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Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years

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ABSTRACT

Food production including dairy has been associated with environmental impacts and resource use that has been steadily improving when adjusted per unit of product. The objective of this study was to conduct a cradle-to-farm gate environmental impact analysis and resource inventory of the California dairy production system to estimate the change in greenhouse gas emissions and water and land use over the 50-yr period between 1964 and 2014. Using a life cycle assessment according to international standards and the Food and Agriculture Organization of the United Nations guidelines, we analyzed contributions from dairy production in California to global environmental change. Production of 1 kg of energy- and protein-corrected milk (ECM) in California emitted 1.12 to 1.16 kg of CO_2 equivalents (CO_2e) in 2014 compared with 2.11 kg of CO_2e in 1964, a reduction of 45.0 to 46.9% over the last 50 yr, depending on the model used. Greater reductions in enteric methane intensity (i.e., methane production per kilogram of ECM) were observed (reduction of 54.1 to 55.7%) compared with manure GHG (reduction of 8.73 to 11.9%) in 2014 compared with 1964. This was mainly because manure management in the state relies on lagoons for storage, which has a greater methane conversion factor than solid manure storage. Water use intensity was reduced by 88.1 to 89.9%, with water reductions of 88.7 to 90.5% in crop production, 55.3 to 59.2% in housing and milking, and 52.4 to 54% in free water intake. Improved crop genetics and management have contributed to large efficiencies in water utilization. Land requirements for crop production were reduced by 89.4 to 89.7% in 2014 compared with 1964. This was mainly due to dramatic increases in crop yields in the last 50 yr. The increases in milk production per cow through genetic improvements and better nutrition and animal care have contributed to reductions in greenhouse gas emissions and land and water usage when calculated per unit of production (intensity) basis.
Key words: dairy, environment, life cycle assessment, greenhouse gas

INTRODUCTION

Milk production is the third largest agricultural industry in the United States, with California being the top dairy-producing state (USDA, 2014). Milk is the most important agricultural commodity produced in the state by farm revenue (Sumner et al., 2015). The California dairy industry, including milk production on farms and milk processing, supported about 190,000 jobs and contributed about $21 billion in economic value to the gross state product in 2014 (Sumner et al., 2015). Relative to the 1960s, total milk production in the state has increased by about 500% (von Keyserlingk et al., 2013). The dramatic rise in production was due to increases in the number of cows, from about 790,000 to 1.78 million, and in milk production per cow, from about 4,850 to about 10,600 kg/cow per year (Sumner et al., 2015). Over the last 50 yr, dairy production in California has undergone significant improvements and advancements in animal husbandry, feeding and housing practices, and in animal and plant genetics and crop production methods.

The dairy industry has been scrutinized regarding its environmental impact. Several studies have indicated that the livestock sector in general contributes to environmental change (e.g., de Vries and De Boer, 2010), including greenhouse gas (**GHG**) emissions, water usage, and land resources. An estimated 70% of global freshwater use by humans is attributed to agriculture, including 38% of freshwater withdrawals in the United States (USGS, 2009). In dairy production, the impact on the environment is mainly from (1) direct GHG emissions from enteric fermentation, manure storage and field application, and crop production; (2) use of

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water resources for feed production and impact on water quality due to excretion of nitrogen and phosphorus; and (3) land requirement for feed production.

Increased animal productivity reduces the environmental impact of the dairy industry when calculated on an emission intensity (GHG emission per unit of product) basis. For example, Capper et al. (2009) calculated that compared with 1944, the 2007 US dairy industry required 21% of the dairy cattle, 23% of the feedstuffs, 10% of the land, and 35% of the water to produce 1 unit of milk. Thoma et al. (2013) summarized several life cycle assessment (**LCA**) studies on the dairy sector and noted that each followed slightly different methodologies with some differences in system boundaries, and allocation of impacts to milk and beef. Some considered only carbon footprint (e.g., Gerber et al., 2010), whereas others included inventories on water and other resources (e.g., Capper et al., 2009). California has unique attributes in its milk production system that have not been analyzed previously, and several advancements in the methodology of calculating emissions have been published since the latest studies were conducted. Our objective was to conduct a cradle-to-farm gate analysis of the California dairy production system to estimate changes in GHG emissions and water and land use over the 50-yr period between 1964 and 2014 using the most up-to-date LCA methodologies.

MATERIALS AND METHODS

The LCA was conducted using GaBi software version 6 (PE International AG, 2015) and conformed to ISO 14040 and 14044 standards (ISO, 2006a,b; Finkbeiner, 2014) and Food and Agriculture Organization of the United Nations (FAO) Livestock Environmental Assessment Protocol guidelines (FAO, 2016a,b). The software includes GaBi content databases providing the costs, energy, and environmental impacts of sourcing and refining every raw material or processed component of a manufactured item. Where information for a product was missing, literature values were sourced and integrated into the GaBi software. The life cycle inventory for feed ingredients was taken from the food and feed extension database of GaBi (http://www.gabi-software.com/deutsch/databases/gabi-databases/food-feed/) and implemented as reported by Liedke et al. (2014). The feed ingredients life cycle inventory was also updated using primary data from California.

System Boundary

The animal production system analyzed in this study represents the milk production system in California. Because the objective was to estimate changes in GHG and water and land use over 50 yr, we selected the reference years 1964 and 2014, primarily based on available inputs for the LCA. The milk production system was divided into 4 processes: feed production, enteric methane, manure storage, and farm management (Figure 1). The LCA model considered "upstream" activities such as the extraction of raw materials for fuels, and intermediate products required in the system such as diesel, electricity, and fertilizer. The system boundary considered these processes up to the farm gate. "Downstream" activities, including milk processing, distribution, retail, or consumption, were not considered.

Functional Unit

Milk varies in its nutrient composition; therefore, the quality of milk must be standardized to allow for a consistent, equitable comparison. The functional unit used for analysis was defined as 1 kg of ECM at the farm gate. The ECM was calculated by multiplying milk production by the ratio of the energy content of the milk to the energy content of standard milk with 4% fat and 3.3% true protein according to NRC (2001) as follows:

$$\text{ECM} = \text{milk production} \times (0.0929 \times \text{fat\%} + 0.0588 \times \text{true protein\%} + 0.192)/[0.0929 \times (4\%) + 0.0588 \times (3.3\%) + 0.192],$$

where fat% and protein% are fat and protein percentages in milk, respectively. All processes in the system were calculated based on 1 kg of ECM. Two scenarios were considered for data collection. Model 1 was based on primary data from 5 commercial dairies located in Tulare and Kings Counties, California (Rossow and Aly, 2013), and these were used to determine the average milk production and composition for this model. The average milk production representing 2014 model 1 levels was 39.8 kg/d, with milk fat and protein percentages of 4 and 3.3%, respectively. Model 2 was based on average diets collected by the California Department of Food and Agriculture (**CDFA**) from 2013, 2014, and 2015 (CDFA, 2013, 2014, 2015). The average milk production for this model was 36.4 kg/d, with similar milk fat and protein as model 1. The average milk yield in 1964 was an average value of California milk production in 1963, 1964, and 1965 from the USDA National Agricultural Statistical Service (USDA-NASS, 1960–2010) at 15.9 kg/d, and milk fat and protein percentages were 3.85 and 3.40%, respectively, calculated from Capper et al. (2009) and assuming an even distribution between large and small breeds.

Data Sources

Data were collected from multiple sources including the USDA National Agricultural Statistical Service (USDA-NASS) and Economic Research Service (USDA-ERS), CDFA, peer-reviewed literature related to multiple aspects of milk production, and other published literature such as extension reports, particularly for 1964. When literature numbers were not available, the next best data were used or an assumption was made. Upstream unit processes associated with fuels, fertilizers, and transportation as well as some feed-based databases were modeled using the GaBi 6 software (PE International AG, 2015). Two different diets with respective milk production were considered for 2014 using IPCC assessment report 5 characterization factors (AR5; IPCC, 2014). Model 1 was based on high-producing cows in Rossow and Aly (2013), whereas model 2 was the average cow based on CDFA cost of milk production reports from 2013 to 2015.

Feed Production

California representative diets were collected from published data for 1964 and 2014 (NRC, 1958; Mead and Ronning 1961; Palmquist et al., 1964; Hutton and Bath, 1967a,b; Rauch et al., 2012, 2014; Rossow and Aly 2013; Swanepoel et al., 2014; Havlin et al., 2015; CDFA, 2014). In 1964, separate diets were used for calves, heifers, pregnant heifers, close-up heifers, and lactating and dry cows (Table 1). For model 1, several representative diets were collected based on the different stages of the life cycle for 2014, including calf (summary of 6 stages from birth to 12 mo), heifer, pregnant heifer, close-up heifer, fresh and high-producing lactating cows, far-off dry cows, and close-up dry cows (Table 2). Model 2 diets (Table 3) were based on reports from CDFA (2013, 2014, 2015). Because the composition of feed varied between different stages of production, the feed for each reference year was a representative weighted average over the whole production cycle to simplify the calculations. The average lifespan of dairy cows in California was assumed to be 4 lactations (H. Rossow), which was used for the normalization of calculations (Tables 1 and 2).

Crop Production

The crop production process included the farm practices to produce the feed, land, water, fertilizers, pesticides/herbicides, energy used for irrigation, and transport from field to farm including in-state and from-out-of-state transport. Data on crop yield/acre and the proportion of irrigated fields were obtained at the state level using a combination of sources, including USDA-NASS Quick Stats (USDA-NASS, 2017), USDA farm and ranch irrigation reports (USDA, 2013), and

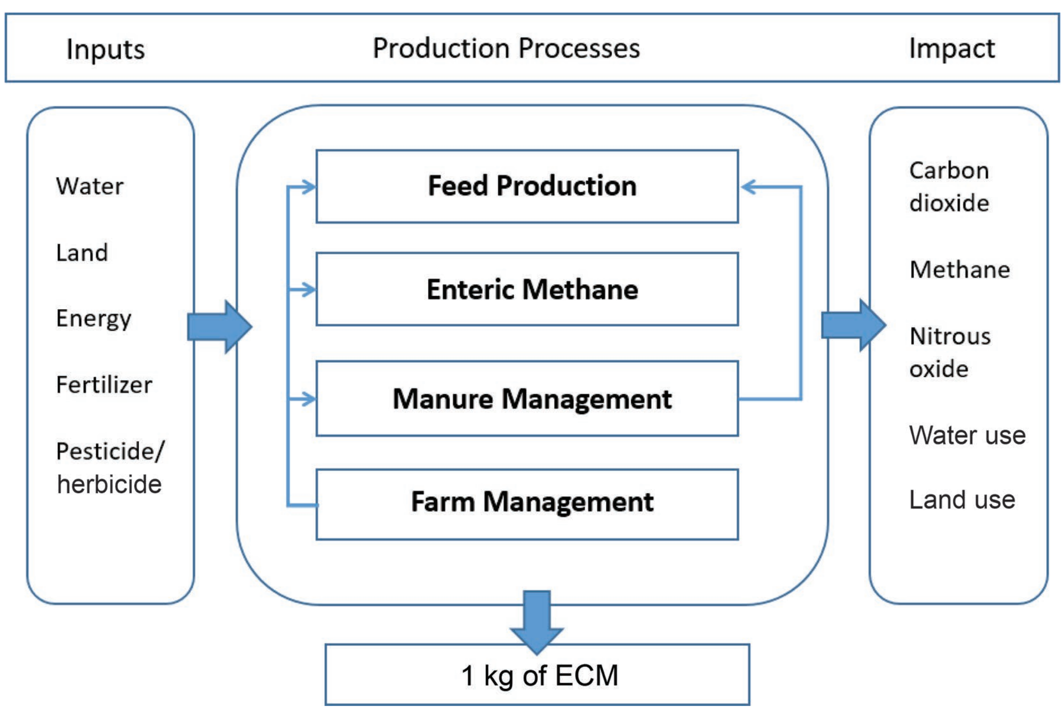

Figure 1. Overview of the milk production system boundary considered in the study.

Table 1. Ingredient and nutrient composition of 1 kg of diet for calves, heifers, and lactating cows in the California dairy system in 1964[1]

Item	Calf		Heifer		Cow		Weighted average
	Up to 6 mo	6–12 mo	Up to calving	Close up	Lactating	Dry	
Ingredient (%)							
Alfalfa hay			20.0	47.8	71.4	70.0	54.1
Oat hay				20.5		30.0	2.58
Pasture		100	79.9				23.2
Barley grains	38.4		0.18		21.7		14.1
Oat grains	26.3						0.459
Beet pulp				8.34	2.89		1.95
Hominy feed				12.2			0.236
Linseed meal	9.10						0.159
Molasses				2.76			0.054
Urea				0.38			0.007
Wheat bran	26.3						0.459
Wheat mixed feed				0.00	4.05		2.51
Wheat mill run				8.15			0.158
Composition							
DMI (kg/d)	3.61	15.1	25.4	24.0	18.8	15.0	17.8
Days in pen	180	180	290	30	1,220	180	
DM (%)	90.5	24.0	28.0	85.3	85.7	78.7	72.1
NDF (% of DM)	30.3	51.8	50.0	41.7	31.9	47.4	37.5
ADF (% of DM)	12.7	30.0	30.6	27.1	26.6	34.3	26.9
Ether extract (% of DM)	3.50	3.30	3.00	2.40	2.10	2.10	2.45
CP (% of DM)	15.7	21.3	21.2	16.9	18.6	17.3	18.8

[1]Data from NRC (1958), Mead and Ronning (1961), Palmquist et al. (1964), and Hutton and Bath (1967a,b).

California-specific agricultural reports (Burt et al., 2003; Johnson and Cody, 2015). For fertilizer use, USDA reports were used (Lin et al., 1995; USDA-ERS, 2011). Pesticide and herbicide usage were based on cost and return studies conducted in California and archived by the UC Agricultural Issues Center (2016). Emission factors for farm operations were based on Lal (2004) and Camargo et al. (2013). When detailed data were not available, University of California crop cost and return studies (UC Agricultural Issues Center, 2016) were used as representative crop production models. Furthermore, some fuel and electricity values required for crop production were extracted from published literature (Liedke and Deimling, 2015). Because of the limited data for 1964, government reports were used when available (US Bureau of the Census, 1967). When data were not available for 1964 crops, 2014 crop inputs were used with 1964 yields. Allocation of emissions for co-products were according to the Livestock Environmental Assessment Partnership (LEAP) guidelines (FAO, 2016a). By-products were treated as residues and carried no emissions burden for production, but transportation to the animal facility was counted toward emissions from the dairy sector.

Enteric Methane

Several mathematical models have been developed to predict enteric methane emissions from cattle (e.g., Mills et al., 2003; IPCC, 2006; Ellis et al., 2007; Moraes et al., 2014). Although most LCA studies use the IPCC (2006) Tier II model to estimate enteric methane emissions, it can overestimate emissions by about 12.5% in North American dairy cattle (Kebreab et al., 2008). Recently, Appuhamy et al. (2016a) evaluated 40 empirical extant models using region-specific independent data. The authors reported that for North America, the best performing model was the one they modified based on Nielsen et al. (2013), which included DMI, fatty acid, and digestible NDF concentration in the diet (Supplemental Table S1; https://doi.org/10.3168/jds.2019-16576). However, because digestible NDF was not available in our data set, the original model of Nielsen et al. (2013), which performed second best of all models in North America, was used to estimate enteric methane emissions in this study.

Farm Management

Farm management activities include the use of energy and water required on farm. Dairy farms use energy and water for many purposes, including crop production; animal consumption; cow comfort through cooling of animals and barns; cooling milk; sanitation operations, including animal hygiene and cleaning of facilities; and collection and transport of wastes. Water intake was estimated using recently published equations based on California cows (Appuhamy et al., 2016b). Separate

Table 2. Ingredient and nutrient composition of 1 kg of diet for different stages of a dairy cow in California in 2014 based on Rossow and Aly (2013) (model 1)

	Calves	Heifer			Lactating		Dry		
Item	Up to 12 mo	AI	Pregnant	Close up	Fresh	High	Far off	Close up	Weighted average
Ingredient (%)									
Alfalfa hay	17.0	35.4	20.3	32.9	23.8	4.15	28.5	29.4	9.00
Wheat hay	2.45		7.46				5.41		0.76
Oat hay				10.3					0.10
Corn silage	8.11	18.6	38.0	38.3	27.6	21.0	37.4	30.7	23.0
Wheat silage	3.67					0.35			0.43
Triticale silage	0.850	7.44							0.12
Corn grains	35.4			3.99		20.2		23.4	17.5
Barley grains	4.97								0.18
Almond hulls		14.1				1.37		8.73	1.49
Canola meal	10.5			9.40	12.2	11.8		7.73	10.3
Citrus, wet						1.97			1.48
Corn gluten meal	7.72				7.78	5.27			4.71
Cottonseed meal					7.78	6.63			5.40
DDGS[1]	1.30	22.4	9.43	5.18	8.76	7.69	5.47		7.44
Molasses	6.24	2.07				0.10			0.35
Soybean hulls	1.52								0.06
Soybean meal					2.43	1.65			1.37
Soybean oil	0.305								0.01
Wheat mill run					9.73	6.59			5.46
Wheat straw			19.1			11.3	18.5		10.4
Whey			5.65				4.69		0.54
Composition									
DMI (kg/d)	4.11	5.76	11.15	12.07	22.6	26.2	12.1	14.1	18.3
Days in pen	360	75	240	30	84	1,080	90	90	
DM (%)	74.3	61.7	50.1	55.3	62.0	67.1	51.2	59.6	64.8
NDF (% of DM)	25.0	41.9	49.6	42.5	36.8	34.3	48	34.2	35.6
ADF (% of DM)	15.9	28.5	32.9	28.6	23.5	21.1	32.3	23.4	22.6
Ether extract (% of DM)	3.65	4.2	3	3.3	3.7	3.9	2.7	3.2	3.66
CP (% of DM)	19.1	17.8	12.2	16.6	26.1	20.6	12.9	14.4	18.8

[1]Distillers dried grains with solubles.

Table 3. Ingredient and nutrient composition of 1 kg of diet for different stages of a dairy cow in California in 2014 based on CDFA (2018) (model 2)

Item	Calves	Heifer			Lactating	Dry	Weighted average
	Up to 12 mo	AI	Pregnant	Close up			
Ingredient (%)							
Alfalfa hay	17.0	35.4	20.3	32.9	15.8	25.5	17.32
Alfalfa haylage					1.68	0.37	1.34
Wheat hay	2.45		7.46		0.34	2.55	1.11
Oat hay				10.3	0.30	4.23	0.64
Corn silage	8.11	18.6	38.0	38.3	18.3	15.5	19.4
Wheat silage	3.67				3.59	24.1	4.63
Triticale silage	0.85	7.44					0.14
Sorghum silage					0.72	3.24	0.78
Pasture					0.27	0.51	0.25
Corn grains	35.4			3.99	17.6	3.54	15.7
Barley grains	4.97				0.34	0.11	0.47
Almond hulls		14.09			8.48	8.15	7.39
Beet pulp					0.64	0.14	0.51
Bakery waste					0.72	0.09	0.57
Canola meal	10.5			9.40	8.96	1.55	7.68
Corn gluten	7.72				3.50	1.73	3.23
DDGS[1]	1.30	22.38	9.43	5.18	5.88	1.05	5.84
Fruits and vegetables					0.99	1.63	0.89
Cottonseed meal					1.85	0.04	1.45
Whole cottonseed					4.99	0.13	3.93
Green chop					0.65	0.93	0.57
Molasses	6.24	2.07					0.30
Soybean hulls	1.52				0.91	0.23	0.80
Soybean meal					0.62	0.04	0.49
Soybean oil	0.30						0.01
Wheat mill run					1.28	0.45	1.03
Wheat straw			19.1		0.40	4.00	2.11
Whey			5.65		1.18	0.22	1.39
Composition							
DMI (kg/d)	4.11	5.76	11.15	12.1	22.6	12.6	16.4
Days in pen	360	75	240	30	1,164	180	
DM (%)	74.4	61.7	50.1	55.3	62.5	50.6	62.0
NDF (% of DM)	25.0	41.9	49.6	42.5	34.9	47.4	36.3
ADF (% of DM)	15.9	28.5	32.9	28.6	23.1	32.0	24.0
Ether extract (% of DM)	3.65	4.20	3.00	3.30	4.20	2.80	3.83
CP (% of DM)	19.1	17.8	12.2	16.6	18.7	14.3	17.6

[1]Distillers dried grains with solubles.

equations were used to estimate water intake by calves and lactating and dry cows, as suggested by Appuhamy et al. (2016b) (Supplemental Table S1). The equation to predict free water intake by lactating dairy cows requires data on sodium and potassium concentrations in the diet. Data were collected from 43 California dairy farms by Castillo et al. (2013) to calculate the mineral content of the diets and used to estimate free water intake.

Values from CARB (2015), PE International AG (2015), and Capareda et al. (2010) were used to determine energy emission factors for on-farm energy use (Supplemental Table S2; https://doi.org/10.3168/jds.2019-16576). Farm water and fuel usage reports do not differentiate between water and energy used for milking or other on-farm practices.

Manure Management

Estimates of methane emissions from manure storage and field application were based on IPCC (2006) guidelines. However, calculation of some variables were modified. The IPCC (2006) equation requires volatile solid (**VS**) output from dairy cows to be estimated before estimation of emissions. Appuhamy et al. (2016c) reported that the VS model they developed based on extensive North American data performed better than that recommended by IPCC (2006) guidelines. Therefore, VS was calculated using the Appuhamy et al. (2016c) model (Supplemental Table S1) and used as an input to the IPCC (2006) equation to determine manure methane emissions. The maximum methane-producing capacity for manure was 0.24 m^3/kg of VS.

The methane conversion factor (**MCF**) is an estimate of the manure carbon (in energy terms) that is converted to methane. The MCF is based on several factors, such as manure storage type and temperature. The average temperature in the state was taken to be 16°C in 2014 and 14°C in 1964 (NOAA, 2014). Based on these average temperatures, the MCF for manure spread daily, in dry lot, solid storage, liquid with natural crust cover, and anaerobic lagoon were 0.5, 1.5, 4, 18, and 75%, respectively for 2014 and 0.1, 1.0, 2, 15, and 73% for 1964 (IPCC, 2006). The following management systems were assumed. For heifers, 11% of manure was spread daily and 88% was in dry lot. For lactating cows, 11% was spread daily, 9% in solid storage, 20% in liquid with crust cover, and 59% in anaerobic lagoon (CARB, 2016). Due to paucity of data, we assumed that manure in 1964 was deposited onto pasture for all stages, except during lactation, where manure was assumed to be managed as liquid slurry (D. Meyer, University of California, Davis, personal communication).

Nitrous oxide (N_2O) emissions were calculated using the IPCC (2006) guidelines. However, a separate methodology was used to calculate total nitrogen output, which is one of the inputs in the IPCC (2006) equation. Johnson et al. (2016) evaluated 45 nitrogen excretion equations for lactating cows, heifers, and nonlactating cows. The authors reported that the equations developed by Reed et al. (2015) for nitrogen excretion performed best. Therefore, the Reed et al. (2015) models were used in this study to estimate total nitrogen excretion instead of using the IPCC nitrogen excretion equation. Combining the Reed et al. (2015) equation for nitrogen excretion with the IPCC (2006) equation, N_2O emissions were predicted (Supplemental Table S1). The total available nitrogen in manure was calculated using the IPCC (2006) guidelines and by determining the amount of nitrogen from synthetic fertilizers. The N_2O emissions from the applied manure and fertilizer were calculated using the IPCC (2006) direct and indirect N_2O emission equations. The direct N_2O emission factor (kg of N_2O-N/kg of N excreted) was negligible (assumed to be zero) for daily spread manure, 0.02 for dry lot, 0.005 for solid storage, 0.005 for liquid with natural crust, and 0 for anaerobic lagoon for both reference years (IPCC, 2006). The indirect N_2O emissions, which include ammonia emissions converted to N_2O, were also calculated based on IPCC (2006) guidelines.

Co-Product Allocation

Meat and milk are produced simultaneously in the dairy industry; therefore, the environmental impact burden must be allocated between the 2 products. Although there are several ways to allocate environmental impact, the International Dairy Federation (IDF, 2015) recommends a biophysical allocation approach. The allocation factor depends on the amount of milk produced by the cow in her lifetime and the live weight of the cow at the time of slaughter. For 2014 and 1964, slaughter weights of 650 and 600 kg, respectively, were assumed. The milk produced for each reference year was used to determine the respective allocation factors. For 2014, the calculated allocation to milk was 91.9%; for 1964, it was 81.1%. The allocation used in this study is on the higher end of values reported in various LCA studies summarized by Thoma et al. (2013). The allocation factor was applied to categories where the burden could be split between meat and milk. For this model, crop production, enteric methane emissions, and the manure management emission categories were allocated to both products. The farm management category was not allocated between meat and milk because the data available for farm energy usage did not differentiate between on-farm milking and non-milking energy. Therefore, milk production carried the full burden of that category.

Assumptions and Limitations

The results of this assessment are limited to the defined goal and scope, and exclusion of certain life cycle impact categories may result in an incomplete picture of the overall performance of the studied products. For instance, social and economic indicators were not covered in this LCA, so trade-offs between environmental, social, and economic factors were not evaluated. Although there is natural animal-to-animal variability in performance, this study assumed an average performance. The data used for the analysis were taken mostly from existing data sets and may be improved by expanding the data through targeted surveys at different locations in the state. Some data were missing for the 1964 analysis, so assumptions were made. Care should be taken in comparing results from this study with those of other studies due to differing methodologies. Specifically, calculations for enteric fermentation and manure storage contain elements that have been published recently so other studies might have relied more on IPCC (2006) methodologies or used information published before 2016. The LCA would be considerably improved if information on current manure management practices is updated and data on soil carbon dynamics and biogenic carbon are incorporated as the research results become available. Due to a lack of data from 1964, we assumed the lifespan of a cow has not changed much over the last 50 yr.

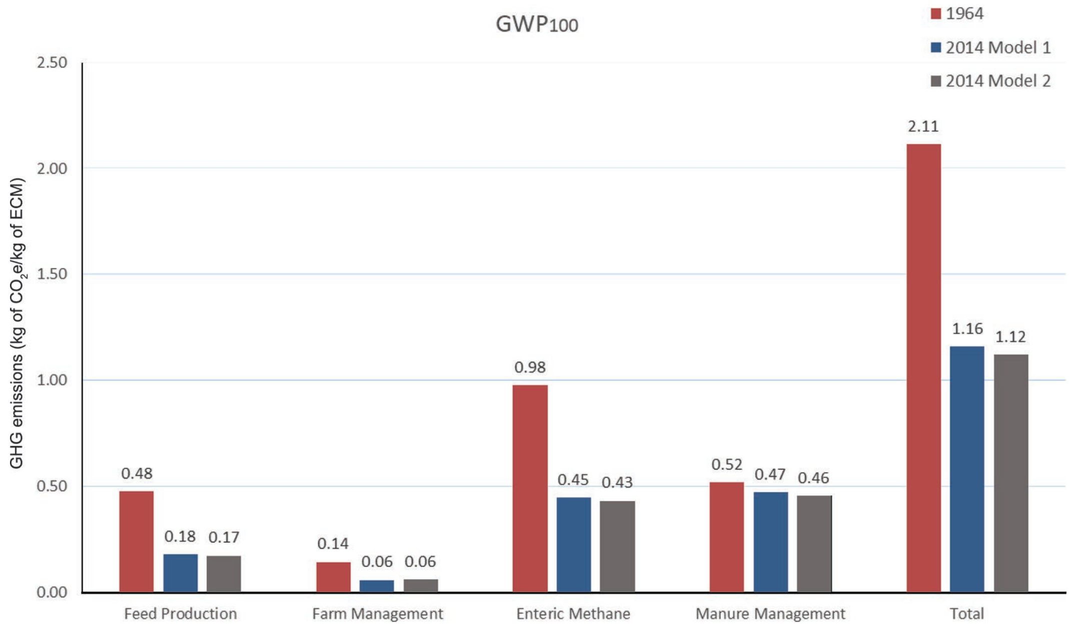

Figure 2. Comparison of global warming potential (GWP) in 1964 and 2014 by emission source for model 1 (using farm sampled diets) and model 2 (based on CDFA, 2013, 2014, 2015). GHG = greenhouse gas; CO_2e = CO_2 equivalents.

RESULTS AND DISCUSSION

The LCA was conducted to estimate the change in environmental impact of California dairy production over the last 50 yr by taking reference years 1964 and 2014. This section discusses the main results for GHG, water use and land use, using IPCC AR5 and taking into consideration the different diets and milk production inputs.

GHG Emissions

Producing 1 kg of ECM in California in 2014 was associated with 1.12 to 1.16 kg of CO_2e emissions compared with 2.11 kg of CO_2e for 1964 (Figure 2). The use of different dietary inputs (model 1 farm-based and model 2 using diets from CDFA) had minor differences in this impact category, with model 2 inputs showing slightly lower GHG emissions than model 1. The 2014 GHG emissions in this study were lower than those of previous LCA values reported. For example, for a cradle-to-farm gate LCA, Thoma et al. (2013) reported the average GHG emissions to be 1.23 kg of CO_2e/kg of ECM, and Gerber et al. (2011) reported 1.20 kg of CO_2e/kg of ECM for North America. In contrast with several other studies (e.g., Thoma et al., 2013), the largest contributor to GHG emissions in California was manure methane, making up about 41% of total emissions in both 2014 models, but only 24.5% in 1964. Enteric methane emissions were the second largest contributor, accounting for 38.5 to 38.7% of emissions in 2014 and 46.1% in 1964. About 15.4% of emissions were attributed to crop production for feed in 2014 and 22.6% in 1964. Farm management contributed to about 5.1 to 5.4% of emissions in 2014 and 6.8% in 1964 (Figure 2). The total amount of emissions went up from about 8.2 Mt of CO_2e/yr in 1964 to 21.8 Mt of CO_2e/yr in 2014. However, if production had remained the same as in 1964, it would take 39.7 Mt of CO_2e/yr to produce the same amount of milk currently produced in California per year.

Emissions from Crop Production. The emissions from crop production were 62.6 to 63.9% lower in 2014 than in1964. The main reasons for the considerable difference in emissions from crop production were (1) the differences in crop yield between the 2 reference years (Supplemental Table S3; https://doi.org/10.3168/jds.2019-16576); (2) energy used for transport, farm operations, seed production, pesticide application, fertilizer application and irrigation; and (3) feed conversion ratio (Supplemental Figures S1 and S2; https://doi.org/10.3168/jds.2019-16576). The contribution of emissions from crop production in 2014 was lower in this study than in other LCA (e.g., Thoma et al., 2013), mainly because California dairy farms typically use greater amounts of by-products compared with other regions in the United States. Russomanno et al. (2012) calculated the average by-product content of diets in 10 states (including California) to be 31.3%. In our analysis, which considered commercial diets from California farms, the by-product use in the average feed in a cow's lifetime was about 49%. This is in contrast to by-product use of about 3% in 1964 (Table 2). California is unique in using by-products such as almond hulls, which replace other feeds and their associated emissions. If by-products were not fed to dairy cattle, they would have to be disposed of by composting, combusting, tilling back to soil, and landfilling (Russomanno et al., 2012). The full effects of the avoided alternate treatment of hulls is not accounted for in this study because it is attributional LCA rather than consequential LCA.

Farm Management Emissions. In agreement with another LCA on dairy production (e.g., Thoma et al., 2013), farm management contributed the least to total global warming potential. Compared with 1964, emissions related to farm management in 2014 were reduced by 57.7 to 59.2%. The main activities contributing to emissions from this category were electricity and diesel used to operate equipment on the farm (Supplemental Table S4; https://doi.org/10.3168/jds.2019-16576).

Enteric Methane Emissions. Only minor differences were found between models 1 and 2 in estimated enteric methane emissions. Compared with 1964, the production of 1 kg of ECM in 2014 led to a 54.1 to 55.7% reduction in enteric methane emissions, mainly due to efficiency gains. In 1964, a cow consumed about 1.93 kg of feed to produce 1 kg of ECM (normalized to a lifetime basis), whereas in 2014, the feed conversion ratio was 0.79 to 0.81 kg of feed/kg of ECM. On a per daily cow·kg ECM basis, in 1964, each cow emitted 0.98 kg of CO_2e of enteric methane compared with 0.43 to 0.45 kg of CO_2e in 2014. Due to the low production of milk in 1964, proportionally more enteric emissions would be attributed to meat production. California dairies produced about 19 Mt of milk in 2014 (Sumner et al., 2015). To produce the same amount of milk using 1964-equivalent cows, an additional 1.3 million cows would be needed. Contributors to the reduction in emission intensity due to increased milk production efficiency include improved genetics, nutrition, cow comfort, and overall management. Dairy cows in California are among the highest milk producers in the world. For example, since 1984, milk per cow in California has increased about 50%, from 7,105 to about 10,900 kg per cow per year (Sumner et al., 2015). However, the variation in the amount of milk produced per lactation and per cow over her lifetime remains large, indicating the high potential for genetic selection to further increase milk production efficiency while decreasing management costs and GHG emissions (Knapp et al., 2011).

The selection of models will make a difference in the absolute amount of enteric methane emissions estimated. The California Air Resources Board (CARB, 2017) calculated enteric methane emissions from dairy cows in California in 2014 to be 8.24 Mt of CO_2e. The number from CARB (2017) is likely to be about 5% overestimated based on recent work that recalculated methane emissions in California accounting for differences in feed intake and emissions factors (Appuhamy and Kebreab, 2018). CARB (2017) follows methodology from the US Environmental Protection Agency (EPA) that uses a methane emission factor (**Ym**) of 4.8% of gross energy intake. The average Ym for North America has consistently been reported to be 5.7% (SE = 0.9; Kebreab et al., 2008; Appuhamy et al., 2016a; Jayasundara et al., 2016), and using this Ym would yield 9.53 Mt of CO_2e, which is very close to our estimate of 9.65 Mt of CO_2e based on IPCC AR5 and diets for high-genetic-merit cows. Thoma et al. (2013) used the model from Ellis et al. (2007), which fitted best to their national database, and if that equation had been used in this study, the estimate would be an adjusted 8.66 Mt of CO_2e. The Ellis et al. (2007) model was not used in this study because it was not in the top 10 models for North American dairy cattle in the evaluation of models conducted by Appuhamy et al. (2016a).

Manure Management Emissions. The GHG emissions from manure management decreased by 8.73 to 11.9%, depending on model used, in 2014 compared with 1964. The main contributing factor for emissions in 2014 was manure management per unit of milk. Although the feed conversion ratio was lower in 2014 than in 1964, most manure in 2014 was stored in lagoons, which has much a greater MCF (solid storage at 15–25°C has an MCF of 4%, whereas an uncovered anaerobic lagoon has an MCF of 74–79%). Our estimate of emissions from manure was very close to that reported by CARB (2017) (9.17 to 12.3 vs. 11.2 Mt of CO_2e, respectively). This was expected because the only difference was the calculation of VS that was based on a new equation from Apphuamy et al. (2016c), developed from cows in North America. Our analysis agrees with that of Thoma et al. (2013), specifically region 5 in their paper, which corresponds to the US West Coast of dairies with farms over 500 head. This region had a significant amount of emissions from manure management. However, there is large uncertainty in estimating emissions from manure because currently there are no GHG emissions measurements published to predict emissions from manure management or land application of dairy manure in California. There are wide variations in GHG emission estimates from manure (e.g., Borhan et al., 2011; Leytem et al., 2011). Some of the variation could be explained by the manure storage method (open, dry lot, wastewater pond, manure lagoon, composted). In addition, temperature plays a major role; in southern Idaho, methane emissions were

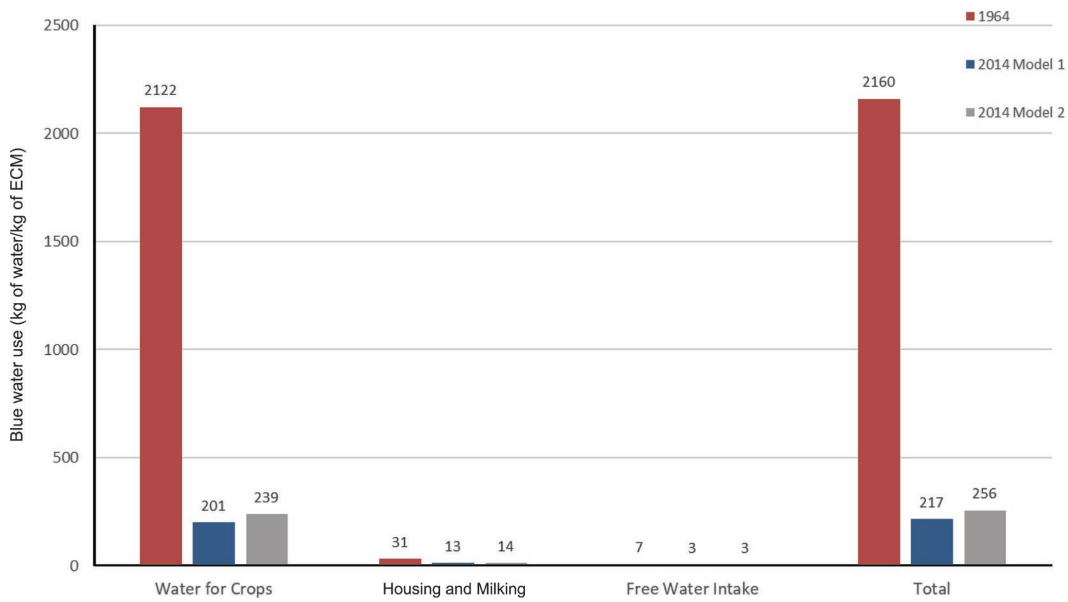

Figure 3. Blue water use to produce 1 kg of ECM in 2014 (blue bars) and 1964 (red bars) using diets from Rossow and Aly (2013; model 1) or California Department of Food and Agriculture (model 2; CDFA, 2013, 2014, 2015).

greatest from open lots in the spring and from manure lagoons for the rest of the year (Leytem et al., 2011). There is also no reported field and laboratory research on GHG sources and sinks and model parameters such as MCF for California. Therefore, default IPCC (2006) values with limited modification as described by CARB (2016) were used. New surveys of manure management practices in California are urgently needed to supplement the work of Meyer et al. (2011). These data would be needed to improve GHG emission estimates and identify best management practices.

A primary source of manure GHG emissions in California is anaerobic lagoons, which represent the most common on-farm dairy manure storage practice in the state. Anaerobic lagoons have more than 10 times the global warning potential of solid manure piles (CARB, 2017). Gerber et al. (2011) assumed anaerobic lagoon and solid storage to represent 12 and 31% of manure management systems in the United States, respectively, whereas in California, it is 59 and 9%, respectively (CARB, 2017). This has considerable implications for GHG emissions because of the dramatically different MCF for solid and liquid stored manure.

Water

Dairy farms use water for many purposes, including crop production, animal consumption, cow comfort through cooling of animals, milk and barns, and cleaning operations. In this study, only blue water was considered (i.e., water that has been sourced from surface or groundwater resources). Water from rainfall (green water) and water needed to dilute pollutants to meet quality standards (gray water) were not considered in this study. The amount of blue water used in California dairy farms to produce 1 kg of ECM in 2014 decreased 88.1 to 89.9% compared with 1964 (Figure 3). The main categories that affect water usage in dairy farms are crop production, housing and milking–related use, and free water intake by the animals. The largest contributor in both 1964 and 2014 was that used for crops, which was estimated to be 98.2% of total water use in the 1964 model and slightly less, 92.5 to 93.2%, in 2014. The results agree with values calculated by Mekonnen and Hoekstra (2012), who suggested that feed was responsible for 98% of total blue water use for global animal production.

To estimate water use for crop production in 1964, a California-specific water-use life cycle inventory was developed using cost analysis conducted by the University of California Agricultural Extension Service for different crops (Fischer and Yeary, 1963; Kearney and Parsons, 1964). The main crops used with their water footprint are given in Supplemental Figure S3 (https://doi.org/10.3168/jds.2019-16576). Water usage for crops in 2014 was only 9.4 to 11.3% of the amount used in 1964 per 1 kg of ECM. The main reason for this reduction was the improved yield and water use efficiency in the last 50 yr (Supplemental Table S3; https://doi.org/10.3168/jds.2019-16576). Improved crop genetics

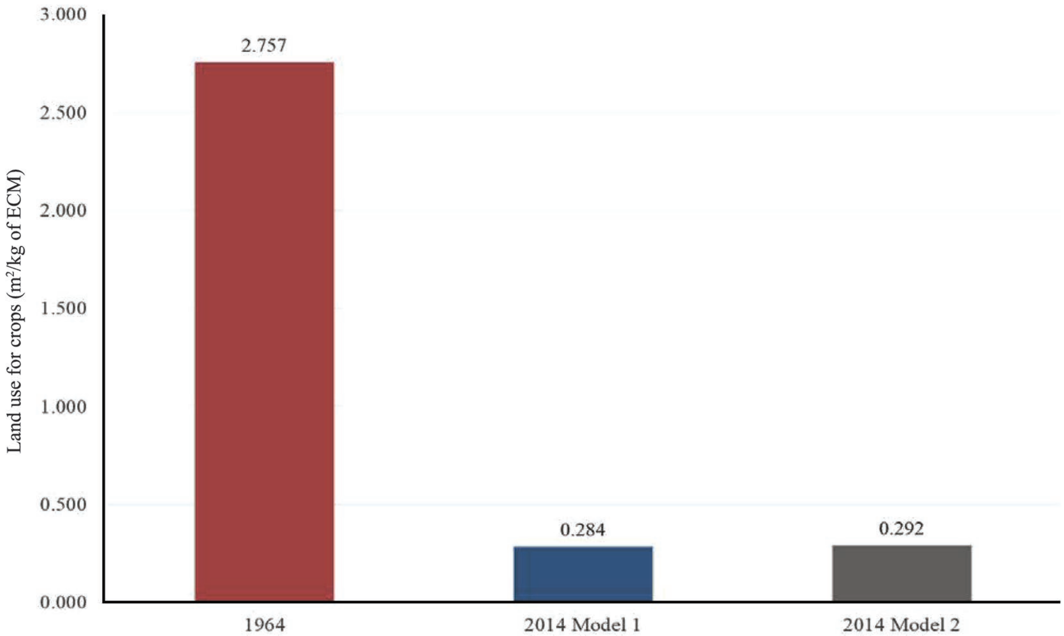

Figure 4. Comparison of calculated land use for crop production for a diet in 1964 and 2 diets in 2014. Model 1 was based on Rossow and Aly (2013) and model 2 on California Department of Food and Agriculture (CDFA, 2013, 2014, 2015).

and management have contributed to large efficiencies in water utilization. Blue water use for irrigation has declined steadily since the 1960s, even though irrigated acreage has increased (USGS, 2009). Irrigation practices have been adopted to improve uniformity of water distribution and efficiency of water delivery with a net benefit of less water needed per unit of crop farmed (CAST, 2012).

On-farm water use values were taken from a study conducted by Meyer et al. (2005). The main activities that required on-farm water use were the milking parlor, sprinkler pens, udder hygiene, milk equipment, sanitation, parlor cleaning, plate coolers, and ice makers. There was a 55.3 to 59.2% reduction in on-farm use (per unit of ECM) in 2014 compared with 1964. This reduction in water use was mainly due to the improvement in milk production per cow in 2014 and improvements in milk equipment such as vacuum pumps and plate coolers, which allow a producer to use the same water for multiple functions. Drinking water contributed only 1.3 to 1.6% in 2014 and 0.34% in 1964. These values agree with Mekonnen and Hoekstra (2012), who suggested that drinking water contributed only 1.1% of the total water footprint.

Land

About 19.5% of land in the United States was classified as cropland in 2002 (USDA-ERS, 2007). One of the main uses of cropland for animal agriculture is to produce grain, hay, and silages for cattle. The amount of land required to produce each ingredient used in the reference years is given in Supplemental Table S5 (https://doi.org/10.3168/jds.2019-16576). Although production of barley grains and soy oil had the greatest land requirement per 1 kg of dry crop weight, their inclusion rate in the diet was low. Corn grains and silages have relatively greater contribution to the diet and to the land requirement to produce 1 unit of ECM. About 72% of the land requirement for 2014 was from out of state and 28% was in state (Supplemental Table S5). Figure 4 shows the cropland used to produce 1 kg of ECM in the reference years. Compared with 1964, 89.4 to 89.7% less land was required to produce 1 kg of ECM in 2014.

Improvements in crop genetics and production practices have dramatically increased crop yields (USDA-NASS, 2011). Similarly, soil erosion has been reduced through sustained research, education, extension, and policy development (USDA-NRCS, 2010). Several strategies for further decreased water use and degradation as well as more efficient use of land have been suggested, including improving irrigation efficiency, waste management, and water productivity; better diet formulation; use of enzymes; improved manure collection, storage, treatment, and utilization; improved land management; and improved livestock distribution (CAST, 2012).

CONCLUSIONS

This study covered a cradle-to-farm gate agricultural LCA for California dairy production and evaluated changes in GHG emissions and water and land use in 1964 and 2014. Two diet input scenarios were considered, which had minor differences in the estimates of the impact categories. The average farm-gate GHG emission for 2014 in the study ranged from 1.12 to 1.16 kg of CO_2e/kg of ECM, depending on the modeled diet. The results are on the lower side compared with other LCA conducted for the US dairy sector. Relative sources of emissions differed, with lower emissions from feed due to its high utilization of by-products, and higher emissions from manure due to anaerobic storage systems. Manure and enteric methane emissions present opportunities to mitigate emissions through innovation. Although total emissions increased due to the volume of milk production, compared with 1964, enteric methane (per kg of ECM) was reduced 54.1 to 55.7%, and manure GHG decreased by 8.73 to 11.9% in 2014 compared with 1964. Total water use was reduced 88.1 to 89.9%, with water reductions of 88.7 to 90.5% in crop production, 57.7 to 59.2% in housing and milking, and 52.4 to 54% in free water intake. Land requirements were also reduced 89.4 to 89.7% in 2014 compared with 1964. As milk production per cow continues to be increased through genetic improvements and better nutrition and animal care, feed conversion efficiency will also improve, leading to further reductions (measured in emission intensity) in environmental impact. More emissions data and improved models such as soil carbon dynamics are needed to accurately quantify this achievement and optimize energy, crop, and economic returns from manure management.

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