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Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008

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ABSTRACT

This article presents a cradle-to-grave analysis of the United States fluid milk supply chain greenhouse gas (GHG) emissions that are accounted from fertilizer production through consumption and disposal of milk packaging. Crop production and on-farm GHG emissions were evaluated using public data and 536 farm operation surveys. Milk processing data were collected from 50 dairy plants nationwide. Retail and consumer GHG emissions were estimated from primary data, design estimates, and publicly available data. Total GHG emissions, based primarily on 2007 to 2008 data, were 2.05 (90% confidence limits: 1.77–2.4) kg CO_2e per kg milk consumed, which accounted for loss of 12% at retail and an additional 20% loss at consumption. A complementary analysis showed the entire dairy sector contributes approximately 1.9% of US GHG emissions. While the largest GHG contributors are feed production, enteric methane, and manure management; there are opportunities to reduce impacts throughout the supply chain.

1. Introduction

Consumers are growing more aware of their impact on the environment, and this may result in changes to their consumption habits. To that end, the US dairy industry is working to further improve the environmental performance of its supply chain in a way that is also economically sustainable. In 2007, approximately 17.4 Tg (million metric tons) of fluid milk of all types were consumed (USDA, 2010a). Analysis of the dairy supply chain from production through ultimate disposal of packaging was necessary to provide the industry with a documented baseline of the carbon footprint of fluid milk an analysis of the dairy supply chain from production through ultimate disposal of packaging was performed. These results serve to identify reduction opportunities through best practices and creation of decision-support tools for producers, processors, and others throughout the dairy supply chain that can be used to foster the long-term viability of the industry. This life cycle analysis (LCA) was performed in compliance with ISO 14040:2006 and 14044:2006 standards, with the exception that a single impact assessment method, global warming potential, was adopted. ISO standards call for a wider range of impact assessment categories. The Innovation Center for US Dairy is addressing additional impact categories in other projects; thus this work represents one aspect of the dairy industry's sustainability evaluation.

A number of life cycle assessment studies have focused on dairy in the past decade (Guinard, Verones, & Loerincik, 2009). There are a variety of methodological approaches used in these studies. Some report on an energy-corrected milk, or fat and protein-corrected basis, and each uses a slightly different milk-to-beef allocation procedure; many have focused on production only, but a few have included additional post-farm components in the analysis. Much of this research has been done in Australia (Lundie, Feitz, Jones, Dennien, & Morian, 2003), Scandinavia (Berlin, 2005; Eide, 2002), and Western European countries (Hospido, Moreira, & Feijoo, 2003).

Previous LCAs for dairy have focused primarily on agricultural production (e.g., Basset-Mens, Ledgard, & Boyes, 2009; de Boer, 2003; Capper, Cady, & Bauman, 2009; Cederberg & Flysjö, 2004;

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Table 1
Summary of previously published life cycle analyses for fluid milk production and consumption (beyond farm gate).

Study	Functional unit (FU)	kg CO_2e per FU	Allocation % to milk	Characterization factors (CO_2, CH_4, N_2O)	Study description
Cederberg et al. (2009)	kg ECM at retail	1.08	85%	1, 25, 298	Sweden, 1990 versus 2005
Eide (2002)	kg milk at end-of-life	~0.54 to 0.65	65%	–	Norway, study of 3 dairies
Gerber et al. (2010)	kg FPCM at retail	2.4	~90%	1, 25, 298	International average
Gerber et al. (2010)	kg FPCM at retail	1.3	~90%	1, 25, 298	US average
Guinard et al. (2009)	kg milk at end-of-life	1.2	Economic	1, 25, 298	Literature review of 60 studies, primarily European

Cederberg & Mattsson, 2000; Flysjö, Henriksson, Cederberg, Ledgard, & Englund, 2011a; Haas, Wetterich, & Kopke, 2001; Thomassen, Dolman, van Calker, & de Boer, 2009). A large body of research exists on packaging in general, with some emphasis on milk packaging in particular (Keoleian & Spitzley, 1999). Little research on transportation of milk has been published. Life cycle-based analysis of dairy processing is less common (Berlin, Sonesson, & Tillman, 2008; COWI, 2000; Tomasula & Nutter, 2011; Xu & Flapper, 2009). Research on the life-cycle of milk from retail to consumer to end-of-life has been minimal (Cederberg, Sonnesson, Henriksson, Sund, & Davis, 2009; Eide, 2002; Gerber, Vellinga, Opio, Henderson, & Steinfeld, 2010; Guinard et al., 2009). Table 1 summarizes several full life cycle study results.

The majority of the studies report similar greenhouse gas (GHG) emissions at the farm gate, ranging from approximately 0.75–1.5 kg CO_2e per kg milk and 75–90% allocation of burdens to milk compared to the co-product beef. A recent comparative study of allocation methods supports this range, noting that system expansion results in somewhat lower (as low as 63%) allocation to milk, while mass allocation is as high as 98% (Flysjö, Cederberg, Henriksson, & Ledgard, 2011b). One of the lowest reported carbon footprints is the study by Eide (2002) that reports 65% allocation to milk and 0.45 kg CO_2e per kg milk. The Food and Agriculture Organization of the United Nations (FAO) reports the US average farm-gate GHG emission as 1 kg CO_2e kg^{-1} fat and protein corrected-milk (FPCM) (Gerber et al., 2010). These studies point to enteric fermentation and manure management as primary sources of GHG emissions in dairy production. Some studies point to on-farm management as a critical area for investigating improvement opportunities (Henriksson, Flysjö, Cederberg, & Swensson, 2011; Thoma et al., 2012b). Other studies investigate simplified approaches to evaluating the potential impact/importance of different parameters in the contribution to carbon footprint (Asselin-Balençon et al., 2012; Flysjö et al., 2011a).

Retail businesses are beginning to engage their supply chains to encourage adoption of best practices and development of innovative solutions that reduce environmental impacts and maintain value. Understanding both the sources of and the factors influencing these environmental impacts is an important first step to identify the most effective reduction opportunities. More detailed analysis of on-farm GHG emissions as well as emissions associated with milk transportation, processing, packaging, distribution are presented elsewhere (Nutter, Ulrich, Kim, & Thoma, 2012; Thoma, Jolliet, & Wang, 2012a; Ulrich, Thoma, Nutter, & Wilson, 2012). The goal and scope of this work were:

- Goal: Determine GHG emissions associated with consumption of 1 kg of milk by US consumers. To account for differences in production at the farm and processing, we used the National Research Council (2001) approach for FPCM.
- Scope: Cradle-to-grave. The system boundaries included the energy use and GHG emissions associated with every step of the life cycle from production of fertilizer through to either landfill or municipal waste incineration of the milk packaging. We explicitly excluded infrastructure in this analysis. Incidental activities such as employee commutes, accounting, legal services, executive air travel, and the cost of heating the farmer's residence, were not included. The primary time frame for the study was 2007–2008.

2. Methods

2.1. Functional unit

The functional unit of this study is 1 kg of milk consumed by US consumers. National scale reference flows for US fluid milk products are presented in Table 2 (USDA, 2007). We created a national "average" milk as the sales volume-weighted average of the four milk-fat content varieties for post-processor calculations. Product loss in the supply chain, including wasted or spoiled milk by consumers and out-of-date milk at retail, is equivalent to 29.6% loss of all milk produced prior to it being consumed (USDA, 2010a). This loss is reported as 12% at retail and 20% at consumption and is not differentiated by milk-fat content. These losses in the supply chain affect the reference flows of upstream processes; specifically, the required flow into the consumption phase is approximately 1.25 kg per kg consumed, and the flow into the retail channel is approximately 1.14 kg per kg delivered to retail. This results in a reference flow of 1.42 kg milk from the farm to milk processing. Because much of the energy in dairy feed is converted to milk solids (e.g., fat and protein), and not all farms produce milk with standard fat and protein composition, we have normalized on-farm production to a standard milk (4% fat, 3.3% protein) using the National Research Council approach (NRC, 2001) for FPCM; this is also referred to as Energy Corrected Milk (ECM) because the calculation is based on the ratio of the energy content, as determined by fat and protein

Table 2
Total US sales of fluid milk products in 2007.

Product	Fat content (%)	Non-fat solids (%)	Water (%)	Density ($kg\ L^{-1}$) @ 4 °C	Total sales (million kg)
Whole milk[a]	3.26	8.6	88.13	1.0333	7398
Reduced fat milk (2%)[a]	1.94	8.8	89.21	1.0346	8742
Low fat milk (1%)[a]	0.96	9.1	89.92	1.0360	5257
Fat-free milk (skim)[a]	0.11	9.1	90.84	1.0364	3971

[a] Includes sales of flavored and organic milk.

concentrations, of produced milk to standard milk. The following relationship was used to convert farm production to a fat- and protein-corrected basis:

$$\text{FPCM} = \frac{0.0929F + 0.05882P + 0.192}{0.0929 \times (4\%) + 0.05882 \times (3.3\%) + 0.192} = \frac{0.092F + 0.05882P + 0.192}{0.7576} \quad (1)$$

In Equation (1), F is the percentage milk fat in the produced milk and P is the percentage protein in the produced milk. While it is important to account for differences in fat and protein concentrations at the farm level, for post-farm stages of the supply chain a volumetric basis is more appropriate for calculations because the milk processing and handling is not different for milk with different fat content. We have used the reported sales for whole, 2%, 1%, and skim milk from this table to determine reference flows for each of these main fluid milk products leaving the processor gate. For purposes of this study we have aggregated flavored milk with the appropriate type based on its fat content; in addition, because the density of the different varieties is nearly the same (Watson & Tittsler, 1961), we have not explicitly accounted for any potential density variation effects.

2.2. Allocation

Attributional LCA is intended to quantify the material and energy inputs and outputs associated with a specific system. In practice, industrial processes usually result in more than one valuable product – milk, cream, and beef in this study. Here it is necessary to apply allocation to the LCA model. Allocation is the partitioning of the input and output flows of a system among the multiple system products. ISO 14040/14044 guidelines recommend a hierarchy of procedures for addressing this issue. System expansion has not been used for this project, primarily due to the lack of LCA for potential substitute products that could be used as a basis for this approach. Physical relationships have been adopted where feasible and economic value or mass allocation has been used as our third option, as described fully by Thoma et al. (2012a). In Table 3, we present a summary of the allocation ratios and approaches adopted for this study. We have made an effort to be consistent with allocation methodologies at each stage of the value chain, i.e., using economic allocation across all feed byproducts. When possible, we have adopted causal relationships to define the allocation ratio.

2.2.1. Feed co-products allocation

Allocation of burdens between co-products arising from feed crop processing (e.g., between distiller's grains and ethanol or grain meals and oils) is necessary. In such situations, we have adopted economic allocation as the standard method. For the economic approach, where available, we have used a five-year average price to define the allocation ratio.

2.2.2. Milk–beef allocation

An important allocation for this study is the allocation of GHG emissions between the co-products of beef and milk from virtually all dairy facilities. For this study, we have chosen to allocate impacts between the co-products milk and meat according to a biological relation following Thoma et al. (2012a).

2.2.3. Cream–milk allocation

To derive allocation factors, we have used national milk consumption rates for different milk fat content products coupled with a milk fat solids mass balance (Thoma et al., 2012a). Information from the USDA regarding the standard composition of various milk products was used to determine the composition of each type of milk on a fat-free basis (USDA, 2010b). Water is primarily a carrier for milk fat and proteins. Since the principal difference between the co-products is the fat content (Table 2), our approach to allocation for these co-products was to assign the entire raw milk burden to milk solids. Then using mass conservation principles, our approach was to assign the appropriate milk protein and milk fat burdens to each of the different milk fat products based on the reported milk fat content of each co-product. The data do not provide sufficient resolution at the processor level to allocate milk processing impacts among the different fat content milk products; in fact, most of the energy requirements are volume- or mass-based. Pasteurization energy is insensitive to milk fat content.

Table 3
Summary of allocation ratios and types used in this study; the base case methodology has been shaded in the table.[a]

Co-products	Economic allocation	Mass allocation	Other	
Soy oil/soy meal	31:69	19.5:80.5		
Soy oil/meal/hulls	56.7:41.2:2.1	19.4:74:6.6		
Cottonseed/lint	19:81	38.5:61.5		
Milk/beef	94.5:5.5	95:5 (Protein content)	88.6:11.4 (causal by feed nutrient content)	
Distiller's Grains (dry)/ethanol	30:70	52:48		
Distiller's Grains (wet)/ethanol	24:76	51:49		
Corn/corn silage[b]	–	–		
Region 1			47:53	Causal relationship based
Region 2			88:12	on crop nitrogen requirements
Region 3			94:6	determined from reported yield
Region 4			92:8	
Region 5			No data	
Fluid milk/cream	–	–	80:20 (mass balance of milk solids)	
Refrigeration	–	–		
Milk:other refrigerated retail (electricity & refrigerants)			1.62:98.38 (shelf space occupied)	
Home (electricity)			1.62:98.38 (space allocation)	
HDPE (recycled)	–	–	System expansion using ecoinvent unit process	

[a] We have adopted economic allocation unless a particular stage allowed an allocation approach higher on the International Organization for Standardization (ISO) hierarchy.
[b] This is not an allocation of burdens of co-products, but an allocation of fertilizer and fuel inputs, which are reported in aggregate, between the two crops. The inputs are used as technosphere flows into separate unit processes for each crop. The large differences between regions are primarily determined by the relative production of each crop. More silage is grown in Region 1 compared with corn grain than the other regions, and therefore the allocation of shared inputs is not nearly equal.

2.2.4. Retail and consumer refrigeration

GHG burdens associated with the retail stage are primarily associated with electricity for compressors and loss of refrigerants due to leakage. The allocation approach for these burdens, between milk and other refrigerated goods, is based on space-occupied and sales velocity metrics. Shelf space occupied, as a fraction of either refrigerated or total store shelf space, is used to allocate annual whole-store GHG emissions to the total sales of the item.

2.3. Data Sources

Data were collected from many sources including the USDA's National Agricultural Statistical Service (NASS) and Economic Research Service, peer-reviewed literature related to LCA of milk, other technical literature, consultation with experts in different fields, and an extensive nationwide survey of dairy farm operations. The survey was distributed to over 5000 producers, of which there were 536 voluntary responses (Popp et al., 2012; Thoma et al., 2012b).

SimaPro 7.1 was used as the primary modeling software and the ecoinvent database was used to provide information on the upstream burdens associated with production of materials including primary fuels and refrigerants (Frischknecht & Rebitzer, 2005). Background, or upstream processes included from the ecoinvent database, which is primarily of European origin, is believed to have a relatively small influence on the calculated footprint because the unit processes in the ecoinvent database are typically representative of modern technologically advanced systems. In addition, a test was performed using a modified version of the ecoinvent database in which all of the background electricity, to the extent feasible has been replaced with the US primary energy production mix. No significant difference in results was observed.

Technosphere flows used in the model, including materials and energy purchased from a supplier, were characterized with a combination of the inherent variability found during the statistical data aggregation and the pedigree matrix of data quality used by the ecoinvent database (Weidema, 1998). Thus inventory flows can be assigned a probability density function (PDF) that describes the likelihood of a particular inventory flow occurrence. The SimaPro software platform enables Monte Carlo Analysis for calculation of propagation of inventory uncertainty to impact uncertainty by choosing inventory flows from the PDF and aggregating over multiple runs. Data from the surveys and other US-specific information were incorporated into the model to the extent available. We have adopted the IPCC (2006) carbon dioxide equivalency factors of 25 for methane and 298 for nitrous oxide.

2.3.1. Dairy rations

In the assessment of GHG emissions associated with production of the principal grains used in animal rations (Adom et al., 2012a; Adom, Workman, Thoma, & Shonnard, 2012b), two main sources of agricultural data were used: crop production data in terms of annual yield, and agricultural chemical use statistics including annual fertilizer and pesticide totals, both reported at the state level from the USDA National Agricultural Statistics Service (USDA, 2008a, 2008b).

Few data have been collected at aggregate levels for cattle forage. GHG emissions estimates from cattle forage production were created from crop production budgets produced by state agriculture extension specialists who provided estimates for the inputs needed to produce alfalfa and grass hay, silage, and pasture. After compiling inputs for specific crop production, these were entered as inputs to a new unit process in the LCA software platform. Detailed tables of regional rations by animal class are given as supplementary materials by Thoma et al. (2012b).

2.3.2. On-farm emissions

On-farm methane measurements are not feasible as a general method for estimation of enteric methane production. As discussed by Thoma et al. (2012b), a comparison of models led to selection of an enteric methane emissions model based on dry-matter intake (Ellis et al., 2007). The American Society of Agriculture Engineers' Standard on manure characteristics (ASAE, 2005) was used to estimate the quantity of manure generated. IPCC (2006) emission factors for methane were applied to calculate the total manure management methane emissions. Daily nitrogen excretion, based on reported crude protein content of rations, ranged from approximately 0.2 kg day^{-1} for open heifers up to 0.43 kg day^{-1} for multiparous lactating cows. These estimates were combined with Tier-2 emission factors for specific manure management technologies (Table 10.21, IPCC, 2006), including an accounting for direct deposition on pasture, to estimate the total on-farm N_2O emissions associated with manure management.

2.3.3. Farm to processor transportation

Raw milk is delivered by unrefrigerated insulated tank trucks from one or more farms to a processing plant (Ulrich et al., 2012). Rail transport is used only for processed dairy products that are not highly perishable and do not have to be delivered on a strict schedule such as ice cream, yogurt and canned milk. The truck makes a round trip, picking up milk at each farm along its route, then delivering the load to the plant. Tank capacities may reach 34 m^3 (9000 gallons) with 22.7 m^3 (6000 gallons) being the most common. This study considered only deliveries made by full 22.7 m^3 trucks delivering an average of 22 m^3.

For this study a value of 2.4 km L^{-1} was used (5.7 miles per gallon), which results in GHG emissions of 1.33 kg CO_2e km^{-1} (2.13 kg CO_2e $mile^{-1}$). Because the deliveries included were restricted to full loads with the same capacity, the emissions-per-m^3 delivered was only a function of the round-trip distance. The average round-trip length was 829 km.

Several large dairy co-operatives have provided an extensive database that includes individual truck delivery from farms to fluid milk processing plants. The combined database has over 300,000 records from 2007 to 2008 and provides average transport distances.

2.3.4. Milk processing, packaging, and distribution

Starting in February 2008, an extensive survey was sent to eight milk processing companies. Surveys were returned for 50 individual processing plants for their production during calendar year 2007 (Nutter et al., 2012). These 50 plants were responsible for approximately 25% of the entire fluid milk volume processed in 2007. Information requested in each survey included plant energy consumption, truck fleet fuel consumption, refrigerant purchases for both the plant and truck fleet, on-site milk packaging production, packaged milk type and sizes, and annual production values for total plant fluid, fluid milk, and packaged milk.

2.3.5. Retail

After distribution from the processor to the retail gate, fluid milk is displayed for consumer purchase. During this phase, there are three distinct emissions streams: refrigerant leakage, refrigeration electricity, and overhead electricity. For the purposes of this LCA, milk sales were aggregated through three channels: supermarkets, mass merchandisers ('big box' stores) and convenience stores. One of the major challenges associated with evaluation of the retail stage is the allocation of whole-store energy consumption to milk. Data on the sales volume, space occupancy, and energy demands of milk were analyzed to allocate the burden of this supply chain stage for fluid milk (EPA, 2008b, 2009; ICF Consulting, 2005; USEIA, 2003).

Table 4
Reference data for supermarket retail outlets.[a]

Parameter	Amount	Reference
Refrigerant load	1814 kg	ICF Consulting (2005)
Annual leak rate	18%	ICF Consulting (2005)
Linear refrigerated milk space	21.3 m	Mateen Personal Communication, Innovation Center for US Dairy, Chicago, IL (2009)
Linear refrigerated total space	1311 m	Mateen (2009)[b]
Linear grocery total space	6934 m	Mateen, (2009)[b]
kW h per square meter	556.5 kW h m^{-2}	ASHRAE (2007)
Total area of store	4343 m^2 (in 2008)	FMI (2012)
Refrigeration demand (% of total)	43%	USEIA (2003)
Overhead demand (% of total)	55%	USEIA (2003)
Natural gas per square meter	15.3 m^3 m^{-2}	USEIA (2003)
Overhead demand (natural gas)	87%	USEIA (2003)
Total milk sales, average US grocery	746551 US$	Mateen (2009)[b]
Average price, liter of milk	0.99 US$	USDA (2007)
R-22 faction in stores	54%	ICF Consulting (2005)
R-404A fraction in stores	46%	ICF Consulting (2005)

[a] Additional information for other sales channels is presented by Thoma et al. (2010).
[b] Personal communication (Innovation Center for US Dairy, Chicago, IL, USA).

According to data from the Interaction Research Institute's database (Mateen, Innovation Center for US Dairy, Chicago, IL, USA: personal communication, 2009), 65% of fluid milk sold in the US is sold through the supermarket channel, 21% through mass merchandise channel and 14% is distributed through drug and convenience stores. Detailed information for the supermarket channel is provided below; additional information for mass merchandizing and convenience stores is reported by Thoma et al. (2010).

Supermarket channel. These stores sell a broad mix of food and a limited mix of general merchandise. Reference information for supermarkets used to allocate retail burdens is provided in Table 4. They have a large land footprint and most use direct expansion refrigerant systems (EPA, 2006). Common refrigerants are R-22, R-404A, and R-507A; for mixtures of these refrigerants, the composition of the mixture was used to determine the appropriate global warming potential (http://www.refrigerants.com/refrigerants.htm). It was assumed that R22 and R404A were used at 54% and 46%, respectively (EPA, 2008b). These systems have a compressor that is housed separately from the refrigeration units, and the refrigerant is pumped in through a pipe network. This piping system is the source of most leaks, due to catastrophic events (e.g., a broken pipe). Supermarkets typically have 1814 kg of refrigerant in a system that leaks 18% annually (EPA, 2009). The USEPA GreenChill Program reports information regarding the sources and causes of refrigerant loss in supermarket systems (EPA, 2009).

Burdens were allocated on an occupied-space basis, using consumer-facing linear shelf length as the space metric. Consumer-facing shelf space information was obtained from a proprietary database available through the project sponsor (Table 5). Milk was allocated a share of refrigerated space and a share of total grocery space to account for the refrigeration and overhead burdens, respectively. Overhead electricity demands allocated to milk include ventilation, lighting, cooling, space heating, water heating, and plug loads. Table 6 presents the fractional consumption of electricity and natural gas in grocery retail outlets (USEIA, 2003); this information coupled with data published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers were used to generate estimates of the overhead burden (ASHRAE, 2007).

Table 5
Proportion of refrigerated space dedicated to milk.

Parameter	Length (m)	Percent attributed to milk
Milk refrigerated shelf length	21.3	100
Refrigerated shelf length, total	1311	1.62
All store shelf length, total	6934	0.31

Table 6
Electricity and natural gas allocation at retail.[a]

End use all channels	Electricity usage (%)		Natural gas usage (%)	
Refrigeration	43			
Cooking	2		13	
Allocated by shelf space		45		13
Ventilation	4			
Lighting	13			
Cooling	14			
Plug Loads	17			
Space heating	2		74	
Water heating	1		13	
Other	4			
Allocated by sales (overhead)		55		87

[a] Sources are EPA (2008b) and USEIA (2003).

Mass merchandisers. Mass merchandisers sell 21% of the milk in the US (Mateen, personal communication 2009). This channel typically sells a large mix of general merchandise as well as grocery items. It is assumed that the grocery section within a mass merchandiser is typical of an average supermarket with a smaller land footprint 3900 m^2 for a mass merchandise grocery compared to 4343 m^2 for a supermarket (Table 7). Burdens associated with the grocery section of mass merchandising were allocated in a manner consistent with the supermarket channel.

Convenience stores. Convenience stores sell 14% of the milk in the US (Mateen, personal communication 2009). These stores sell a mix of grocery and general merchandise items and have the smallest land footprint of 434 m^2. This study included all stores within the channel, and did not distinguish between fuel-selling and non-fuel-selling locations. Convenience stores differ from typical grocery stores in that the refrigeration systems are fully-enclosed units, indicating that the compressors for the refrigerants are housed within the unit itself, eliminating the need for external piping and virtually eliminating the risk of system leakage. Current regulations require that refrigerants be captured to be recycled or destroyed at the end of useful life of the refrigeration system. We have assumed that any small leakage from this recovery process is below the cut-off criterion for the study.

2.3.6. Consumer transportation, storage and waste

For the consumer contribution, we allocated a fraction of in-home refrigeration (1.62% of refrigeration use) to milk storage. We allocated fuel for consumer travel based on an estimate of the sales percentage that milk represents in typical grocery purchases

Table 7
Average annual electrical energy consumption for retail channel outlets.[a]

Sales channel	25th percentile	Average usage	75th percentile
Grocery and convenience	347	565	586
Convenience store	467	743	847
Convenience store w/gas station	406	667	850
Grocery store/food market	347	566	586

[a] Units are kW h m^{-2} y^{-1}; data source is ASHRAE (2007).

(0.307%), and an assumed transportation distance of 10.9 km round-trip to the grocery store; 175 trips and 229.2 kg purchased per household (Table 8). An assumption in this analysis is that convenience stores, supermarkets, and mass merchandise outlets all have the same transportation distances and associated milk purchases. It is likely that customers of convenience stores will typically purchase smaller quantities of milk and customers of supermarkets on each trip. Thus it is possible that there is an overestimate of the transportation burden for this sales channel; however, it may also be the case that trips to the convenience store are not dedicated to purchase of groceries, and that some fraction of the entire trip should actually be allocated to other consumer activities. For this reason we have simply taken the average values as described above.

We modeled waste scenarios in SimaPro with unit processes from ecoinvent to model consumer disposal of milk packaging material. Industry data provided for conventional white milk shows that 89% of milk is delivered in high density polyethylene (HDPE) containers, 11% in paperboard, and 1% in polyethylene terephthalate (PET) (Klein, personal communication 2009). Franklin Associates (2008) reports that HDPE is recycled at a 29% rate, while the paperboard gable top cartons are not currently being recycled to any measurable degree. This report also indicates that an estimated 14% of post-consumer waste is incinerated with energy recovery. We have modeled the incineration of these materials, however have not accounted for energy recovery, as it will fall below the one percent cutoff.

2.3.7. Product loss

The Economic Research Service (ERS) of the USDA publishes estimates of food loss for most commodity foods, including dairy (USDA, 2010a). These estimates are the best available, and report 12% loss of fluid milk from retail to consumer, and an additional 20% loss due to cooking loss, spoilage and waste at the consumer. We have accounted for disposal as a volumetric flow equal to the volume of waste milk loss to municipal sewage treatment. For the milk loss at retail, our assumption is that it is further processed into dry milk solids that are used as a feed supplement for cattle or other animals. We have assumed that it displaces dried whey as an animal feed. Because milk is approximately 13% solids, the waste flow from retail into the return channel is taken as 13% of the out-of-date milk weight.

3. Results and discussion

3.1. Supply chain analysis

3.1.1. Cradle-to-farm gate

Thoma et al. (2012b) present a detailed analysis of the cradle-to-farm gate GHG emissions. The GHG emissions were reported as 1.23 kg CO_2e kg^{-1} FPCM. Due to the scaling required by the product loss in the system, 1.42 kg FPCM is required at the farm gate to provide one kg consumed. Thoma et al. (2012b) present a summary of the farm-gate results by production region: Region 1: Northeast; Region 2: Southeast; Region 3: Upper Midwest; Region 4: Southwest plus High Plains; Region 5: West Coast (Popp et al., 2012).

3.1.2. Farm to processor transportation

Emissions from this phase of the value chain are dominated by tailpipe emissions from the trucks. Loss of refrigerants is negligible since the trucks are not refrigerated according to Ulrich et al. (2012). The average round-trip length was 829 km giving average emission levels of 0.049 kg CO_2e kg^{-1} milk delivered to the processor gate (Ulrich et al., 2012). Due to milk loss in the supply chain, the transportation burden is 0.0696 kg CO_2e kg^{-1} milk consumed.

3.1.3. Processing, packaging and distribution

GHG emissions associated with processing, packaging, and distribution are provided in Table 9. All major emission sources, from raw milk entering the refrigerated storage silo, through delivery of packaged fluid milk to the retailer, are accounted. The gate-to-gate cumulative GHG emission is 0.203 (±0.017) kg CO_2e kg^{-1} of packaged fluid milk. This is reported as the mean with 95% confidence interval and represents the inherent variability in this supply chain stage. The contribution of the processing supply stage is 0.288 kg CO_2e kg^{-1} milk consumed.

3.1.4. Retail channels

The retail stage of the supply chain contributes 0.099 kg CO_2e kg^{-1} milk refrigerated, or 0.141 kg CO_2e kg^{-1} milk consumed assuming that all milk (including out of date returns) at retail was refrigerated. As shown in Table 10, the burden from electricity, refrigerants, and natural gas contribute 64.4%, 35.5%, and 0.15%, respectively.

3.1.5. Consumer transportation and storage

As described previously, in-home allocation fractions are based on the assumption that the generic American food pantry is roughly equivalent to grocery store stock, i.e., there is a nearly steady state flow of food through retail outlets and the American consumer's home. This will slightly overestimate the burden as there are items that must be refrigerated once opened that are not refrigerated at the retail outlet. We used a consumer transportation distance of 10.9 km round-trip to the grocery store for each shopping as shown in Table 8 (FHA, 2009).

Table 8
Energy consumption for in-home refrigeration and consumer transport.

Energy consumption area	Amount
In-home refrigeration	
Annual refrigeration energy (USEIA, 2005)	1345 kW h y^{-1}
Per capita milk consumption (USDA, 2010a)	76.4 kg y^{-1} (calculations assume 3 persons per household, thus 229.2 kg y^{-1})
Burden allocated to milk (1.62%)	0.097 kW h kg^{-1} purchased
Consumer transport	
Travel for shopping from home (FHA, 2009)	10.9 km $trip^{-1}$; 175 trips per year
Attributed to dairy	0.307% retail shelf space allocation fraction

Table 9
Summary of greenhouse gas (GHG) emissions from milk processing.

Unit process	Gate-to-gate GHG emissions (kg CO_2e kg^{-1} packaged milk)[a]
Processing	
Purchased electricity	0.054 (±0.0090)
Onsite fuel combustion	0.022 (±0.0044)
Refrigerant loss	0.001 (±0.0014)
Total	0.077 (±0.0109)
Packaging	
Raw material	0.034 (±0.0034)
Container formation	0.020 (±0.0012)
Total	0.054 (±0.0044)
Distribution	
Mobile fuel combustion	0.058 (±0.0091)
Refrigerant loss	0.014 (±0.0037)
Total	0.072 (±0.0102)
Overall	0.203 (±0.0174)

[a] Numbers in parentheses indicate 95% confidence interval of mean, but do not account for propagation of input uncertainty.

Table 10
GHG burdens at retail stage of milk value chain.[a]

Component	$kgCO_2e\ kg^{-1}$ milk	Total MT CO_2e annual
Supermarket		
Refrigerants	0.0423	472,571
Electricity	0.0529	591,252
Natural Gas	0.0001	1515
Total	0.0953	1,065,338
Mass merchandizer		
Refrigerants	0.0273	96,360
Electricity	0.0342	120,560
Natural Gas	0.0001	309
Total	0.0616	217,229
Refrigerants		N/A
Convenience store		
Electricity	0.1311	320,538
Natural Gas	0.0002	587
Total	0.1313	321,126
All channels		
Refrigerants		568,931 (35.48%)
Electricity		1,032,351 (64.37%)
Natural Gas		2411 (0.15%)
Total		1,603,693 (100%)

[a] Values are per kg milk sold (not per kg milk consumed – retail losses are accounted, but not consumer losses).

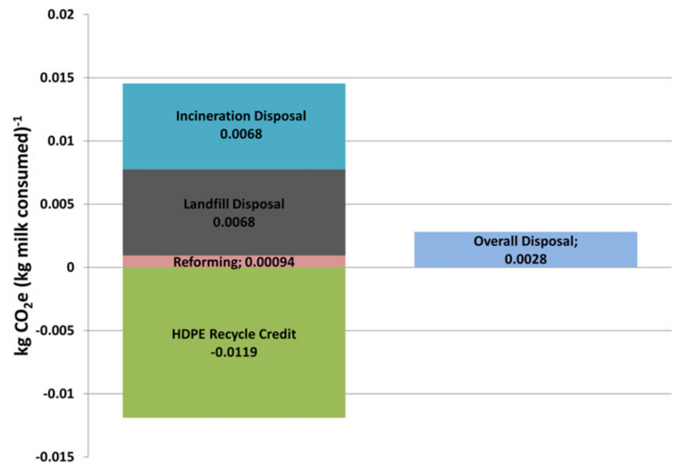

Fig. 2. Packaging disposal greenhouse gas emissions for national mix of primary packaging. Reforming refers to electricity necessary for the recycling process of high density polyethylene containers.

Fig. 1 presents the summary of the retail and consumer use phases. The bar in the natural gas column for consumers represents the gasoline consumption associated with travel to the store for groceries; natural gas consumption at retail is too small to appear. The use phase also includes the impact of disposal of wasted milk to a municipal wastewater treatment facility; the flow was taken to be the estimated volume of spoiled milk disposed. Fig. 1 accounts for product loss in the supply chain, whereas Table 10 only accounts for gate-to-gate retail contributions.

3.1.6. *Post-consumer waste management*

End-of-life analysis of the packaging was based on the distribution of primary packaging materials used for milk delivery in the US and is summarized in Fig. 2. Of total HDPE packaging, 29% was recycled and an avoided product credit was accounted. No recycling credit for PET or paperboard was claimed; all non-recycled waste packaging was considered to be disposed in a landfill or incinerated (86% of all non-recycled waste was assumed to be disposed in a landfill and the remaining 14% incinerated). We used standard ecoinvent unit processes for waste management, including incineration of post-consumer waste. Incineration unit processes contribute less than 0.4% of GWP when summed across the entire supply chain. Spoiled or wasted milk at the consumption phase was assumed to be disposed into a municipal wastewater treatment facility modeled with an ecoinvent unit process.

3.1.7. *Supply chain loss/waste*

In this project, we have explicitly accounted for estimated product loss through the supply chain. Based on USDA food loss reports, we accounted for a 12% loss (return) at retail and an additional 20% loss from cooking, spoilage and waste at the consumer stage. Fig. 3 shows the effect of different waste rates on the footprint of consumed milk. The best-case scenario (3% retail loss and 5% consumer loss) results in a 23% decrease in GHG emissions compared with the base case. This appears to present a significant reduction opportunity; however, interpreting the consequences of changes in consumer behavior is difficult. For example, if consumer waste is reduced because children stop leaving half-full cereal bowls, there will be essentially no change in the overall system emissions, with the exception of a small reduction in municipal wastewater treatment emissions, because there will be no change in the quantity of milk moving through the

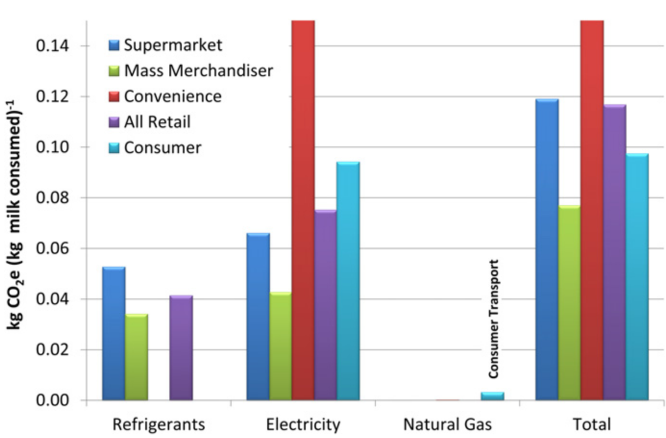

Fig. 1. Greenhouse gas emissions from retail and consumer use phases. The turquoise bar under natural gas is transport by consumers from retail to their home.

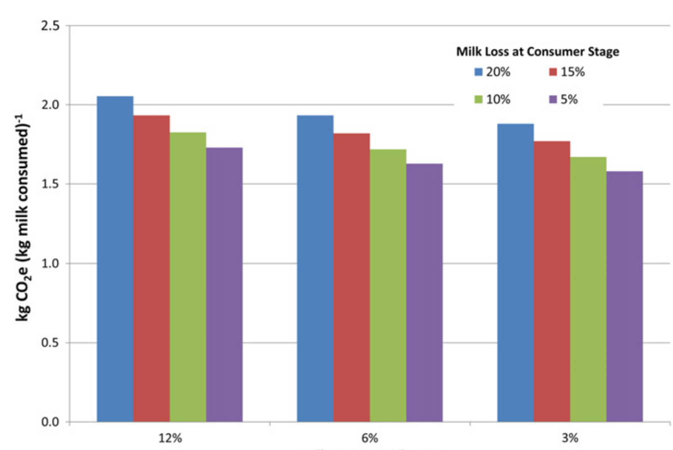

Fig. 3. Product loss is modeled at the retail and consumption stages. This figure presents a sensitivity analysis of the carbon footprint as it is influenced by the degree of loss/waste.

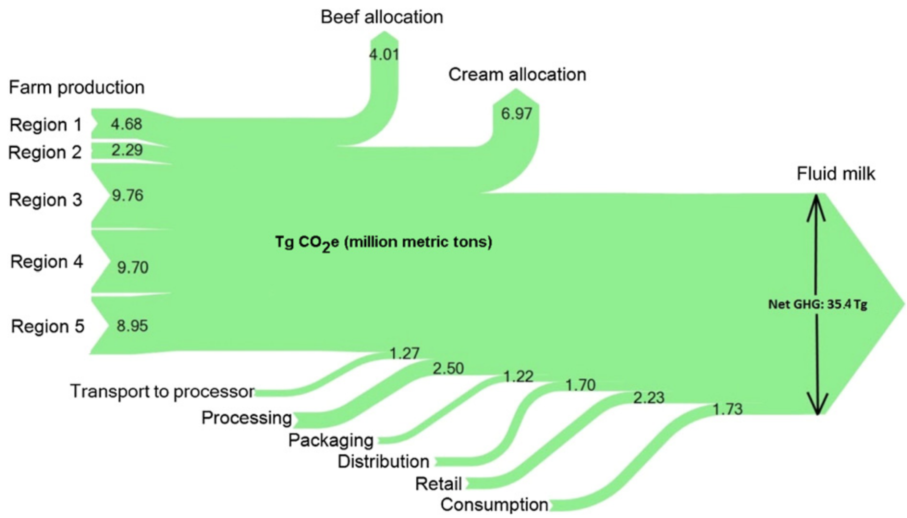

Fig. 4. Greenhouse gas flow through the milk supply chain. All values (including beef and cream allocation) are Tg CO_2e for all fluid milk consumed in 2007. This diagram includes an accounting for both the regional production of milk destined for consumption as a beverage and the national mix of whole, skim, 1%, and 2% milk for 2007.

system. However, if parents were to put less milk on the cereal, their milk purchase would last longer, and their consumption of milk would remain constant, but they would purchase less to meet that consumption demand. Thus, while the effect of consumer waste makes a large difference in the footprint of the consumed milk, the effects of change in this behavior on the cumulative GHG emissions are difficult to predict.

3.2. National scale impact of fluid milk consumption

Fig. 4 shows the flow of GHG emissions associated with the production of fluid milk in the United States. The contribution of each stage in the supply chain is denoted both numerically and by the width of each arrow. Each region's contribution was determined from the USDA reported milk production (corrected to kg FPCM) and regional GHG emission intensity (kg CO_2e kg^{-1} milk) to create a national scale contribution due to production of fluid milk. The arrows leaving the top of the chart represent allocation of cumulative up-stream burden to co-products that is removed from the fluid milk supply chain at that point. The calculations also account for the different quantities of milk (whole, skim, 1%, and 2%) consumed in the United States and for product loss across the supply chain. In 2007, approximately 17.4 Tg of fluid milk of all types were consumed (USDA, 2007). This resulted in an estimated 35.4 Tg CO_2e in GHG emissions. The breakdown of these emissions by supply chain stage and source is presented in Fig. 5. Enteric methane contributes approximately 8.8 Tg CO_2e and manure management 8 Tg CO_2e (6.2% of all ruminant enteric methane reported as 140.8 Tg in 2005, and 13.5% of GHG emissions from manure management, reported as the 62.1 Tg in 2005) (EPA, 2008a). These values are for fluid milk only, and, of course, exclude the allocation to co-products beef and excess cream.

The cumulative GHG emission is 2.05 kg CO_2e per kg milk consumed (17.6 pounds CO_2e per gallon of milk consumed). Fig. 6 presents the breakdown of GHG emissions across the supply chain. There is, of course, natural variability in production and

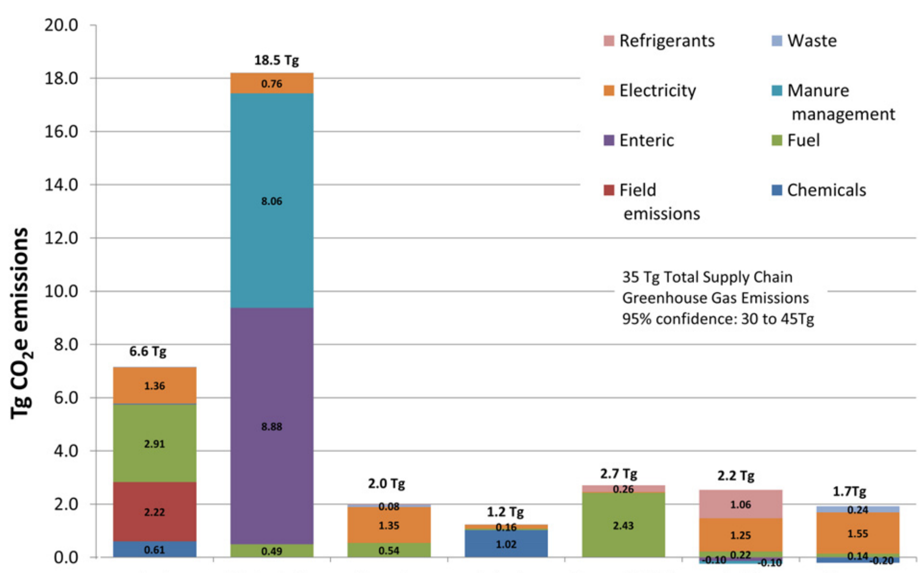

Fig. 5. Greenhouse gas emissions by supply chain stage. Values are reported in Tg, and values smaller than 0.04 Tg are not reported to maintain readability of the chart.

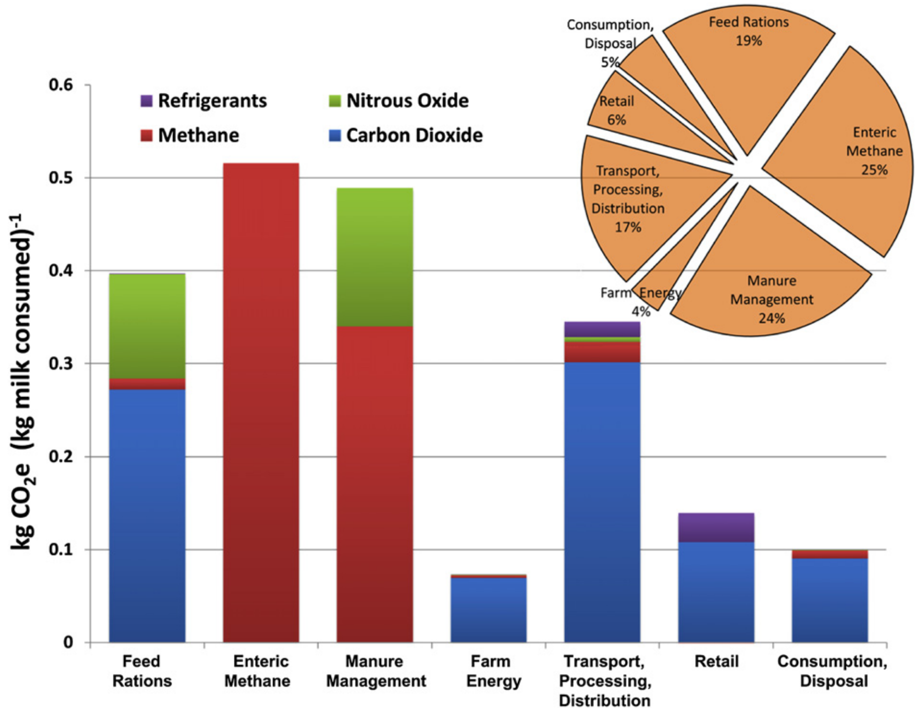

Fig. 6. Supply chain contribution to carbon footprint of 'generic' milk. Generic milk refers to regional-production-weighted (raw milk input) and purchase-volume-weighted (milk fat content) average milk consumed in the US during 2007. Note that fuels, fertilizer, and milling are included in the feed stage. In addition, there is a 12% product loss accounted in retail, and an additional 20% wasted product in the consumption phase.

supply chain activities as well as uncertainty in reported values for many parameters necessary for computation of the footprint. To account for this, a Monte Carlo uncertainty analysis was performed, as described in Section 2.3, with the result that the 90% confidence band varies from 1.77 to 2.4 kg CO_2e kg^{-1} milk consumed. Of total burden associated with consumption of fluid milk, 72% is accrued by the dairy farm gate. This highlights the significant opportunity for the industry in on-farm improvements, specifically in terms of manure management and controlling enteric methane emissions. These emissions sources as well as the incoming burden of the feed are significantly influenced by the on-farm feed conversion efficiency. Improving conversion efficiency reduces GHG emissions from all three sources. Manure management offers additional potential reductions through adoption of management technologies that reduce methane emissions, such as digesters or wider adoption of daily spread and other low emission approaches. Even though the majority of emissions occur during production, it should be noted that some "extra" emissions are induced by waste in the downstream supply chain due to product loss or waste.

3.3. Dairy sector contribution to the US greenhouse gas inventory

In an effort to place the entire dairy sector into context of overall emissions of GHG in the United States, we have combined estimates from several sources (EPA, 2011; Thoma et al., 2012b; USCB, 2011) to create an estimate of the relative contribution of the dairy sector to the overall US greenhouse gas inventory in 2008. To maintain comparability from year-to-year reports of GHG emissions, the EPA reports the GHG equivalents based on an earlier version of the IPCC global warming potentials (IPCC, 1995). This analysis was based on the global warming potentials published (for the IPCC) by Forster et al. (2007). Table 11 presents a comparison of the global warming potentials from the two IPCC reports.

Table 12 presents the GHG inventory for the United States for the years 2007 through 2009 based upon the two IPCC reports. There is an approximately 1.6% increase in the estimate of GHG emissions based on the revised global warming potentials. Note that the values reported in Table 12 do not include sequestration-associated forestry because the current study does not include sequestration associated with the crop production for the dairy

Table 11
Comparison of second and fourth IPCC global warming potential equivalency factors.

Gas	SAR (IPCC, 1995)	AR4 (Forster et al., 2007)
CO_2	1	1
CH_4	21	25
N_2O	310	298
HFC-125	2800	3500
HFC-134a	1300	1430
HFC-143a	3800	4470
HFC-152a	140	124
SF6	23,900	22,800

Table 12
Comparison of US greenhouse gas emission inventory for the second (SAR; IPCC, 1995) and fourth (AR4; Forster et al., 2007) Intergovernmental Panel on Climate Change (IPCC) reports; sequestration of carbon dioxide is not included.

Gas	SAR (Tg CO_2e)		AR4 (Tg CO_2e)	
	2007	2008	2007	2008
CO_2	6120	5921	6120	5921
CH_4	665	677	791	806
N_2O	325	311	313	299
HFCs	130	129	127	131
SF_6	17	16	16	15
Total	7263	7061	7366	7172

Table 13
Energy consumption by dairy manufacturing industry sector.

NAICS[a] code	Sector description	Electricity purchased (MW h)	Tg CO_2e	Purchased fuels (US$1000)	Tg CO_2e[b]
31151N	Fluid milk and butter	3,905,802	3.23	$236,516	0.198
311513	Cheese	3,765,102	3.11	$284,802	2.06
311514	Dry, condensed, and evaporated product	1,524,350	1.26	$187,245	1.36
31152	Ice cream and frozen dessert	1,317,111	1.09	$27,397	1.71

[a] NAICS, North American Industry Classification System.
[b] Based on 2008 national average cost of natural gas of US$9.65 MCF^{-1} http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm.

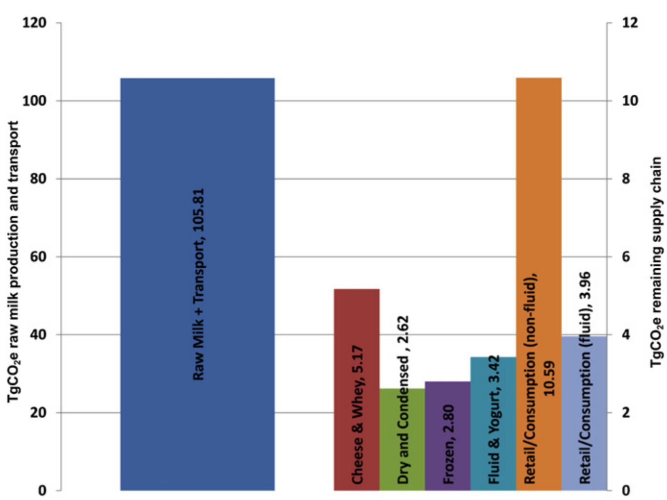

Fig. 7. Estimated contribution to the US greenhouse gas emissions inventory in 2008. Sequestration of CO_2 has not been accounted for in this analysis.

ration, and therefore is a more directly comparable baseline for estimation of the dairy sector contribution.

3.3.1. Estimation of overall dairy sector GHG emissions

The USDA reported 82.67 Tg of milk produced in 2008 with an average milk fat content of 3.68%. As reported by Thoma et al. (2012b) and Ulrich et al. (2012) the GHG emissions up to the processor receiving silos is approximately 1.28 kg of CO_2e kg^{-1} FPCM. This assumes roughly equivalent transportation distances for both fluid milk and non-fluid milk uses, which is probably a slight overestimate for milk destined for cheese production facilities, resulting in 105.8 Tg CO_2e emissions. Based on information from the US Census Bureau, shown in Table 13, it is possible to estimate the GHG emissions from the manufacturing stages for non-fluid milk dairy products. Combining these estimates with the retail and consumption information reported elsewhere in this paper, and using the assumption that retail and consumption for non-fluid milk dairy products is in the same proportion to manufacturing as for fluid milk (approximately 70% as shown in Fig. 4), the total dairy sector GHG emissions is estimated to be 133.6 Tg, or 1.9% of the US total for 2008 from Table 12 (7172 Tg, AR4). The breakdown by supply chain stage is presented as Fig. 7.

4. Conclusions

This work establishes a sound and defensible baseline for GHG emissions associated with production and consumption of fluid milk in the United States during 2007–2008. In the future, as the industry moves to meet its 2020 goals of 25% reduction in GHG emissions, progress can be assessed against this baseline emission level. An important caveat is that this LCA exclusively focuses on carbon emissions, and does not account for other environmental impacts, such as water or air quality. Decisions made solely on the basis of GHG emissions do not account for potential trade-offs with other environmental impacts, and caution should be exercised in making decisions based on a single metric. Future comparison against the baseline developed this study will be facilitated by the availability of the life cycle inventory model in public US databases. The data are currently being prepared for submission in the near future.

The results of this study show that, on average, 2.05 kg CO_2e are emitted per kg milk consumed, but a more accurate interpretation is that based upon knowledge uncertainty and characteristic variability, we can be 90% confident that the GHG footprint of milk lies between 1.77 and 2.4 kg CO_2e kg^{-1} milk consumed. These error bounds are a combination of both knowledge uncertainty and characteristic variability.

Other LCA studies for dairy production have been performed over the past decade and report similar GHG emissions at the farm gate (Basset-Mens et al., 2009; Capper et al., 2009; Cederberg & Flysjö, 2004; Cederberg & Mattsson, 2000; Cederberg et al., 2009; Eide, 2002; Gerber et al., 2010; Guinard et al., 2009; Haas et al., 2001; Thomassen et al., 2009). A recent UN Food and Agricultural Organization report states that the US average farm-gate GHG emission is 1.0 kg CO_2e kg^{-1} FPCM (Gerber et al., 2010), which is approximately 20% lower than that found in this study: 1.23 kg CO_2e kg^{-1} FPCM (90% CI: 1.1–1.45 kg CO_2e kg^{-1} FPCM).

The LCA results give insight into the innovation opportunities of the dairy supply chain; however, these opportunities should be carefully evaluated and explored. Innovations and changes in supply chain activities may yield unintended results, or may simply shift burdens in the system without causing any real reduction in environmental impact. A major conclusion of this study is that there is opportunity to reduce impacts throughout the entire supply chain, across feed and milk production, processing, distribution and consumption. The on-farm and processing GHG emissions showed significant variability (Nutter et al., 2012; Thoma et al., 2012b).

Identification and recognition of this variability suggests that opportunities exist for improvement of those lower performers. There is significant value in understanding the sources and causes of variability. Uncertainty in the system indicates opportunities for improving modeling techniques and further exploration of the methodology used for those calculations.

This work has pointed to manure management, feed production, and enteric methane as three areas for innovation research (Thoma et al., 2012b). Nutrient management strategies on the dairy farm that link inorganic fertilizer use with application of manure for crop production should be integral to any GHG reduction approach. Anaerobic lagoons on larger farms and deep bedding on smaller farms are manure management systems for which the GHG emissions are significantly greater than other systems, such as dry lot and solid storage. On the surface, this seems to indicate that a shift in practices could result in emission reductions; however, both the economic cost and potential environmental burden shifting that could result from changing to a different system must be considered. Methane digesters have great potential as a way to capture and potentially utilize methane that is otherwise lost to the atmosphere, and should be considered a high priority for these larger systems; however, the possibility of additional land requirements for managing nutrients retained in the digester solids must be evaluated. Because this study only considers GHG emissions, there is need for further study to understand the full range of environmental impacts before making decisions.

The analysis of fluid milk processing plant GHG emissions suggests some opportunities to reduce individual emissions. Therefore, a focus on truck fleet fuel usage and plant electricity consumption is prudent since these two components are the greatest GHG contributors.

Implementation of standard energy efficiency practices should be considered for the refrigeration system, compressed air system, motors, and lighting. Similarly, plant fuel reductions could be realized through improved steam system efficiency and operating practices. Emission savings for packaging could come from improved bottle designs resulting in reduced material use and upgrades to modern, energy-efficient formation equipment. As an example, changing the bottle cap manufacturing process from injection-molding to thermoforming may lower environmental burdens, as has been recommended for the yogurt cup manufacturing process (Keoleian, Phipps, Dritz, & Brachfeld, 2004). Finally, careful study of plant specific optimization of the transport distances (i.e., truck miles) and the future selection of transport refrigeration systems using low GWP refrigerants may reduce emissions for the fluid milk industry.

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