵Rounded to the nearest SCC from the DairyMetrics (DRMS, 2018) SCS score.⁶Estimated as a function of mortality data sourced from USDA (2007b).⁷Derived from de Vries et al. (2008).⁸Derived from Overton (2005).⁹Data from review of Cady (1977), Powell et al. (1975), and Silva Del Rio et al. (2007).¹⁰Data from review of Cady and Van Vleck (1978) and Silva Del Rio et al. (2007).¹¹USDA (2007b).¹²Derived from USDA (2016).

freemartins, and excess heifers) were assumed to enter the beef supply chain immediately after birth and, therefore, their contribution to dairy's environmental impact was de minimis. Average sex ratio, ignoring that conferred by sexed semen use, and twinning rate (Table 1) were used to estimate the number of heifer calves born per year. The percentage of mixed sex twins was used to estimate the number of freemartins to be removed from the replacement population. Mortality rates as outlined by USDA (2007b) were allocated across months of life between birth and first calving to determine survivability of

newborn fertile heifers. Heifer growth rates were based on the optimum growth curves published by Heinrichs and Losinger (1998), assuming a weight at first calving of 85% of dairy cow mature weight. Therefore, heifers in the 2007 population reached 617 kg bodyweight at first calving (26.0 mo), with an average weight of 556 kg between conception and parturition and average daily liveweight gains (DLWG) of 0.79 kg/d preconception and 0.62 kg/d precalving compared to heifers in the 2017 population reaching 636 kg bodyweight at first calving (25.7 mo), an average weight of 573 kg between conception and

Table 2. Body weight and performance data for each cattle group within the model for 2007 and 2017

Cattle group	2007						2017					
	BW, kg	Growth rate, kg/d	Milk yield, kg/d	Fat, %	Protein, %	ECM, kg/d	BW, kg	Growth rate, kg/d	Milk yield, kg/d	Fat, %	Protein, %	ECM, kg/d
Primiparous lactating cows												
4.5 to 13.6 kg milk/d	612	0.68	—	—	—	—	635	0.70	—	—	—	—
13.7 to 27.2 kg milk/d	612	0.68	22.8	3.71	3.05	23.4	635	0.70	23.9	4.02	3.24	25.8
27.3 to 40.7 kg milk/d	612	0.68	30.9	3.71	3.05	31.7	635	0.70	32.4	4.02	3.24	35.0
40.8 to 54.4 kg milk/d	612	0.68	—	—	—	—	635	0.70	—	—	—	—
>54.4 kg milk/d	612	0.68	—	—	—	—	635	0.70	—	—	—	—
Multiparous lactating cows												
4.5 to 13.6 kg milk/d	726	—	—	—	—	—	748	—	—	—	—	—
13.7 to 27.2 kg milk/d	726	—	20.6	3.48	2.86	20.3	748	—	22.2	3.98	3.21	23.8
27.3 to 40.7 kg milk/d	726	—	33.5	3.48	2.86	33.0	748	—	33.2	3.98	3.21	35.6
40.8 to 54.4 kg milk/d	726	—	42.1	3.48	2.86	41.4	748	—	44.1	3.98	3.21	47.3
>54.4 kg milk/d	726	—	—	—	—	—	748	—	—	—	—	—
Other cows												
Cows in first 5 days of lactation	726	—	29.1	3.71	3.05	29.9	748	—	31.9	4.02	3.24	34.4
Far-off dry cows	726	—	—	—	—	—	748	—	—	—	—	—
Close-up dry cows	726	—	—	—	—	—	748	—	—	—	—	—
Replacement heifers												
Preweaned	72	0.73	—	—	—	—	73	0.76	—	—	—	—
Weaning to conception	286	0.79	—	—	—	—	295	0.82	—	—	—	—
Conception to calving	556	0.62	—	—	—	—	573	0.64	—	—	—	—
Bulls												
<12 mo of age	219	0.98	—	—	—	—	226	1.00	—	—	—	—
12–36 mo of age	652	0.70	—	—	—	—	672	0.72	—	—	—	—
>36 mo of age	930	0.06	—	—	—	—	959	0.06	—	—	—	—

parturition, and average DLWG of 0.82 kg/d preconception and 0.64 kg/d precalving.

The number of required AD for milking cows within each lactation to produce the required 1.0 MMT of salable milk was determined by an iterative process. The first step was to establish average lactation curves as described in [Capper and Cady \(2012\)](#) based on [Keown et al. \(1986\)](#) and shown in [Figures 1a and b](#). Salable milk was considered to be all milk produced except for milk/colostrum produced in the first 5 d of lactation and milk withheld for 3 d from cows treated for mastitis. Convergence to an appropriate solution for the required number of AD within each lactation was met when the difference between the estimated amount of total ECM produced by the model and required ECM was less than $\pm 0.001\%$ while preserving the proportion of AD within each lactation equal to that documented by the DRMS information. Lactating AD were assumed to be uniformly distributed across days in milk within each lactation because there was no accounting for seasonality in calving or herd growth/reduction ([Table 2](#)). Determination of supporting population AD for dry cows and bulls were estimated as in [Capper and Cady \(2012\)](#), with dairy bulls included in the population at a rate of 1 bull per 25 cows adjusted for the percentage of cows served by artificial insemination ([de Vries et al., 2008](#)), resulting in a ratio of 1.2 bulls per 100 cows in the herd.

[Agricultural Modeling and Training Systems \(2018\)](#) ration formulation software was used to predict daily dry matter intake, nutrient requirements, voluntary water intake, and manure output for all cattle and was used to formulate balanced, nutritionally appropriate rations for cattle within each animal

group. Within each year's population, there existed 14 groups of cattle according to production level and/or age: six groups of lactating cows (either primiparous or multiparous), two groups of dry cows (close-up or far-off), three groups of heifers preweaned (<2 mo of age), preconception, or postconception, and three groups of bulls (<12, 12–24, and >24 mo of age) as shown in [Table 2](#). Details of each individual cattle diet are beyond the scope of this paper, but the diet ingredients fed to the cattle are summarized in [Table 1](#). Dietary ingredients have not changed significantly within the past decade, save for an increase in the use of distillers grains; therefore, diets for both time points (2007 and 2017) were formulated based on the same principal ingredients as detailed by [USDA \(2016\)](#), modified according to the dietary requirements for that group of animals. Diet formulation for each animal group allowed quantification of the population nutrient requirements and, therefore, the direct (feedstuffs and water) and indirect (cropland fertilizer and fuels) inputs associated with feed production.

Enteric methane production from all dairy cattle was calculated according to dietary formulation as described by [Ellis et al. \(2007\)](#). The fraction of nitrogen emitted as enteric nitrous oxide was calculated from data reported by [Kaspar and Tiedje \(1981\)](#) and [Kirchgessner et al. \(1991\)](#). Methane emissions from stored manure were estimated using methodology prescribed by the U.S. Environmental Protection Agency ([U.S. EPA, 2010](#)) based on the quantity of volatile solids (i.e., the volatile components of feces) excreted, maximum methane-producing potential (0.24 m³/kg of volatile solids), and a conversion factor (21.7) for liquid storage systems. [IPCC \(2006\)](#) emission factors were used to calculate nitrous oxide emissions from manure.

Cropping data were derived from [USDA \(2019\)](#) based on 5-yr averages of annual cropping yields. Crop yield averages for 2007 and 2017 are shown in [Table 3](#). Whenever byproduct feeds resulted from a specific crop (e.g., soybean meal, wet distillers grains, or wheat straw), the yields and resource inputs required to produce the byproduct feed were prorated according to either mass (soybean meal and wet distillers grains) or economic allocation (straw). For feeds not grown on farm (corn grain, soybean meal, wet distillers grains, and wheat straw), feed transport was accounted for based on an average transport distance of 558 km based on the principal states producing this crop: a truck feed capacity of 25,000 kg, a fuel usage efficiency of 2.54 km/liter ([Davis et al., 2009](#)), and a fuel energy content of 34.8 MJ/liter ([U.S. Energy Information Administration, 2019](#)).

Fertilizer use and pesticide use were derived from National Agricultural Statistics Service (NASS) Quick Stats ([USDA, 2019](#)) according to the most appropriate census year ([Table 3](#)). Transport fuel for cropping inputs was based upon transport distance (845 km for N fertilizer, 1,099 km for P and K fertilizers, and 805 km for pesticides and insecticides) derived from [the Fertilizer Institute \(2019\)](#), a truck fertilizer capacity of 17,000 kg and the same fuel efficiency values as before. Time-point-specific crop diesel usage data were not available; therefore, diesel usage for both 2007 and 2017 according to [Camargo et al. \(2013\)](#) was derived. Irrigation water usage was derived from NASS Quick Stats ([USDA, 2019](#)) and [U.S. Census Bureau \(2014\)](#) and irrigation energy from [U.S. Census Bureau \(2014\)](#). Water recycling was accounted for using data from [U.S. Census Bureau \(2014\)](#) and [Parsons et al. \(2010\)](#). Annual electricity use for cattle housing (e.g., lighting and ventilation) was 326 kW per animal, with an additional 247 kW per lactating cow for milk cooling and storage ([Ludington and Peterson, 2005](#)). The [Energy Information Administration \(2001\)](#) provided data from which to calculate a nationwide factor for carbon dioxide emissions from electricity generation, which was applied to electricity use within the model. Daily sanitation water (used for cleaning and disinfection of milking equipment) was added at a rate of 28.4 liters per lactating cow ([Brugger, 2006](#)).

Nitrous oxide emissions from fertilizer application were calculated according to the factors published by [IPCC \(2006\)](#). It

should be noted that fertilizer use quoted by the [USDA \(2019\)](#) does not include fertilizer applied in the form of organic manure; therefore, GHG emissions from manure application were additive to those from inorganic fertilizer application. Carbon dioxide emissions from fertilizer and pesticide manufacture were derived from [West and Marland \(2002\)](#). Due to a lack of reliable data and the number of assumptions involved in applying a land use factor to cropland, carbon sequestered into soil was not included in the model calculations. Total GHG emissions were calculated by applying carbon dioxide-equivalent 100-yr factors from [IPCC \(2013\)](#) to methane (34) and nitrous oxide (298) to calculate the total carbon footprint as the sum of all methane, nitrous oxide, and carbon dioxide emissions expressed in carbon dioxide equivalents. A back calculation was also performed using the carbon dioxide-equivalent factors from [IPCC \(2006\)](#), whereby methane had a 100-yr value of 28 in order to provide some basis for comparing the results of the current analysis with those of [Capper et al. \(2009\)](#).

Results and Discussion

The U.S. dairy cattle industry has made considerable strides over past decades in acknowledging and responding to consumer concerns regarding the environmental impacts of dairy production. The need to be socially responsible, including demonstrating stewardship of natural resources and care for animal health and welfare has never been more prevalent ([von Keyserlingk et al., 2009](#); [von Keyserlingk et al., 2013](#); [Cardoso et al., 2017](#)), and it is clear that a “One Health” approach within which human, animal, and ecosystem health will be considered as an intersecting matrix ([Buller et al., 2018](#)) will be the lens through which sustainability issues may be viewed in future ([Capper, 2017](#)). The original paper comparing U.S. dairy cattle production in 1944 and 2007 by [Capper et al. \(2009\)](#) took a long-term historical view of the resource use, nutrient excretion, and GHG improvements garnered by improving lactation yield over seven decades, albeit with significant shifts in production system and industry structure, including a large-scale move from extensive, pasture-based systems to intensive housed

Table 3. Yields and input data for U.S. crop production in 2007 and 2017

	Yield ¹ , kg/ha	Resource use ² , kg/ha						Diesel ³ , liter/ha	Water ⁴ , liter/ha
		N	P	K	Herbicides	Insecticides			
2007									
Alfalfa hay	7.43 × 10 ³	14.0	56.0	168	1.12	0.26	276	2.37 × 10 ⁶	
Corn silage	39.2 × 10 ³	145	50.2	66.8	2.10	0.01	276	1.60 × 10 ⁶	
Grass hay	4.33 × 10 ³	84.1	56.0	78.5	1.12	0.26	68.9	3.48 × 10 ⁵	
Wheat straw	1.63 × 10 ³	15.4	6.29	0.89	0.06	0.00	28.4	4.57 × 10 ⁴	
Corn grain	9.38 × 10 ³	145	50.2	66.8	2.10	0.01	241	1.39 × 10 ⁴	
Soybean meal	2.18 × 10 ³	0.86	5.69	14.9	1.17	0.01	81.0	5.60 × 10 ³	
2017									
Alfalfa hay	7.45 × 10 ³	14.0	56.0	168	1.12	0.26	276	2.44 × 10 ⁶	
Corn silage	45.5 × 10 ³	152	48.8	57.9	2.45	0.00	276	1.32 × 10 ⁶	
Grass hay	4.48 × 10 ³	84.1	56.0	78.5	1.12	0.26	68.9	1.22 × 10 ⁵	
Wheat straw	1.85 × 10 ³	17.1	5.74	1.15	0.02	0.00	28.0	5.11 × 10 ⁴	
Corn grain	10.6 × 10 ³	152	48.8	57.9	2.45	0.00	241	1.49 × 10 ⁴	
Soybean meal	2.57 × 10 ³	2.77	14.2	23.6	1.47	0.03	81.0	6.37 × 10 ³	
Wet distillers grains	3.22 × 10 ³	46.1	14.8	17.6	0.74	0.00	73.2	4.52 × 10 ³	

¹Five-yr average of crop yields from NASS Quick Stats ([USDA, 2019](#)).

²Data from NASS Quick Stats ([USDA, 2019](#)).

³Data from [Camargo et al. \(2013\)](#).

⁴Data from NASS Quick Stats ([USDA, 2019](#)) and [U.S. Census Bureau \(2014\)](#).

systems, a shift from small, high milk solids-producing breeds (Jerseys and Guernseys) to higher-milk yielding Holstein cattle, and the adoption of technologies including inorganic fertilizers, bulk tanks, and artificial insemination. Capper et al. (2009) clearly demonstrated that the multifactorial improvements in milk yield between 1944 and 2007 had significant impacts on reducing resource inputs and GHG emissions. Achieving sustainability is a constantly moving target: a system can be considered sustainable compared to another system or at a specific time point but must always be considered as a series of continuous improvements (Capper and Bauman, 2013) rather than a fixed point to be conquered. Updating the original 1944–2007 comparison (Capper et al., 2009) to examine further progress made by the U.S. dairy industry is, therefore, a timely endeavor. Compared to earlier assessments of environmental impacts associated with dairy production (de Boer, 2003; Garnsworthy, 2004; Hospido and Sonesson, 2005; Thomassen and de Boer, 2005; Capper et al., 2008; Thomassen et al., 2008; Capper et al., 2009; Capper and Cady, 2012; Thoma et al., 2013), science has evolved considerably, the scope of modeling resource use, nutrient excretion, and GHG emissions has been enhanced, and a greater amount of relevant data are available; therefore, the results of the current study cannot be applied directly to those of Capper et al. (2009). For example, the model used for the current study includes a more detailed description of herd structure and animal performance factors, more specific crop yields, irrigation water use, transport of purchased feedstuffs, and cropping inputs and manure applied to crop land, which were excluded from the original study because of lack of comparative data. Therefore, although the 1944 vs. 2007 results are valid in the context of that comparison, the current results should not be extrapolated back to compare with 1944.

Considerable advances have been made in dairy cattle nutrition, genetics, management, and health over the past century (Drackley et al., 2006; Eastridge, 2006; LeBlanc et al., 2006; Shook, 2006; Bewley et al., 2017; Thatcher, 2017), which have contributed to improved efficiency and productivity and allowed for the production of a greater quantity of milk using fewer resources via the “dilution of maintenance” concept (Baumgard et al., 2017). This was highlighted by Capper et al. (2008), given its role in reducing the environmental impacts of dairy production through diluting the “fixed costs” of lactation (i.e., the maintenance nutrient requirements of lactating cows plus supporting dry cows, heifers, calves, and bulls) over a greater quantity of output, that is, kg or t of milk. The current study again shows the role of this nutritional concept in mitigating environmental impacts as the annual ECM yield per cow increased from 9,150 kg in 2007 to 11,195 kg in 2017 (a consequence of both the 13.6% increase in milk yield and increases in milk fat and protein percentages of 12.1% and 10.3%, respectively), the total dairy cattle population required to produce 1.0 MMT ECM was reduced by 56.5×10^3 AY (31.5×10^3 lactating cows, 24.3×10^3 heifers, 0.66×10^3 bulls; Table 4). This effect is not wholly dependent upon ECM yield. Capper and Cady (2012) reported that other KPI, including age at first calving, calving interval, dry period length, and output per unit of bodyweight may also have significant impacts upon productivity and, thus, environmental impacts. As shown in Table 1, the increase in ECM yield (per year and per cow lifespan) between 2007 and 2017 was also accompanied by reductions in SCC (350,000 cells/mL in 2007 vs. 250,000 cells/mL in 2017), calving interval (426 d in 2007 vs. 414 d in 2017), and dry period length (60 d in 2007 vs. 57 d in 2017), which would all improve system feed use efficiency. The concurrent reduction in

expected number of lifetime lactations (2.97 in 2007 vs. 2.71 in 2017) and consequent days of life (1,634 d in 2007 vs. 1,496 d in 2017) might have been expected to counter this trend; however, this was outweighed by improved ECM yield over time. Although the reduced dairy cow days of life exhibited by the 2017 data could be interpreted as suggestive of impaired health or welfare (Oitenacu and Algers, 2005), this KPI is affected by myriad factors, including the availability of heifers entering the herd and the economic balance between milk price, rearing heifers, keeping older cows in the herd, or culling dairy cattle for beef (de Vries et al., 2008; Langford and Stott, 2012), and, therefore, cannot be assumed to be a simple reflection of cattle health or welfare, especially given the lack of a significant difference in cow mortality between the two time points.

Total feed requirements for milk production are not necessarily linearly associated with the number of cattle required—although fewer cattle were required to produce an equivalent quantity of ECM in 2007 and 2017 (Table 4), the total nutrient requirement for milk production only (i.e., not maintenance, pregnancy, or growth) was similar between the two time points and the quantity of feed was influenced by nutritional composition and dietary formulation. In contrast to the previous 1944 vs. 2007 comparison (Capper et al., 2009), which compared pasture-based and intensive feeding systems, diet formulations for dairy cattle did not differ considerably between the two time points in the current study, with the majority (>75%) of U.S. dairy operations feeding diets containing corn silage, alfalfa hay, corn grain, and soybeans (USDA, 2016). The exception to this was the inclusion of wet distillers grains in diets for 2017 cattle, a byproduct feed that has gained significant popularity as the market for ethanol and associated products

Table 4. Modeled milk production and cattle groups (animal years) per 1.0 MMT (million metric tonnes) of saleable energy-corrected milk^{1,2}

	2007	2017
Total ECM produced, MMT	1.10	1.07
Cattle groups, $n \times 10^3$		
Cows		
Cows in first 5 days of lactation	1.43	1.05
First lactation cows	37.4	28.4
Second lactation cows	27.7	20.7
Third lactation cows	36.9	25.9
Total lactating cows	103.4	76.0
Far-off dry cows	5.10	3.85
Close-up dry cows	9.46	6.61
Total dry cows	14.6	10.5
Total adult cows	117.9	86.4
Heifers		
Preweaned replacement heifers	8.30	6.43
Preconception replacement heifers	60.9	47.2
Postconception replacement heifers	34.9	26.2
Total replacement heifers	104.1	79.8
Heifer:cow ratio	0.88	0.92
Bulls		
Young bulls	0.35	0.26
Adolescent bulls	0.71	0.52
Mature bulls	1.41	1.04
Total bulls	2.47	1.81
Total cattle population	224.5	168.0

¹One animal year equals 365 animal days and may be thought of as one animal surviving through the calendar year.

²Apparent summation errors due to rounding error.

has developed within the United States over the past decade (Liu and Rosentrater, 2016). Gains in dairy herd productivity between 2007 and 2017 conferred a 0.33×10^9 kg reduction in feedstuffs required for production of 1.0 MMT ECM due to the dilution of maintenance effect, equivalent to a 17.3% change (Table 5). The associated reduction in land use for milk production (Table 5), equal to 0.52×10^5 ha (a 20.8% decrease), is a significant selling point for the dairy industry given that a considerable quantity of global land is used for animal feed production, leading to the “feed vs. food” (Council for Agricultural Science and Technology [CAST], 2013; Manceron et al., 2014) debate, whereby livestock systems are often cited as being less-efficient systems for food production than growing food crops directly edible by humans. This is a nuanced issue subject to oversimplification in public forums as considerable differences exist between the human food cropping potential of fertile, well-drained arable land capable of growing a variety of crops with relatively little inputs compared to the majority of global grazing land, which tends to be unsuitable for crop production because of unfavorable climate, terrain, water supply, or lack of soil nutrients. Livestock industries also use considerable quantities of byproduct feeds from global human food and fiber production such that land tends to be misallocated to animal feed production rather than to a combination of products for human and animal use. Furthermore, although a relatively high proportion of global agricultural land is used for grazing, the extent to which the land’s potential is realized through the application of best management practices and technologies is highly variable across regions. The potential, therefore, exists to improve land and cattle productivity and, therefore, reduce the quantity of hectares required for grazing (Eisler et al., 2014).

To put the land-related resource gains into context, the total of 0.52×10^5 ha land per 1.0 MMT ECM freed for other purposes by productivity gains between 2007 and 2017 (Table 5) is equivalent to the total area of Tulsa, OK, or the land required to produce 127×10^3 loaves of bread (based on a wheat yield of 3,210 kg/ha; USDA, 2019; and 4,940 loaves being produced per hectare; Kansas Wheat, 2015). Land use results within the current study are influenced by cropping yields in addition to cattle productivity gains; however, the impact of improved cropping yields over time is only half of that conferred by cattle gains. As shown in Table 6, running the 2017 model scenario with 2007 cropping yields and inputs (i.e., no changes in crop productivity over time) resulted in a 0.17×10^5 ha land reduction from improvements in crop yields and a 0.35×10^5 ha reduction from cattle productivity gains. Feed crop production is an important component of the dairy industry’s environmental impacts and, as such, cannot be disassociated or ignored, yet it is interesting to note that over the 10-yr interval, cropping had a relatively minor impact compared to gains in cattle productivity. This suggests that although advances in agronomy will continue to be important and should be pursued, especially when crop production is directly under the dairy producer’s control, the dairy industry should focus on the animal component of the system in order to realize the greatest gains. This is of particular relevance to GHG emissions as running the 2017 analysis with 2007 cropping inputs and yields (Table 6) only changed the total GHG emissions by 1%.

The use of cropping inputs per hectare did not change significantly for the majority of feed crops between 2007 and 2017; thus, combined improvements in cropping and cattle productivity conferred reductions in fertilizer (2.31×10^6 kg of

Table 5. Resource use and greenhouse gas emissions from U.S. dairy production in 2007 and 2017 per 1.0 MMT (million metric tonnes) of saleable energy-corrected milk

	2007	2017	2017 as a percentage of 2007
Resource use			
Total feedstuffs ¹ , kg	1.90×10^9	1.57×10^9	82.7
Cropping land, ha	2.48×10^5	1.96×10^5	79.2
N fertilizer, kg	1.18×10^7	9.49×10^6	80.3
P fertilizer, kg	9.10×10^6	6.79×10^6	74.6
K fertilizer, kg	1.76×10^7	1.31×10^7	74.5
Herbicides, kg	3.11×10^5	2.46×10^5	78.9
Insecticides, kg	3.35×10^4	2.33×10^4	69.6
Fossil fuels, MJ	1.36×10^9	1.08×10^9	79.8
Electricity, kWh	8.20×10^7	6.06×10^7	73.9
Cattle drinking water, liter	5.94×10^9	4.59×10^9	77.3
Irrigation water, liter	2.27×10^{11}	1.57×10^{11}	69.3
Sanitation water, liter	9.43×10^8	6.93×10^8	73.5
Total water, liter	2.33×10^{11}	1.62×10^{11}	69.5
Waste output			
Nitrogen excretion, kg	2.00×10^7	1.65×10^7	82.5
Phosphorus excretion, kg	2.20×10^6	1.88×10^6	85.7
Manure ¹ , kg	3.43×10^9	2.72×10^9	79.4
GHG			
Methane, kg	4.95×10^7	4.01×10^7	80.9
Nitrous oxide, kg	5.11×10^5	4.17×10^5	81.5
GHG from livestock ² , kg CO ₂ -eq	1.83×10^9	1.48×10^9	80.8
GHG from cropping, kg CO ₂ -eq	2.20×10^8	1.75×10^8	79.5
GHG from manure application, kg CO ₂ -eq	4.77×10^7	3.93×10^7	82.5
GHG from transport ³ , kg CO ₂ -eq	7.41×10^6	8.30×10^6	112
Total GHG ⁴ , kg CO ₂ -eq	2.10×10^9	1.70×10^9	80.8

¹Freshweight.

²Excluding respiration from cattle.

³Includes transport of feed and crop inputs but does not include milk transport.

⁴Equal to total GHG emissions from the U.S. dairy cattle industry of 1.77×10^{20} kg CO₂-eq for 2007 and 1.79×10^{20} kg CO₂-eq for 2017—a 1.0% increase.

N, 2.31×10^6 kg of P, and 4.49×10^6 kg of K), herbicide (6.58×10^4 kg), and insecticide (1.02×10^4 kg) use per 1.0 MMT ECM (Table 5). Similarly, fossil fuel use was reduced by 2.75×10^8 MJ and electricity by 2.14×10^7 kWh per 1.0 MMT ECM between 2007 and 2017. The former resource savings is equivalent to the energy consumption of 3.38×10^3 residential U.S. households (8.13×10^4 MJ per household use; U.S. Energy Information Administration, 2018). The need to find alternatives to nonrenewable and mined resources (N, P, K and fossil fuels) is an issue that will become more urgent in future as mines become exhausted and it appears certain that a greater investment will have to be made in both reducing nonrenewable inputs and finding alternative (renewable) energy sources. As an industry that is ultimately reliant on both energy and nutrient recycling, agriculture would seem well placed to adopt relevant technologies, yet these have not always been widely realized across in the industry. For example, only 248 anaerobic digesters are currently in use on U.S. livestock farms (albeit they tend to be associated with larger operations that have a greater opportunity to generate considerable quantities of electricity) compared to 107 in 2007 (U.S. EPA, 2019).

Water use may be the most significant resource issue that dairy production faces, both now and in future. The direct water use (i.e., that drunk by cattle and used for sanitation) on dairy farms in 2007 and 2017 was relatively low at 6.89×10^9 liters per 1.0 MMT ECM and 5.29×10^9 liters per 1.0 MMT ECM, respectively (Table 5). However, this accounted for only 2.95% (2007) and 3.26% (2017) of the total water use, the majority of which resulted from irrigated crop production. The simple mitigation response would be to shift cattle feed ingredients from crops that require greater quantities of water for growth (e.g., alfalfa)

Table 6. Impacts of using 2007 crop yields and inputs when modeling selected resource use and greenhouse gas emissions from U.S. dairy cattle production in 2017 per 1.0 MMT (million metric tonnes) of saleable energy-corrected milk

	2017 with 2007 crop yields and inputs	Indexed change (no change = 1.0) ¹
Resource use²		
Total feedstuffs ³ , kg	1.57×10^9	1.00
Cropping land, ha	2.13×10^5	1.09
N fertilizer, kg	1.01×10^7	1.06
P fertilizer, kg	7.12×10^6	1.05
K fertilizer, kg	1.37×10^7	1.05
Herbicides, kg	2.63×10^5	1.07
Insecticides, kg	2.35×10^4	1.01
Fossil fuels, MJ	1.15×10^9	1.06
Electricity, kWh	6.06×10^7	1.00
Irrigation water, liter	1.73×10^{11}	1.10
Total water, liter	1.78×10^{11}	1.10
GHG		
Methane, kg	4.01×10^7	1.00
Nitrous oxide, kg	4.26×10^5	1.02
GHG from cropping, kg CO ₂ -eq	1.86×10^8	1.06
GHG from transport, kg CO ₂ -eq	8.40×10^6	1.01
Total GHG, kg CO ₂ -eq	1.71×10^9	1.01

¹Indexed compared to modeling using 2017 crop yields and inputs with 2017 data (as shown in Table 5) set as equal to 1.0.

²Includes only resource use directly or indirectly impacted by changes in cropping yields and inputs

³Freshweight.

toward more arid crops and to move crop production from regions that require irrigation (e.g., California) to those that have a greater annual precipitation. However, this myopic approach neglects to account for other factors that have prevailed in segmenting crop production across the United States, including climate, terrain, infrastructure, market access, land value, policy, etc. (Parton et al., 2007). Furthermore, some water use analyses still persist in accounting for precipitation in total water use (Drastig et al., 2010; Hoekstra, 2012; Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013) without acknowledging that this input cannot be diverted or controlled, resulting in inflated water footprint statistics that are inherently invulnerable to mitigation strategies. Livestock producers have a responsibility to reduce water use where possible and to ensure that which is used is as unchanged by the milk production process as possible, that is, leaves the operation with minimal pollution or contamination. As with the reduction in land use seen between 2007 and 2017, the majority of the change in irrigation water use (and, therefore, total water use) resulted from improvements in cattle productivity. If this continues as a long-term trend, it could improve the social acceptability of dairy production, not least because some dairy-alternative beverages (e.g., those based on almonds) have a greater “water footprint” (Fulton et al., 2019), have a less desirable ratio of GHG emissions to nutrient density index (Smedman et al., 2010), and are limited in their provision of essential nutrients (Vanga and Raghavan, 2018). It is worth noting that the reduction in total water use per 1.0 MMT ECM was equivalent to the annual requirements of 3.48×10^5 U.S. households (based on 2.53 people per household and 8.10×10^4 liters per capita daily use; Water Research Foundation, 2017), a considerable achievement that could prove valuable given the drought issues that continue to plague several regions of the United States. To put this into context, if the current U.S. dairy industry produced the same quantity of milk as in 2007, the savings made in water use would be equivalent to the annual requirements of 2.93×10^7 U.S. households.

Over the past century, we have made significant strides in understanding cattle metabolism and nutrition such that modern dairy cattle are more feed efficient and are fed more precisely balanced diets than their ancestors (Eastridge, 2006). Total manure output from cattle in 2017 (2.72×10^9 kg per 1.0 MMT ECM) was 20.6% lower than that of 2007 (3.43×10^9 kg per 1.0 MMT ECM) and can be directly attributed to the reductions in cattle numbers and feed use between these two time points as digestibility values were similar for equivalent diets across the two time points (Table 5). No specific changes in dietary formulation relating to N and P excretion were widely adopted by the U.S. dairy industry between 2007 and 2017; therefore, the reductions in excretion of these nutrients (3.50×10^6 kg N per 1.0 MMT ECM and 3.20×10^5 kg P per 1.0 MMT ECM) within the current study were entirely due to cattle productivity gains. Nonetheless, given the environmental burdens of N in terms of NH₃ production, acidification and associated human and animal health effects, plus the eutrophication potentials of N and P released into waterways and consequences for ecosystem health, following the example of the swine industry by investigating further mechanisms for reducing nutrient excretion (Pomar et al., 2011) would be a valuable future research focus.

From a food industry stakeholder, media, and governmental perspective, GHG emissions appear to be the most important environmental impact metric under current discussion. From the global Kyoto agreement that sets internationally binding GHG emission reduction targets to regional initiatives to reduce

meat consumption in an attempt to cut dietary GHG emissions (Morris, 2018), the word sustainability appears to be inherently linked with this metric. Concern over climate change and the impacts of rising global temperatures in combination with the fact that GHG emissions are relatively easy to model (Jose et al., 2016; Rotz, 2018) and, if necessary, regulate (Thompson et al., 2014), means that this metric is likely to remain at the top of sustainability agendas for the foreseeable future. The impact of improved dairy cattle productivity upon GHG emissions is well documented from the FAO (2010) lifecycle assessment study that showed a direct negative correlation across global regions between solids-corrected milk yield and GHG emissions per kilogram of milk; to U.S.-specific studies examining cradle-to-grave dairy production systems (Thoma et al., 2013), the impacts of technology use (Capper et al., 2008), breed choice (Capper and Cady, 2012), or comparing historical production systems with those of more modern dairying (Capper et al., 2009). Irrespective of dairy production system, ECM yield, and other associated KPIs that improve milk output per kilogram of cattle bodyweight are the major determinants of GHG emissions per kilogram of milk produced (Capper and Cady, 2012). The previous 1944 vs. 2007 U.S. dairy industry comparison by Capper et al. (2009) reported a 63% decrease in the GHG emissions per kilogram of milk produced over the 63-yr time period (Figure 2); however, this did not simply reflect improvements in dairy cattle efficiency at the animal level but a myriad of infrastructural changes that transformed thousands of pasture-based systems averaging 5–9 cows per herd (U.S. Census Bureau, 1942) into a modern industry averaging 122 cows per herd, predominantly in conventional, housed operations and fed total mixed rations (USDA, 2007a). The changes evidenced by the current dairy industry over the decade between 2007 and 2017 are far less extreme than those observed between 1944 and 2007; therefore, it could be expected that less progress would have been made over time; however, the considerable gains in cattle productivity in combination with improved cropping yields between 2007 and 2017 reduced the total GHG emissions per 1.0 MMT ECM from 2.10×10^9 kg CO₂-eq (2007) to 1.70×10^9 kg CO₂-eq (2017), a reduction of 19.2% (Table 5). Consequently, although U.S. ECM production increased by 24.9% in the decade from 2007 to 2017, the total GHG emissions arising from this production increased by only 1.0%. This remarkable result, especially in light of the milking cow population increasing by 2.1% (Table 1), is primarily due to increased productive efficiency in both feed and milk production. In other words, the dilution of maintenance effect almost compensated for the increase in the cow population. Also notable is that the average annual linear reduction in GHG emission from 2007 to 2017 was 0.040 kg/kg of ECM. This compares to an average reduction from 1944 to 2007 of 0.037 kg/kg of milk (Capper et al. 2009). While the later rate of reduction is numerically greater, there may not be a significant difference between the rate of reduction in the two time periods; it appears that, at least, the U.S. annual rate of reduction of emissions per kilogram has not declined. Similar results have been observed elsewhere—for example, the United Kingdom dairy industry recently reported a 24% decrease in GHG emissions from dairy production between 1990 and 2015 (The Dairy Roadmap, 2018). A global drive exists to measure and improve GHG emissions from dairy production—initiatives that will improve not just environmental responsibility but also social acceptability over time. Furthermore, correlations between economic viability and environmental responsibility based on improved productivity and reduced resource use (Capper, 2013) may make this a triple win for sustainability metrics.

As previously discussed, improvements in model structure and function since Capper et al. (2009) mean that the GHG emissions per kilogram of milk (1.35 kg CO₂-eq per kg milk for 2007 according to Capper et al., 2009 and 2.10 kg CO₂-eq per kg ECM for 2007 in the current study) cannot be directly compared. The 1944 vs. 2007 comparison is still valid as is the magnitude of the difference between the time points; it is simply that the exact totals that have changed.

The IPCC's decision to change the global warming potential (GWP; 100-yr horizon) of CH₄ from 28 to 34 also made a considerable impact on the current results if comparing back to the original 1944 vs. 2007 comparison. At over 75% of total GHG emissions, CH₄ makes a significant contribution (Figure 3); therefore, the switch from a GWP of 28 to 34 increased the 2007 GHG emissions from 1.66 CO₂-eq per kg ECM to 2.10 CO₂-eq per kg ECM and the 2017 GHG emissions from 1.34 CO₂-eq per kg ECM to 1.70 CO₂-eq per kg ECM (Figure 2). As the science continues to evolve, this emphasizes the importance of using comparative analyses (between systems, production practices, or time points) to assess progress in environmental impacts rather than relying on singular absolute figures. Results of the current analysis are within the ranges published by other studies examining the GHG emissions of U.S. dairy production (FAO, 2010; Thoma et al., 2013; U.S. EPA, 2019) despite, as discussed by Bertrand and Barnett (2011), variations between studies in terms of differences in system boundaries, functional units, and methodology, including the decision not to apply allocation in the current study and the use of the updated IPCC GWP for CH₄. Given the interdependence of the U.S. dairy and beef industries, with up to 25% of total U.S. beef originating from the dairy industry (cull heifers, cows, and bulls, plus dairy calves reared for beef), an analysis of the environmental impacts from the entire U.S. cattle industry (dairy, veal, and beef) would fill an important knowledge gap relating to future mitigation opportunities.

To reduce GHG emissions from dairy cattle production still further, it is important to examine the sources from which they arise. Separated out by source and gas, Figure 3 shows that enteric and manure CH₄ contributes by far the greatest proportion of total CO₂-eq, whereas N₂O from manure and CO₂ from on-farm electricity, cropping, fertilizer and manure application, and transport are all relatively minor sources. Considerable future

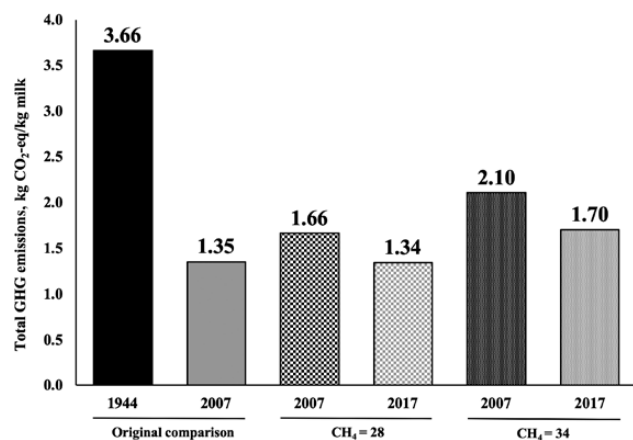


Figure 2. Greenhouse gases (CO₂-eq) per kilogram of milk in original 1944 vs. 2007 comparison (Capper et al., 2009) compared to the current 2007 vs. 2017 comparison with global warming potential values for methane set at 28 (IPCC, 2006) and 34 (IPCC, 2013).

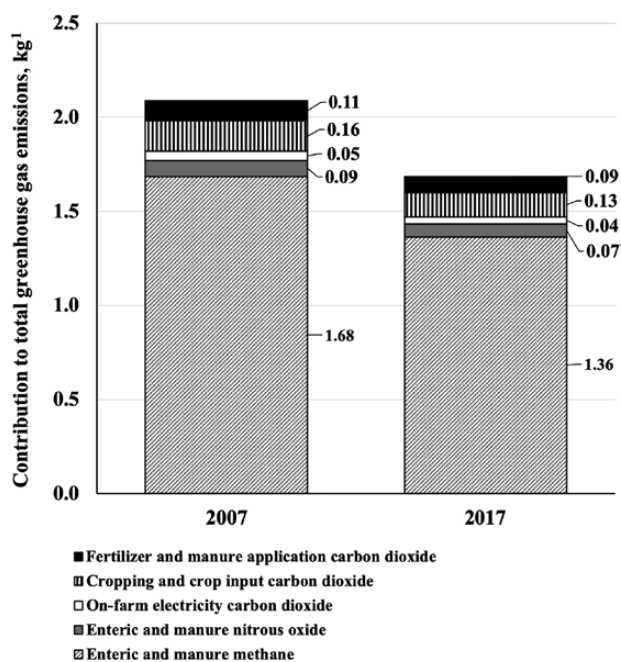


Figure 3. Greenhouse gas sources as contributors to total emissions (CO₂-eq) per kilogram of energy-corrected milk. A value of 0.01 for feed and crop input transport carbon dioxide is not shown.

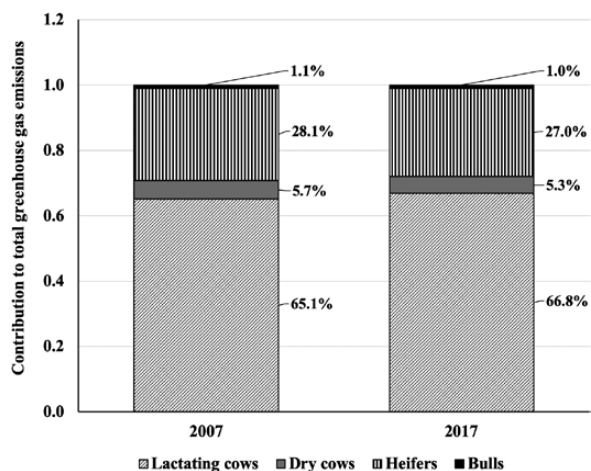


Figure 4. Cattle groups as proportions of total greenhouse gas emissions (CO₂-eq) per kilogram of energy-corrected milk.

gains could, therefore, be achieved by focusing on dairy cattle and manure management—with specific reference to lactating cows and heifers as the predominant contributors to GHG emissions within the herd (Figure 4). Adopting management practices and technologies that enhance productivity and lead to improvements in efficiency KPIs (e.g., milk production, calving rate, heifer growth, age at first calving, days dry, morbidity, and mortality) should, therefore, pay significant dividends. Moreover, although animal health is a key contributor to whole herd efficiency and studies have evaluated the environmental impacts of specific disease issues (Hospido and Sonesson, 2005; Mostert et al., 2018; Özkan Gülzaria et al., 2018), there is relatively little information available as to the relative impacts of different diseases and, therefore, little opportunity to target specific health issues as part of an environmental mitigation

program (Capper and Williams, 2019). More research into this area is, therefore, warranted.

A danger exists, however, that despite the body of evidence that high dairy cow productivity is conducive to increased herd longevity and better lifetime performance, the perception still exists that dairy producers may “push” cows toward greater performance without due regard for health and welfare and has led some to conclude that improving dairy cow productivity is not necessarily congruent with enhanced sustainability (Tucker et al., 2013; von Keyserlingk et al., 2013; Herzog et al., 2018). Nonetheless, a significant difference exists between pushing cattle to exceed their metabolic or genetic capacity and simply allowing cattle to fulfill their potential through optimal nutrition and management (Baumgard et al., 2017). The most recent world record cow, kept in a 360 cow-herd in Wisconsin, United States, produced 35,457 kg of milk in a single lactation (Dickrell, 2017), which is 241% more than the average U.S. cow in 2017; it, therefore, appears that a genetic plateau for milk production has not yet been reached and that productivity gains similar to those described in this study can continue to be realized into the future. The challenge to the U.S. dairy industry is to achieve these gains with due regard for both the One Health concept and the crucial importance of social acceptability, that is, positive consumer, retailer, and policy-maker opinions relating to dairy production (Crony and Anthony, 2011; von Keyserlingk et al., 2013).

The sustainability gains that have been made by the U.S. dairy industry in terms of improving milk yield and dairy cattle performance and reducing resource use, nutrient extraction, and GHG emissions per unit of milk between 1944 and 2007 have demonstrably continued into 2017 and, for this, the industry should be applauded. To maintain this culture of continuous improvement into the future, U.S. dairy producers must demonstrate their devotion to excellent cattle health and welfare, producing safe, affordable, high-quality food, and caring for the local and wider community and be prepared to answer increasing questions about dairy production practices in order to maintain social license to operate. Consumer and retailer pressures may change the future face of dairy production. For example, grazing periods of >120 d per year are already mandated by some European milk processors, antimicrobial use is being benchmarked across operations with compulsory reductions in the use of specific classes of medicine, and individual calf housing continues to be an area of concern for some consumers. The focus must, therefore, be on improving all three facets of sustainability (environmental responsibility, economic viability, and social acceptability) in a holistic manner—a challenge that the U.S. dairy industry should be able to meet most successfully.

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Conflict of interest statement

The authors declare no conflict of interests related to this work.

Literature Cited

Agricultural Modeling and Training Systems (AMTS). 2018. *Cattle pro*. Ithaca (NY): Cornell Research Foundation.

- Bartl, K., C. A. Gómez, and T. Nemecek. 2011. Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. *J. Clean. Prod.* **19**:1494–1505. doi:10.1016/j.jclepro.2011.04.010
- Bauman, D. E., S. N. McCutcheon, W. D. Steinhour, P. J. Eppard, and S. J. Sechen. 1985. Sources of variation and prospects for improvement of productive efficiency in the dairy cow: a review. *J. Anim. Sci.* **60**:583–592. doi:10.2527/jas1985.602583x
- Baumgard, L. H., R. J. Collier, and D. E. Bauman. 2017. A 100-year review: regulation of nutrient partitioning to support lactation. *J. Dairy Sci.* **100**:10353–10366. doi:10.3168/jds.2017-13242
- Bell, M. J., R. J. Eckard, M. Haile-Mariam, and J. E. Pryce. 2013. The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. *J. Dairy Sci.* **96**:7918–7931. doi:10.3168/jds.2012-6289
- Bell, M. J., E. Wall, G. Russell, G. Simm, and A. W. Stott. 2011. The effect of improving cow productivity, fertility, and longevity on the global warming potentials of dairy systems. *J. Dairy Sci.* **94**:3662–3678. doi:10.3168/jds.2010-4023
- Bertrand, S., and J. Barnett. 2011. Standard method for determining the carbon footprint of dairy products reduces confusion. *Anim. Front.* **1**:14–18. doi:10.2527/af.2011-0011
- Bewley, J. M., L. M. Robertson, and E. A. Eckelkamp. 2017. A 100-year review: lactating dairy cattle housing management. *J. Dairy Sci.* **100**:10418–10431. doi:10.3168/jds.2017-13251
- de Boer, I. J. M. 2003. Environmental impact assessment of conventional and organic milk production. *Livest. Prod. Sci.* **80**:69–77. doi:10.1016/S0301-6226(02)00322-6
- Brugger, M. 2006. Water use and savings on a dairy farm: paper #064035. American Society of Agricultural and Biological Engineers, St Joseph, Michigan, Annual International Meeting; Portland (OR).
- Buller, H., H. Blokhuis, P. Jensen, and L. Keeling. 2018. Towards farm animal welfare and sustainability. *Animals.* **8**:1–13. doi:10.3390/ani8060081
- Cady, R. A. 1977. *Dystocia and related calving traits in dairy cattle* [masters thesis]. Ithaca (NY): Cornell University.
- Cady, R. A., and L. D. Van Vleck. 1978. Factors affecting twinning and effects of twinning in Holstein dairy cattle. *J. Anim. Sci.* **46**:950–956.
- Camargo, G. G. T., M. R. Ryan, and T. L. Richard. 2013. Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool. *Bioscience.* **63**:263–273. doi:10.1525/bio.2013.63.4.6
- Capper, J. L. 2013. Should we reject animal source foods to save the planet? A review of the sustainability of global livestock production. *S. Afr. J. An. Sci.* **43**:233–246. doi:10.4314/sajas.v43i3.1
- Capper, J. L. 2017. Looking forward to a sustainable future—how do livestock productivity, health, efficiency and consumer perceptions interact? *Catt. Prac.* **25**:179–193.
- Capper, J. L., and D. E. Bauman. 2013. The role of productivity in improving the environmental sustainability of ruminant production systems. *Annu. Rev. Anim. Biosci.* **1**:469–489. doi:10.1146/annurev-animal-031412-103727
- Capper, J. L., and R. A. Cady. 2012. A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. *J. Dairy Sci.* **95**:165–176. doi:10.3168/jds.2011-4360
- 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. doi:10.2527/jas.2009-1781
- 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. doi:10.1073/pnas.0802446105
- Capper, J. L., and P. Williams. 2019. *Healthy livestock produce sustainable food*. Milton Keynes (UK): MSD Animal Health.
- Cardoso, C. S., M. A. G. von Keyserlingk, and M. J. Hötzel. 2017. Brazilian citizens: expectations regarding dairy cattle welfare and awareness of contentious practices. *Animals.* **7**:1–15. doi:10.3390/ani7120089
- Casey, J. W., and N. M. Holden. 2005. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. *J. Environ. Qual.* **34**:429–436. doi:10.2134/jeq2005.0429
- Christie, K. M., R. P. Rawnsley, and R. J. Eckard. 2011. A whole farm systems analysis of greenhouse gas emissions of 60 Tasmanian dairy farms. *Anim. Feed Sci. Tech.* **166–167**:653–662. doi:10.1016/j.anifeedsci.2011.04.046
- Council for Agricultural Science and Technology (CAST). 2013. *Animal feed vs. human food: challenges and opportunities in sustaining animal agriculture toward 2050*. Issue Paper 53. Ames (IA): CAST.
- Crone, C., and R. Anthony. 2011. Ruminating conscientiously: scientific and socio-ethical challenges for US dairy production. *J. Dairy Sci.* **94**:539–546. doi:10.3168/jds.2010-3627
- Dairy Records Management Systems (DRMS). 2018. DRMS. Available from <https://www.drms.org/>. Accessed May 1, 2018.
- Davis, S. C., S. W. Diegel, and R. G. Boundy. 2009. *Transportation energy data book: edition 28*. Oak Ridge (TN): Oak Ridge National Laboratory.
- Dickrell, J. 2017. New national milk production record set by Wisconsin Cow. Available from <https://www.dairyherd.com/article/new-national-milk-production-record-set-wisconsin-cow>. Accessed May 27, 2019.
- Drackley, J. K., S. S. Donkin, and C. K. Reynolds. 2006. Major advances in fundamental dairy cattle nutrition. *J. Dairy Sci.* **89**:1324–1336. doi:10.3168/jds.S0022-0302(06)72200-7
- Drastig, K., A. Prochnow, S. Kraatz, H. Klauss, and M. Plöchl. 2010. Water footprint analysis for the assessment of milk production in Brandenburg (Germany). *Adv. Geosci.* **27**:65–70. doi:10.5194/adeo-27-65-2010
- Eastridge, M. L. 2006. Major advances in applied dairy cattle nutrition. *J. Dairy Sci.* **89**:1311–1323. doi:10.3168/jds.S0022-0302(06)72199-3
- Eisler, M. C., M. R. Lee, J. F. Tarlton, G. B. Martin, J. Beddington, J. A. Dungait, H. Greathead, J. Liu, S. Mathew, H. Miller, et al. 2014. Agriculture: steps to sustainable livestock. *Nature* **507**:32–34. doi:10.1038/507032a
- Ellis, J. L., E. Kebreab, N. E. Odongo, B. W. McBride, E. K. Okine, and J. France. 2007. Prediction of methane production from dairy and beef cattle. *J. Dairy Sci.* **90**:3456–3466. doi:10.3168/jds.2006-675
- Energy Information Administration. 2001. *Updated state-level greenhouse gas emission factors for electricity generation*. Washington (DC): U.S. Department of Energy.
- FAO. 2006. *Livestock's long shadow—environmental issues and options*. Rome (Italy): FAO.
- FAO. 2010. *Greenhouse gas emissions from the dairy sector: a life cycle assessment*. Rome (Italy): FAO.
- FAO. 2013. *Tackling climate change through livestock—a global assessment of emissions and mitigation opportunities*. Rome (Italy): Food and Agriculture Organization of the United Nations.
- FAO. 2019. FAOSTAT. Available from <http://faostat.fao.org>. Accessed June 2, 2019.
- Fulton, J., M. Norton, and F. Shilling. 2019. Water-indexed benefits and impacts of California almonds. *Ecol. Ind.* **96**:711–717. doi:10.1016/j.ecolind.2017.12.063
- Garnsworthy, P. C. 2004. The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions. *Anim. Feed Sci. Tech.* **112**:211–223. doi:10.1016/j.anifeedsci.2003.10.011
- Gerbens-Leenes, P. W., M. M. Mekonnen, and A. Y. Hoekstra. 2013. The water footprint of poultry, pork and beef: a comparative study in different countries and production systems. *Water Resour. Indust.* **1–2**:25–36. doi:10.1016/j.wri.2013.03.001
- Gerber, P., T. Vellinga, C. Opio, and H. Steinfeld. 2011. Productivity gains and greenhouse gas emissions intensity

- in dairy systems. *Livest. Sci.* **139**:100–108. doi:10.1016/j.livsci.2011.03.012
- Heinrichs, A. J., and W. C. Losinger. 1998. Growth of Holstein dairy heifers in the United States. *J. Anim. Sci.* **76**:1254–1260. doi:10.2527/1998.7651254x
- Herzog, A., C. Winckler, and W. Zollitsch. 2018. In pursuit of sustainability in dairy farming: a review of interdependent effects of animal welfare improvement and environmental impact mitigation. *Ag. Ecosys. Env.* **267**:174–187. doi:10.1016/j.agee.2018.07.029
- Hoekstra, A. Y. 2012. The hidden water resource use behind meat and dairy. *Anim. Front.* **2**:3–8. doi:10.2527/af.2012-0038
- Hospido, A., and U. Sonesson. 2005. The environmental impact of mastitis: a case study of dairy herds. *Sci. Total Environ.* **343**:71–82. doi:10.1016/j.scitotenv.2004.10.006
- IPCC. 2006. *IPCC guidelines for national greenhouse gas inventories*. Kanagawa (Japan): Institute for Global Environmental Strategies (IGES) for the IPCC.
- IPCC. 2013. *Climate change 2013—the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva (Switzerland): IPCC Secretariat.
- Jose, V., V. Sejian, M. Bagath, A. Ratnakaran, A. Lees, Y. Al-Hosni, M. Sullivan, R. Bhatta, and J. Gaughan. 2016. Modeling of greenhouse gas emission from livestock. *Front. Environ. Sci.* **4**:1–10. doi: 10.3389/fenvs.2016.00027
- Kansas Wheat. 2015. What does a bushel of wheat mean to me? Available from <http://kswheat.com/news/2015/07/22/what-does-a-bushel-of-wheat-mean-to-me>. Accessed May 21, 2019.
- 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.
- Keown, J. F., R. W. Everett, N. B. Empet, and N. H. Waddell. 1986. Lactation curves. *J. Dairy Sci.* **69**:769–781. doi:10.3168/jds.S0022-0302(86)80466-0
- von Keyserlingk, M. A. G., N. P. Martin, E. Kebreab, K. F. Knowlton, R. J. Grant, M. Stephenson, C. J. Sniffen, J. P. Harner, A. D. Wright, and S. I. Smith. 2013. Sustainability of the US dairy industry. *J. Dairy Sci.* **96**:5405–5425. doi:10.3168/jds.2012-6354
- von Keyserlingk, M. A. G., J. Rushen, A. M. de Passille, and D. M. Weary. 2009. The welfare of dairy cattle - key concepts and the role of science. *J. Dairy Sci.* **92**:4101–4111. doi:10.3168/jds.2009-2326
- Kirchgeßner, M., W. Windisch, H. L. Muller, and M. Kreuzer. 1991. Release of methane and of carbon dioxide by dairy cattle. *Agribiol. Res.* **44**:2–9.
- Langford, F., and A. Stott. 2012. Culled early or culled late: economic decisions and risks to welfare in dairy cows. *Anim. Welfare.* **21**:41–55.
- LeBlanc, S. J., K. D. Lissemore, D. F. Kelton, T. F. Duffield, and K. E. Leslie. 2006. Major advances in disease prevention in dairy cattle. *J. Dairy Sci.* **89**:1267–1279. doi:10.3168/jds.S0022-0302(06)72195-6
- Liu, K., and K. A. Rosentrater. 2016. *Distillers grains. Production, properties, and utilization*. New York (NY): AOCG Publishing.
- Ludington, D., and R. C. Peterson. 2005. How much energy does your dairy use? *Northeast Dairy Business*. September:20–21.
- Manceron, S., T. Ben Ari, and P. Dumas. 2014. Feeding proteins to livestock: global land use and food vs. feed competition. *Oils. Fats Crops Lip.* **21**:D408–D417. doi:10.1051/ocl/2014020
- Mekonnen, M. M., and A. Y. Hoekstra. 2012. A global assessment of the water footprint of farm animal products. *Ecosystems.* **15**:401–405. doi:10.1007/s10021-011-9517-8
- Morris, C. 2018. “Taking the politics out of broccoli”: debating (de)meatification in UK national and regional newspaper coverage of the meat free Mondays campaign. *Sociol. Rural.* **58**:433–452. doi:10.1111/soru.12163
- Mostert, P. F., C. E. van Middelaar, E. A. M. Bokkers, and I. J. M. de Boer. 2018. The impact of subclinical ketosis in dairy cows on greenhouse gas emissions of milk production. *J. Clean. Prod.* **171**:773–782. doi:10.1016/j.jclepro.2017.10.019
- Olesen, J. E., K. Schelde, A. Wieske, M. R. Weisbjerg, W. A. H. Asman, and J. Djurhuus. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. *Ag. Ecosys. Env.* **112**:207–220. doi:10.1016/j.agee.2005.08.022
- Oltenuacu, P., and B. Algers. 2005. Selection for increased production and the welfare of dairy cows: are new breeding goals needed? *AMBIO.* **34**:311–315.
- Overton, M. W. 2005. Cost comparison of natural service sires and artificial insemination for dairy cattle reproductive management. *Theriogenology* **64**:589–602. doi:10.1016/j.theriogenology.2005.05.015
- Özkan Gülzari, Ş., B. Vosough Ahmadi, and A. W. Stott. 2018. Impact of subclinical mastitis on greenhouse gas emissions intensity and profitability of dairy cows in Norway. *Prev. Vet. Med.* **150**:19–29. doi:10.1016/j.prevetmed.2017.11.021
- Parsons, L. R., B. Sheikh, R. Holden, and D. W. York. 2010. Reclaimed water as an alternative water source for crop irrigation. *HortSci.* **45**:1626–1629. doi:10.21273/HORTSCI.45.11.1626
- Parton, W., M. Gutmann, and D. Ojima. 2007. Long-term trends in population, farm income, and crop production in the Great Plains. *Bioscience.* **57**:737–747. doi:10.1641/B570906
- 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. doi:10.1016/S0065-2113(09)03001-6
- Pomar, C., L. Hauschild, G. H. Zhang, J. Pomar, and P. A. Lovatto. 2011. Precision feeding can significantly reduce feeding cost and nutrient excretion in growing animals. In: D. Sauvant, J. Van Milgen, P. Faverdin, and N. Friggens, editors, *Modelling nutrient digestion and utilisation in farm animals*. Wageningen (The Netherlands): Wageningen Academic Publishers. p. 327–332. doi:10.3920/978-90-8686-712-7_36
- Powell, R. L., H. D. Norman, and F. N. Dickinson. 1975. Sire differences in sex ratio of progeny. *J. Dairy Sci.* **58**:1723–1726.
- Rotz, C. A. 2018. Modeling greenhouse gas emissions from dairy farms. *J. Dairy Sci.* **101**:6675–6690. doi:10.3168/jds.2017-13272
- Shook, G. E. 2006. Major advances in determining appropriate selection goals. *J. Dairy Sci.* **89**:1349–1361. doi:10.3168/jds.S0022-0302(06)72202-0
- Silva Del Rio, N., S. Stewart, P. Rapnicki, Y. M. Chang, and P. M. Fricke. 2007. An observational analysis of twin births, calf sex ratio, and calf mortality in Holstein dairy cattle. *J. Dairy Sci.* **90**:1255–1264. doi:10.3168/jds.S0022-0302(07)71614-4
- Smedman, A., H. Lindmark-Mansson, A. Drewnowski, and A.-K. Modin Edman. 2010. Nutrient density of beverages in relation to climate impact. *Food Nutr. Res.* **54**:1–8. doi:10.3402/fnr.v54i0.5170
- Thatcher, W. W. 2017. A 100-year review: historical development of female reproductive physiology in dairy cattle. *J. Dairy Sci.* **100**:10272–10291. doi:10.3168/jds.2017-13399
- The Dairy Roadmap. 2018. *The UK dairy roadmap—showcasing 10 years of environmental commitment*. Stoneleigh (UK): AHDB Dairy.
- The Fertilizer Institute. 2019. Transportation. Available from <https://www.tfi.org/our-industry/state-of-industry/fertilizer-transportation> Accessed May 1, 2019.
- Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, and F. Adom. 2013. Greenhouse gas emissions from milk production and consumption in the United States: a cradle-to-grave life cycle assessment circa 2008. *Int. Dairy J.* **31** (Suppl. 1):S3–S14. doi:10.1016/j.idairyj.2012.08.013
- Thomassen, M. A., and I. J. M. de Boer. 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. *Ag. Ecosys. Env.* **111**:185–199. doi:10.1016/j.agee.2007.06.001
- Thomassen, M. A., K. J. van Calster, M. C. J. Smits, G. L. Iepema, and I. J. M. de Boer. 2008. Life cycle assessment of conventional

- and organic milk production in the Netherlands. *Ag. Sys.* **96**:95–107. doi:10.1016/j.agsy.2007.06.001
- Thompson, T., S. Rausch, R. Saari, and N. Selin. 2014. A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat. Clim. Chang.* **4**:917–923. doi:10.1038/nclimate2342
- Tucker, C. B., J. A. Mench, and M. A. G. von Keyserlingk. 2013. Animal welfare: an integral component of sustainability. In: E. Kebreab, editor, *Sustainable animal agriculture*. Wallingford (UK): CABI. p. 42–52.
- Tyrrell, H. F., and J. T. Reid. 1965. Prediction of the energy value of cow's milk. *J. Dairy Sci.* **48**:1215–1223. doi:10.3168/jds.S0022-0302(65)88430-2
- de Vries, A., M. Overton, J. Fetrow, K. Leslie, S. Eicker, and G. Rogers. 2008. Exploring the impact of sexed semen on the structure of the dairy industry. *J. Dairy Sci.* **91**:847–856. doi:10.3168/jds.2007-0536
- U.S. Census Bureau. 1942. *Sixteenth census of the United States: 1940. Agriculture—cows milked and dairy products*. Washington (DC): United States Department of Commerce.
- U.S. Census Bureau. 2014. *2012 Census of agriculture. Farm and ranch irrigation survey (2013). Volume 3, special studies, part 1*. Washington (DC): USDA.
- U.S. Department of Agriculture (USDA). 2007a. *Dairy 2007, part II: part II: changes in the U.S. Dairy Cattle Industry, 1991–2007*. Fort Collins (CO): USDA-APHIS-VS.
- USDA. 2007b. *Dairy 2007: Heifer calf health and management practices on U.S. Dairy Operations, 2007*. Fort Collins (CO): USDA:APHIS;VS.
- USDA. 2016. *Dairy 2014: Dairy cattle management practices in the United States, 2014*. Fort Collins (CO): USDA–APHIS–VS–CEAH–NAHMS.
- USDA. 2018. *Memorandum of understanding between United States Department of Agriculture and the Innovation Center for U.S. Dairy*. Washington (DC): USDA.
- USDA. 2019. Data and statistics. Available from <https://quickstats.nass.usda.gov/>. Accessed May 01, 2019.
- U.S. Energy Information Administration. 2018. Residential energy consumption survey. Available from <https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce3.1.pdf>. Accessed May 21, 2019.
- U.S. Energy Information Administration. 2019. Energy units and calculators explained—British Thermal Units (Btu). Available from https://www.eia.gov/energyexplained/index.php?page=about_btu. Accessed May 1, 2019.
- U.S. Environmental Protection Agency (EPA). 2010. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008*. Washington (DC): US EPA.
- U.S. EPA. 2019. AgSTAR data and trends. Available from <https://www.epa.gov/agstar/agstar-data-and-trends#adfacts>. Accessed May 21, 2019.
- U.S. EPA. 2019. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2017*. Washington (DC): U.S. EPA.
- VandeHaar, M. J., and N. St-Pierre. 2006. Major advances in nutrition: relevance to the sustainability of the dairy industry. *J. Dairy Sci.* **89**:1280–1291. doi:10.3168/jds.S0022-0302(06)72196-8
- Vanga, S. K., and V. Raghavan. 2018. How well do plant based alternatives fare nutritionally compared to cow's milk? *J. Food Sci. Technol.* **55**:10–20. doi:10.1007/s13197-017-2915-y
- Wall, E., M. Coffey, and G. E. Pollott. 2012. The effect of lactation length on greenhouse gas emissions from the national dairy herd. *Animal.* **6**:1857–1867. doi:10.1017/S1751731112000936
- Water Research Foundation. 2017. Water efficiency. Available from http://www.waterrf.org/knowledge/water-efficiency/FactSheets/water-efficiency_water-use-estimates_factSheet.pdf. Accessed May 21, 2019.
- Weiske, A., A. Vabitsch, J. E. Olesen, K. Schelde, J. Michel, R. Friedrich, and M. Kaltschmitt. 2006. Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. *Ag. Ecosys. Env.* **112**:221–232. doi:10.1016/j.agee.2005.08.023
- 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. *Ag. Ecosys. Env.* **91**:217–232. doi:10.1016/S0167-8809(01)00233-X
- White, R. 2016. Increasing energy and protein use efficiency improves opportunities to decrease land use, water use, and greenhouse gas emissions from dairy production. *Ag. Sys.* **146**:20–29. doi:10.1016/j.agsy.2016.03.013
- Zehetmeier, M., J. Baudracco, H. Hoffmann, and A. Heißenhuber. 2011. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. *Animal.* **6**:154–166. doi:10.1017/S1751731111001467:1–13