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Abstract

Infant formula contributes to greenhouse gas emissions at all stages of the lifecycle, from dairy farm to landfill. Although the health concerns of infant formula are well documented the environmental impacts have not been examined. This study is a partial lifecycle assessment of the total greenhouse gas emissions from all stages in a model U.S. infant formula lifecycle. 14.7 kg CO_2-eq are emitted per kg of infant formula consumed, or over 2.6 million tons CO_2-eq for total U.S. production in 2005. Offsetting these emissions would cost about \$8 per infant per year of consumption. Greatest contributing sectors to the lifecycle are raw milk production at the dairy farm (55.4%) and consumer preparation activities (17.4%). The results of this preliminary LCA suggest that breast milk substitution is a significant source of anthropogenic greenhouse gases. Evidence-based advocacy for breastfeeding may benefit from understanding the environmental consequences of infant formula.

BACKGROUND AND CONTEXT

Breastfeeding is the optimal feeding practice for infant and young child health. According to the World Health Organization, infants should be exclusively breastfed[1] for six months and up to two years with additional foods added. However, according to the U.S. Center for Disease Control and Prevention, one in four American breastfed infants consume infant formula within the first two days post-birth and in 2007 only 13% were exclusively breastfed for six months[2]. Millions of American families are choosing infant formula over human milk to support the survival and growth of their children. These decisions are influenced by complex individual and societal conditions including social context, working and time limitations, lack of paid maternity leave, and limited access to and breastfeeding support from the health system. Because infant formula is a *consumer* product, marketing pressures and perceived convenience also contribute to infant feeding decisions. Advocacy directed at consumer populations may therefore be an effective method to promote increased breastfeeding rates. Environmental consideration is one rapidly emerging trend in consumer food choices. If evidence can demonstrate the environmental consequences of infant formula in comparison to human milk, opportunity may exist to harness consumer preferences for "green" food products to promote breastfeeding. This study evaluates the environmental impact to anthropogenic climate change caused by greenhouse gas emissions from the lifecycle of U.S. infant formula, from "cradle to grave".

I. *Infant formula in America*

Infant formula is the sole source of nutrition during the first months of life for non-breastfed infants- a time at which nutrient requirements and growth rates are highest (Kessler & Shahala 1996). Designed for special dietary substitution for human milk, infant formula production alters and combines cow's milk products attempt to mimic the nutritional composition and digestibility of human milk[3] (USDA 2009, Kessler & Shahala 1996). If prepared correctly infant formula can meet basic caloric and nutritional needs for children less than six months of age[4]. This product comes at a cost to the consumer; powdered infant formulas generally cost about $0.88 per eight ounce serving (O'Connor 2009, USDA 2009). Infant formula is the largest sector of the overall baby food industry; in 2008 infant formulas held four of the top baby food company market shares. Mead Johnson Nutritionals' "Enfamil" holds the largest share of the total domestic baby food market with 32.7% of all sales in 2008, followed by Abbott Laboratories Ross Products' "Similac" (20.2%) and Nestle USA's "Good Start" (17.0%)

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[1] "Exclusive breastfeeding" is feeding only human milk and no other substance (including water).

[2] U.S. formula supplementation rates are correlated with certain socioeconomic and demographic factors; for example, supplementation within two days post birth is over 30% for mothers younger than 20 years (CDC 2010).

[3] Soy-based formulas and other special dietary and allergenic formulations also exist.

[4] After six months, additional foods are necessary to complement both infant formula and human milk for adequate nutrition. Manufactured infant formulas can never completely replicate human milk due to passive and active antibodies and other biological compounds that are unique to human milk.

In 2009 U.S. sales of standard milk formulas alone made over three million dollars (Euromonitor 2010). Beyond private consumers the U.S. Women, Infant and Children (WIC) program is also significant purchaser of infant formula: in 2005, infant formula comprised 17.4% of all WIC food purchases at a value of over $600 million (IDFA 2008a). As the number one global milk producer, the U.S. is also a major exporter of infant formula[5]. In 1998 over 21,308 metric tons were exported globally and exports have grown in the past decade with the emerging global middle class (FAO 2009; US Census 1998; Liu 2008).

Infant formula is regulated by the U.S. Food and Drug Administration (FDA) under the Infant Formula Act of 1980. Despite these standards for nutrient requirements, quality control, and safety procedures, there are many dangers associated with infant formula (Kessler & Shahala 1996). Recalls due to product adulteration and contamination are common in the U.S. and abroad[6]. Other economic and health concerns are well documented and strategies are being implemented at all levels of global public health to tackle these challenges (Tinling 2009). However, the environmental consequences of not breastfeeding have not been quantitatively investigated. Somewhat controversially, infant formula marketing practices have been criticized for depleting the "natural resource" of human milk, especially in developing regions[7] (Miller 1983). Infant formula first came under serious environmentalist scrutiny in 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil, where Andrew Radford of the Baby Milk Action Network argued that replacing human milk with formulas "should be seen in the same light as logging in the rainforest or over-fishing our seas". Radford qualitatively analyzed various ecological effects of the lifecycle of infant formula, including water pollution, waste generation, natural resource consumption, land use change, and even overpopulation[8]. In the decades since the Rio conference, however, these environmental hypotheses have not been supported by quantitative research.

I. *Greenhouse gases & infant formula*

The lifecycle of infant formula consumption implicates numerous greenhouse gas emitting processes. For example, manufacturing of both product and packaging requires electricity generation and transportation requires combustion of fossil fuels. As the majority of infant formula is made from bovine milk products, greenhouse gas emissions are also implicated by association with the dairy sector. In 2007 the global milk production system emitted almost 2,000 million tons of carbon dioxide equivalents (CO_2-

[5] The world's largest provider of private-label infant formula (PBM) is based in Gordonsville, Virginia (Mintel 2010).
[6] For example, on September 20, 2010 Abbot Nutrition recalled a Similac brand after detecting small warehouse beetles and larvae in formula produced in their factory located in Sturgis, MI (FDA 2010).
[7] Alan Berg argues that replacing human milk in developing countries with an imported product is akin to depletion of crude oil preserves and unnecessarily burdens individual and collective economic assets (Miller 1983).
[8] Exclusive breastfeeding confers protection against becoming pregnant (lactational ammenhorea).

eq),[9] accounting for 2.7% of global anthropogenic greenhouse gas (GHG) emissions (±26%) (FAO 2010). Methane was responsible for over 50% of these dairy sector emissions. Methane (CH_4) is a significant GHG because it has 25 times the global warming potential[10] of carbon dioxide (IPCC 2007). As a result of increased emissions over the past century there is more methane in the atmosphere today from anthropogenic sources than from natural sources (IPCC 2007). Once emitted, methane remains in the atmosphere for over eight years before removal by atmospheric chemical processes (IPCC 2007). The largest source of CH_4 emissions in the dairy industry is enteric fermentation: the release of gases by digestion in stomachs of ruminant animals. Manure management is also releases CH_4 as well as nitrous oxide (N_2O), which has 298 times the global warming potential (GWP) of carbon dioxide. Carbon dioxide (CO_2) emissions in the dairy sector are released by agricultural activities such as harvesting crops and producing concentrate fodder or for energy use in-situ such as electricity consumption and fossil fuel combustion in dairy machinery. The GHGs emitted by the dairy sector are increasing with rising global dairy demand for milk and meat products and subsequent increases in dairy production (Smith et al. 2007).

II. Lifecycle assessments

In order to inform consumers, legislators, and other decision makers of the environmental impacts infant formula, evidence must first be collected and reported. One standardized tool for generating such information is the lifecycle assessment (LCA): a systematic process that quantifies environmental impacts of a product, process or service by tracing energy and material flows through a defined lifecycle system. LCA results provide a factual basis for decision-making at industry, policy, and consumer levels (Guinée 2002). For industries, LCAs can illuminate "hotspots" of waste and other inefficiencies to inform product and process improvements. This holistic view helps industries avoid decisions that might transfer environmental burdens without reducing the overall impact[11] (SAIC 2006). LCA information also provides a factual basis for policy makers in crafting regulatory activities such as GHG reporting for agricultural activities[12]. As consumer environmentalism develops, LCA offers the infant formula industry a unique opportunity to improve their somewhat contentious corporate reputation (Hofstetter 1998). The current success of consumer-oriented labeling schemes such as *USDA Organic* and *Fair Trade USA* suggests that infant formula and other food products could one day also boast environmental labels such as "carbon neutral". LCAs

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[9] "Carbon dioxide equivalents" are an aggregated measure of the total climate change effect from different greenhouse gases.
[10] Global warming potential is a measure of the heat trapping capacity of a certain gas relative to that of carbon dioxide.
[11] For example, whereas one food may seem superior on the basis of greenhouse gas emissions, an LCA may show that it is actually has greater total environmental impacts when solid waste and air pollution are included. To avoid this issue, ISO explicitly states that more than one impact category should be used in comparative LCAs for public use.
[12] In accordance with the UNFCCC the U.S. reports an annual national inventory of greenhouse gas emissions; however, the U.S. does not currently regulate or require greenhouse gas reporting from agricultural sources.

could provide the standardized evidence and reporting to support these product certifications and market strategies.

LCA theory and practice evolved from divergent American "Resource and Environmental Profile Analyses" (REPAs) and European "Eco-balances" in the 1960's. Today, LCA practice is merged under a globally standardized protocol maintained by the International Standards Organization (ISO). First published in 1996, the ISO framework defines LCAs in four stages: 1) Goal and Scope Definition; 2) Lifecycle Inventory (LCI); 3) Lifecycle Impact Assessment (LCIA); and 4) Lifecycle Interpretation (ISO 2006) [Figure 1]. Although LCA protocol has greatly advanced in the last half century, significant limitations persist. First, LCA can only provide generalized information on a model physical lifecycle; it does not evaluate economic, social, or cultural characteristics, nor can it localize impacts on spatiotemporal scales (Guinée 2002). Extensive data requirements force practitioners to make simplifications and assumptions that may reduce accuracy, and inherent subjectivity in defining system boundaries also limits comparisons among studies (Yelishetty 2009). Finally, the practical application of LCA outcomes is must bridge differing value systems between practitioners, industry and decision-makers (Hofstetter 1998).

Dairy food products have long figured in the LCA record, from early LCAs comparing milk packaging systems in Europe to contemporary LCA practice by Stonyfield Farm, Inc. Numerous LCAs have been conducted for liquid milk production and processing all over the world; however, secondary dairy products such as cheese and whey powder are less studied [Appendix D]. To my knowledge, no LCA studies of GHG emissions of powdered milk products have been conducted beyond a 1997 screening analysis by Blonk et al. This study aims to assess the environmental impact to anthropogenic GHG emissions produced by the manufacturing lifecycle of milk-based powdered infant formula in the United States.

GOAL & SCOPE DEFINITION

This study is a partial lifecycle assessment (LCA) to estimate the greenhouse gas (GHG) emissions attributable to U.S. production of milk-based[13] powdered infant formula. The goals are 1) estimate the total GHG emissions by all production stages in a model lifecycle of infant formula, from "cradle to grave"; 2) identify the stages responsible for the greatest percentage of GHG emissions. A secondary objective is to organize information that will simplify subsequent analyses of environmental impacts of infant formula to develop evidenced-based advocacy for breastfeeding.

This LCA only assesses only one environmental impact: GHG emissions. Other impact categories commonly employed in LCAs of milk products include acidification potential, eutrophication potential, photochemical oxidant creation potential, and ozone depletion potential[14]. However, most studies that have examined dairy products beyond the fluid milk stage have focused only on primary energy use or GHG emissions [Appendix D]. Despite the evolving concept of "carbon footprint" there is currently no international protocol for carbon footprint methodology[15]. Therefore, this study follows steps I-III of the International Organization for Standardization LCA methodology as defined in the ISO 14040 series on Environmental Management[16,17] (ISO 2006). GHG emissions considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) and are reported in aggregated metric tons of "carbon dioxide equivalents" (CO_2-eq) on a 100-year time scale as defined by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007).

Equation 1: Example calculation of carbon dioxide equivalents (CO2-eq)

$$TotalCO2-eq=\sum(m_{CO2})+(m_{CH4}\times 25)+(m_{N2O}\times 298)$$

The boundaries of this model infant formula lifecycle are set from the "cradle" at the dairy farm to the "grave" at end-of-life municipal solid waste disposal within the geopolitical boundaries of the continental United States. Raw materials and energy consumption are tracked throughout the system in six phases: 1) Dairy farm; 2) Dairy plant "black box"; 3) Infant formula factory; 4) Consumer; 5) Waste, and 6) Transportation [Figure 2]. Other lifecycle segments such as warehouse storage and retail sales are excluded due to lack of quality data. Energy and materials for water infrastructure, capital goods and employee activities are not included. Figure 2 depicts the

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[13] Only milk-based powdered formula is considered although other types exist because the greenhouse gas emissions from milk production and dairy cows will greatly differ from those of vegetable-based products such as used in soy-based formulas.

[14] ISO uses "potential" impacts because LCA results are not time space-specific and will depend on methodology (Guinée 2002).

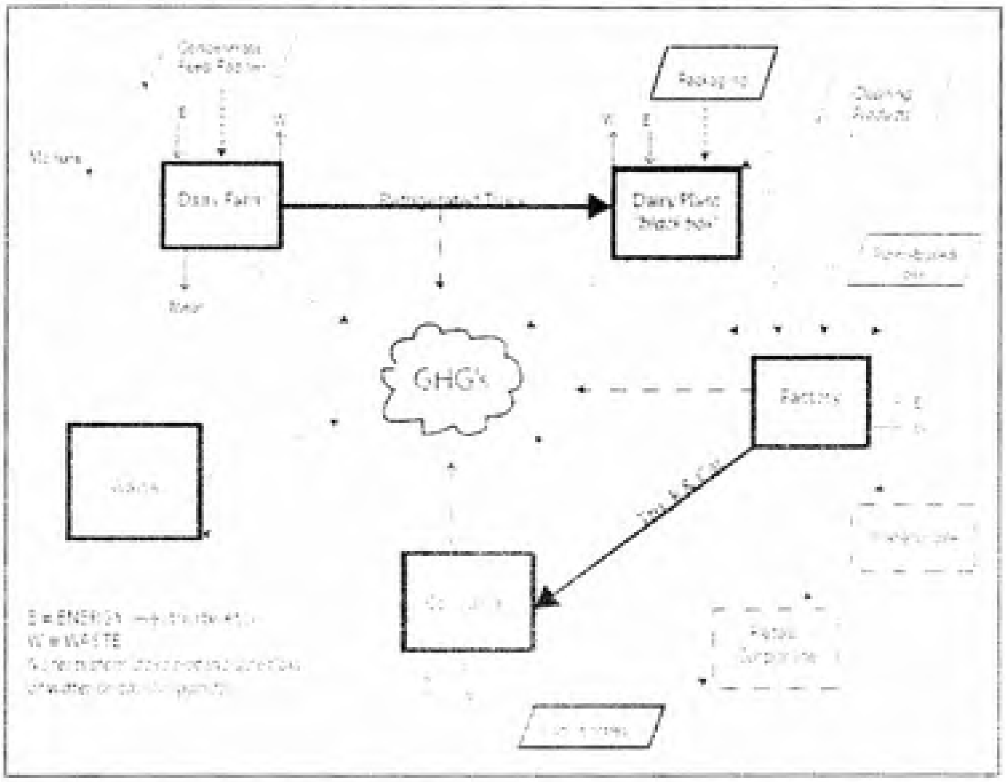
[15] ISO and the World Resources Institute Greenhouse Gas Protocol are currently developing such standards.

[16] ISO protocol documents are not publicly accessible; therefore, this LCA follows ISO methodology as described in the U.S. EPA NRML document entitled *Lifecycle Assessment: Principles and Practice* (SAIC 2006).

[17] Step IV of ISO LCA protocol (Interpretation) is excluded from this study because there was not sufficient time for external third-party review of results.

model lifecycle: the foreground system is represented by the darker central boxes while the background system is positioned around the periphery in the lighter boxes. Bolded vectors represent transportation "legs" for which GHG emissions were estimated in the "Transportation" phase. Dotted boxes and vectors represent material and energy flows and transportation legs that were not included in this model lifecycle. This partial LCA is classified as *Scope II* because it accounts for all direct GHG emissions (e.g. enteric fermentation) and all indirect emissions from energy consumption within the model system, but only accounts for some tertiary emissions (e.g. consumer waste disposal). The formula for the total GHG emissions from all sectors of the model infant formula lifecycle was conceptualized with a basic algorithm based on "Simplified tools for global warming potential evaluation: when "good enough" is best," (Bala et al. 2010).

Figure 2: Lifecycle production system of powdered cows-milk-based infant formula meta-product



Equation 2: Simplified algorithm for total GHG of the model infant formula lifecycle

$$GHG = GHG_{milk} + GHG_{dairy\_plant} + GHG_{formula\_factory} + GHG_{consumer} + GHG_{waste} + \sum_{i=1}^{3} GHG_{transport}$$

METHODS

"LCA, like any modeling technique, is only as good as the modeler and the assumptions and data employed in the exercise," states Ralph Horne in his 2009 book Lifecycle Assessment: Principles, Practice, and Prospects. Although internationally standardized by the ISO, in practice LCA allows for considerable flexibility in modeling such as setting system boundaries and selecting data sources [Appendix D]. These methodological choices have decisive impacts on the LCI results. ISO therefore divides LCA protocol into four separate stages in order to separate subjectivity and assumptions from objective data collection (Hofstetter 1998) [Figure 1]. Major assumptions and other subjective model elements employed in this LCA are described below.

I. Major Assumptions

Numerous assumptions were made at the start of the data collection phase. One full "batch" of formula must be industrially manufactured in order to yield even a single serving of infant formula. The reference flow for this model lifecycle is therefore one 10,000 lb. batch of infant formula produced in an industrial manufacturing establishment (P. Cole; GEA, personal communication, 3.29.2011). I converted this batch size to 4,536 kg for use throughout the lifecycle because most GHG emissions factors are reported in metric units. This "batch" reference flow enables tracing material and energy inputs and GHG outputs at each of the six defined stages in the model lifecycle. I also assumed that one infant consumes 55 kg of powdered infant formula in one year, and that this formula is prepared in the home in single serving sizes by mixing 32 g of powder per 8 fluid oz. of boiled water[18]. This sub-unit facilitated estimations of consumer energy consumption such as from boiling water and dishwashing. In all stages, GHGs from capital goods, employee activities, and water infrastructure were excluded.

The GHG emissions for each of the six stages were calculated by determining the energy requirement for each stage (e.g. kWh electricity) and multiplying by an "emissions factor" defined by the U.S. Energy Information Administration (EIA) and other reputable sources. Emissions factors are reported in units of GHGs or CO_2-eq emitted per unit of energy consumed. For example, the EIA emissions factor for average U.S. natural gas combustion in-situ is 53.06 kg CO_2-eq per MMBTU (EIA 2011). The GHGs from natural gas use for a certain process or stage are therefore calculated by multiplying the required MMBTU[19] of natural gas by the EIA emissions factor. For transportation, emissions factors are generally in units of CO_2-eq per ton of cargo per km travelled.

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[18] In general, one 8-gram "scoop" of powdered infant formula should be added per every two fluid oz. of water, therefore 32 grams of powder are needed per 8 oz. serving size.
[19] 1,000,000 BTUs = 10 therms

Equation 3: Example CO_2-eq calculation for MMBTU natural gas

$$kgCO_2eq = (0.78MMBTU) * \left({53.06kgCO_2} / {MMBTU} \right) = 41kgCO_2eq = 0.04tonsCO_2eq$$

Several of the stages in the model lifecycle required electricity input. GHGs from electricity generation vary by regional differences in power sources such as coal and hydropower. I combined emissions factors for CO_2, CH_4 and N_2O for the average U.S. electricity generation mix (1999-2002) as reported by EIA (2007) into one measure of tons CO2-eq/MWh [Equation 4]. Within this calculation, raw GHG emissions values for CH_4 and N_2O are multiplied by a 100-year global warming potential (GWP) coefficient to obtain a total CO_2-eq value. I used 100-year GWP coefficient from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: 25 for CH_4 and 298 for N_2O (Forster et al. 2007)[20]. This equation was used throughout the lifecycle wherever electricity was consumed.

Equation 4: Emissions factor for electricity consumption (CO_2-eq/MWh)

$$kgCO_2 - eq_{electricity} / MWh = (676.76kgCO_2 - eq / MWh) + [(0.0182kgCO_2 - eq / MWh) * 25] + [(0.0105kgCO_2 - eq / MWh) * 298]$$
$$kgCO_2 - eq_{electricity} / MWh = 680.35$$

II. Meta-product

A meta-product is an abstraction of a product group that describes a general formulation for the product (Canals et al. 2010). Because the exact recipes for infant formulas are proprietary information, I created a meta-product for a milk-based powdered infant formula based on a recipe of suggested percentages of dry components for infant formulas published by the U.S. Dairy Export Council (Lloyd 2002). The meta-product included five ingredients: fluid skim milk, lactose[21], whey protein, nonfat milk powder, and palm kernel oil (excluded vitamins, minerals and other micro-ingredients). Based on personal communication with GEA Process Engineering, Inc.[22], I assumed the manufacturing process mixes wet "slurry" that is twice the volume of the final dried powder and is 50% solids content (3.29.2011). For the modeled batch size, this was 9,072 kg of slurry with 4,536 kg solids content.

With this volume of slurry and the suggested percentages of each dry dairy component I then determined the amounts of each ingredient that would need to be

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[20] GWPs differ by time scale; for example, CH_4 has a 100-year GWP factor of 25, but a 25-year GWP factor of 72. The 2007 values were chosen for this study because they are the most recent estimates. Other LCA studies may use older IPCC GWPs.

[21] The primary, unique carbohydrate of milk (Walstra et al. 1999).

[22] GEA manufactures liquid processing, evaporation, drying, powder conveying, and packaging technologies as well as overall dairy plant design. GEA technologies "are used by all the infant formula manufacturers in the USA and around the world to a greater and lesser extent depending on the company and the systems that they use in the manufacture of the powders and liquid infant formulas." (P.Cole: GEA Process Engineering, Inc., personal communication, 11.27.2010).

externally manufactured and added per model batch. I assumed that the primary dilutent in the formula slurry is fluid skim milk (K. Breeden: PBM Nutritionals, personal communication, 2.28.2011). According to Dairy Technology: Principles of Milk Properties and Processes, milk is 87% water content (Walstra et al. 1999). Therefore, to obtain 50% water content (4,536 kg) in the slurry batch, I estimated 5,213.8 kg of fluid milk were required (4,536 kg / 0.87 = 5,213.8).

Table 1: Meta-product infant formula batch recipe adaptation assuming 50% dilution by fluid milk into 9,072 kg slurry[23]

US Dairy Export Council Recipe (Lloyd 2002)	Usage	Meta-product adaptation	Product per batch of meta-product slurry
Whey protein conc. 34%	18.5%	Subtract whey present in fluid & nonfat milk powder from the 18.5%	762.7 kg
Lactose	37%	Subtracted lactose present in fluid & nonfat milk powder from the 37%	1,047.1 kg
Nonfat milk powder	16%	Maintained percentage	725.8 kg
Fat blend	27%	Maintained percentage- used palm oil	1224.7 kg
Vitamins and minerals	*1.0%*	*Not included*	/
Lecithin	*0.5%*	*Not included*	/
*Fluid Skim Milk (dilutent)			5,213.8 kg
		Total slurry meta-product	8,974.0 kg
		Total slurry theoretical (2x dry batch)	9,072 kg
			-0.8 % error
		Total dry batch	4,536 kg (10,000 lb.)

In order to determine the total amount of raw milk needed from the Dairy farm to make enough whey, nonfat milk powder and lactose for one batch of infant formula meta-product, I next needed to determine the amounts of each of these dry ingredients required for the slurry mix (3,858.2 total kg dry ingredients). Based on the US Dairy Export Council recipe, nonfat milk powder should comprise16% of infant formula, or 16% of the solids for this model slurry. As shown in Table 1, about 725.8 kg of nonfat powdered milk are required (0.16 * 4,536 = 725.8).

Whey and lactose are inherently present in fluid and non-fat milk powder. Therefore, I subtracted the amounts of these ingredients that were already present in fluid and powdered milk ingredients to avoid double-counting them in the meta-product batch. According to Jacobson (1992), milk is 9% solids-non-fat, and of those solids 55% is lactose and 37% is protein. I estimated that for one batch of slurry, 258.1 kg of the solids content of the milk dilutent is lactose and 172.6 kg is protein. Within the total protein content of both skim milk and non-fat milk powder, 82% is casein protein and 18% is whey protein[24] (Jacobson 1992). For the fluid milk this percentage yields 31.3 kg of whey. In milk powder, 93.5% of the total volume is solids-non-fat. Multiplying for the same 55% lactose and 37% protein as for milk, I estimated that the nonfat milk powder

[23] Values in tables are subject to rounding. Contact the author at mtinling@gmail.com for questions about calculations.
[24] Human milk is whey-predominant while cow's milk is casein predominant. Extra whey is therefore added to infant formula to mimic the nutritional composition of human milk. This is important for digestibility. Different formula brands use different whey to casein ratios (interestingly, the ratio in human milk changes over time). This meta-product follows the US Dairy Export Council recipe ratio of 48:52.

added brings along 373.2 kg of lactose and 251.1 kg of protein (45.2 kg whey protein). Finally, the amounts of lactose and whey protein that needed to be added separately as independent dried products were calculated by subtracting the amounts already present in skim milk and nonfat milk powder from the amounts suggested by the Dairy Export Council percentages. The amount of oil per batch was maintained at the recommended 27% of the solid content (1,224.7 kg). Other ingredients such as lecithin, vitamins, and long-chain fatty acids[25] are not considered. In summary, to produce 9,072 kg of 50% solid slurry for one batch of 4,536 kg powdered meta-product, I estimated 762.7 kg whey, 1047.1 kg lactose, 725.8 kg nonfat milk powder, 1224.7 kg oil, and 5213.8 kg fluid milk dilutent [Table 1].

III. Allocation

The lifecycle of infant formula production involves several multi-output processes. For example, dairy cows may themselves become beef and leather. Milk processing and dairy manufacturing also involve myriad interconnected processes. For example, whey may be produced as a by-product of milk separation in cheese manufacture. In multi-output phases of the lifecycle, how can we determine how much of the GHG emissions of milk production and dairy manufacturing should be attributed to *infant formula*?

Partitioning of material and energy flows to multiple outputs is termed "allocation" in LCA practice. For the GHG emissions of milk production at the farm stage I selected an emissions value reported in a 2010 study commissioned by the Innovation Center for U.S. Dairy and conducted by the Applied Sustainability Center at the University of Arkansas and Michigan Technological University (UA & MTU). This was the only available study specific to U.S. dairy conditions; in fact, the authors state it was "the first U.S. national-level fluid milk carbon footprint study" [Appendix D]. Of the total estimated CO_2-eq emitted before the farm gate, the authors allocated 4.01 pounds (~25%) to beef by feed conversion. In using their GHG estimations I am limited to the assumptions and allocation methods of their model. Other models use different allocation methods [Appendix D]. For example, the Green Design Institute at Carnegie Mellon University conducts "economic input-output" lifecycle assessments (EIO-LCAs) that determine outputs per dollar value of product, thereby allocating the sub-processes based on economic value[26]. Because milk pricing varies by supply, demand, and government price supports, economic allocation is not the best choice for milk-based products. Other methods of allocation for milk and meat will find different CO_2-eq emissions at the farm gate.

[25] First patented in 1995 by Martek Biosciences Corporation as "Formulaid", a microbial blend of docosa-hexaenoic acid (DHA) and arachidonic acid (ARA) to support visual and cognitive development (Consumers Research Magazine 1995).

[26] The EIO-LCA model estimates milk production causes 4260 tons CO_2-eq per million dollars of milk. Carnegie Mellon 2011).

For the consumer stage of the lifecycle I allocated 5% of the electricity consumption from using the dishwasher to the infant formula lifecycle, assuming that four baby bottles included in the model would comprise about 5% of dishes in an average wash load. For consumer travel to and from a food retail site to purchase infant formula, I assumed that one trip was taken for every three canisters purchased (about one trip per week), and that within each trip the formula would be one of about 20 grocery items purchased. Therefore, I allocated 5% of the modeled consumer transportation emissions to the infant formula. No other allocations are performed: it is assumed that all other manufacturing processes and consumer activities are absolutely necessary to the infant formula lifecycle and their emissions are therefore fully attributed to infant formula. Choice of allocation methods has decisive impacts on the results of the LCA; therefore subsequent LCAs of infant formula might obtain different lifecycle results if different allocation methods are used (Yelishetty 2009).

IV. Data quality

The practical applicability of an LCA is directly dependent on the quality and transparency of the data and estimates. The data quality goal in this study was to use data from primary sources in the U.S. reported in the past five years (2005-2010) that were directly relevant to the model system[27]. Sub-optimal data from secondary/literature, international, and/or outdated sources were used wherever these data goals could not be achieved. All data sources are documented for each LCI stage and graded as "highest quality" or "adequate quality" [Appendix C]. Where data for a sub-process or emissions factor were unavailable they were excluded from the inventory and documented as assumptions. For example, I obtained high quality data on annual energy use by U.S. warehouses and food retail buildings; however I could not estimate the numbers of these buildings involved in the U.S. infant formula system, so these stages of the lifecycle were excluded. Overall, highest quality data comprised 77% of the sources used in the Lifecycle Inventory. The consumer phase was especially lacking in high quality data; five out of nine sources used in estimating the CO_2-eq from the consumer phase were sub-optimal data quality. This challenge is consistent with LCA literature of food products as individuals' home behavior is uncertain.

Data access was a significant barrier to the scope and boundaries of this LCA. Infant formula recipes and manufacturing information are proprietary and could not be obtained from industry or government sources[28]. Industry confidentiality is a challenge to the

[27] Data quality is especially important for emissions factors because they are calculated for a certain set of conditions. For example, the CO_2-eq of electricity consumption will vary by regional electricity generation fuel sources (coal, hydropower, etc.).
[28] In repeated phone calls infant formula companies consistently declined to share manufacturing information that was "confidential" or "proprietary". One company even suggested that I could be the competitor company in disguise. Tom

success of LCA overall. Many manufacturers actually conduct their own LCAs but do not disclose or publicize their results for concern over exposing sensitive information (NREL 2010; D. Trader: Sonoco, personal communication, 3.5.2011). Where LCA practitioners are able to obtain industry information they often take precautions to maintain confidentiality such as normalizing results to a non-representative standard or depicting results only in bar graphs and charts but not quantifying them (Feitz et al. 2007). Another data limitation in this LCA was lack of resources, especially regarding LCI databases such as EcoInvent v2.0 that require paid subscriptions for data access. Resource limitations also prohibited access to widely used LCA modeling software such as SimaPro 2007. Considering the many challenges to accessing high-quality data for this study, a heuristic method was employed to create the best approximate model of the production system of infant formula. According to Bala et al (2010), a simplified algorithm can still produce accurate estimates of GHG emissions when using a lifecycle approach.

Lorenz of the U.S. Energy Information Administration explained that even the government is limited in reporting manufacturing information due to risk of "disclosures" (personal communication, 3.29.2011).

LIFECYCLE INVENTORY (LCI)

The lifecycle inventory (LCI) is the data collection stage in which inputs of material and energy and environmental outputs (GHGs here) are quantified for each stage of the model lifecycle. The boundaries of this model infant formula lifecycle are set from the "cradle" at the dairy farm to the "grave" at end-of-life municipal solid waste disposal in six phases: 1) Dairy farm; 2) Dairy plant "black box"; 3) Infant formula factory; 4) Consumer; 5) Waste; and 6) Transportation [Figure 2]. Based on the literature regarding GHG emissions from milk and dairy products I predicted the greatest percentage of the total lifecycle GHG emissions would be at the Dairy Farm (stage 1) due to enteric fermentation [Appendix D]. The model infant formula lifecycle includes many GHG emitting processes beyond the farm gate, and the main ingredients are essentially *condensed* dry milk products that each requires multiple times the amount of raw milk to produce equivalent amounts of dairy products[29]. Therefore, the total GHG emissions per kg of infant formula are likely to be several times greater than that of fluid milk.

I. Dairy farm

The Dairy farm represents all activities required for milk production prior to milk leaving the "farm gate", including on-site and upstream agricultural processes. According to a 2010 report by the Food and Agriculture Organization of the United Nations (FAO), milk production emits a global average of 2.4 kg CO_2-eq per kg "fat and protein corrected milk" (FPCM) at the farm gate (±26%)[30]. The FAO estimate ranges from 1.3 kg CO_2-eq per kg FPCM in industrialized regions to 7.5 kg CO_2-eq per kg milk in developing regions[31]. In a literature review of 25 LCA studies of milk in Europe and North America, I found the average GHG emissions from fluid milk were 1.3 kg CO_2-eq per kg [Appendix D]. Emissions of raw milk production systems vary regionally by agricultural practices, dairy breed, climate, and other variables[32]; therefore, data specific to *U.S.* dairy farming practices were required for this study. Although the U.S. Environmental Protection Agency (EPA) reports annual GHG emissions from dairy cow enteric fermentation and manure management[33], no national CO_2-eq estimates are available for the overall milk production sector. Attempting to estimate CO_2-eq unit milk solely based on available national data for enteric fermentation and manure would leave out important emissions from fodder production, on-farm energy use, and other sources. Therefore, I selected a more comprehensive estimate of GHG emissions for milk production at the farm gate from a 2010 study commissioned by the Innovation Center for US Dairy and conducted by the Applied Sustainability Center at the University of Arkansas and Michigan Technological University (UA & MTU).

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[29] For example, 1 kg of cheese requires about 10 kg of raw milk (IDF 2009).

[30] Or 4% (±26%) when the system is expanded to include related meat production from dairy cows (FAO 2010).

[31] Differences due to different agricultural practices, different species of cows, different feed production, etc.

[32] Emissions also vary *within* regions by season and age and health of dairy cows.

[33] These values are published annually in the EPA National Inventory of Greenhouse Gases, in accordance with the UNFCCC.

This study was the first national-level study of the American "fluid milk carbon footprint". Dividing the U.S. into five regions, the authors estimated GHG emissions through eight phases: feed production, milk production, transport, processing, distribution, retail, consumption and waste. Data were gathered from the USDA National Agricultural Statistics Service and Economic Research Service, the EcoInvent database, peer reviewed literature, technical and expert consultations, and a survey of fluid milk processing facilities. The authors modeled the data using SimaPro 7.1 LCA software and quantified uncertainty by a Monte Carlo analysis. This study estimated 2.05 kg CO_2-eq per kilogram of *consumed* milk (through municipal waste disposal) with a 95% confidence interval of 1.77 to 2.4 kg CO_2-eq per kg of milk consumed. The authors also stated that 72% of the total modeled lifecycle emissions occurred before the farm gate for livestock feed, enteric fermentation, fuel use, and manure management. Therefore, I calculated 72% of the average 2.05 kg CO_2-eq /kg consumed milk to estimate the GHG contribution from milk at the farm gate: 1.48 kg CO_2-eq per kg of milk[34].

In order to use this estimate of farm GHGs per unit milk to estimate emissions from this model infant formula lifecycle I first needed to estimate the amount of raw milk needed to produce one batch of infant formula. As described on page 9, I calculated a meta-product recipe by adapting percentages of dry ingredient requirements reported by the U.S. Dairy Export Council (2008) to a model batch of 4,536 kg of dry infant formula produced from 9,072 kg of mixed slurry containing 5,213.8 kg liquid milk dilutent [Table 1]. I then used milk-solids concentration factors from Feitz et al. (2007) to back-calculate from the amounts of dry ingredients needed to produce one meta-product batch to the quantities of fluid milk required to produce the three dried products: lactose, whey, and nonfat milk powder. Feitz et al. also report the quantities of milk solids that are present in various dry dairy products and the relative amounts of raw milk required to produce these ingredients [Equation 5]. For example, Feitz et al. report a lactose concentration factor of 8, meaning producing one unit of dry lactose requires 8 units of milk. I used their factors for lactose (8.0), whey protein (7.6) and nonfat milk powder (7.7) to estimate the amount of raw milk input required for each ingredient to make complete batch. For accuracy I cross-checked the non-fat milk powder concentration factor with another estimate reported by Blonk et al. (1997) in their LCA of milk powder: 8.0. These nonfat milk powder concentration factors from Feitz et al. and Blonk were less than 5% different. I selected the more recent concentration factor from Feitz et al. for consistency.

Equation 5: Example milk-solids concentration factor (Feitz et al. 2007)

$$
\begin{aligned}
&\mathit{Whey\ ProteinConcentrate.} = 95.4\%\mathit{milksolids};\\
&\mathit{RawMilk} = 12.5\%\mathit{milksolids};\\
&\therefore 95.4/12.5 = 7.6\text{"}\mathit{concenrationfactor}\text{"}
\end{aligned}
$$

[34] (2.05 kg CO_2-eq / kg milk consumed) * (0.72 farm gate milk consumed) = 1.48 kg CO_2-eq / kg farm gate milk.

From these concentration factors I estimated a total of 24,974.9 kg of liquid milk are required to produce all ingredients required for one batch of infant formula slurry, including the fluid milk dilutent [Table 2]. I then multiplied the individual amounts of milk needed for each batch ingredient by the University of Arkansas and Michigan Technological University (UA & MTU) emissions factor of 1.48 kg CO_2-eq per kg of fluid milk. As shown in Table 2, the total GHG emissions from the raw milk required to produce one batch of infant formula were approximately 37 tons CO_2-eq. In the discussion section of this paper (p. 31) I conduct a sensitivity analysis for the emissions from this Dairy farm stage using the upper and lower bounds of the 95% confidence interval [1.77-2.4 kg CO_2-eq /kg milk] reported by UA & MTU.

Table 2: Tons CO_2-eq of fluid milk requirements for one 4536 kg batch meta-product (9,072 kg wet slurry)

Ingredient	*kg product / batch*	*Concentration factor (Feitz et al. 2007)*	*kg milk req. / product/ batch*	*Emissions factor UA & MTU 2010*	*CO_2-eq (kg/batch)*
		(kg milk/kg item)			
Fluid skim milk	5213.79	1.0	5213.79	1.48 kg CO_2-eq per kg milk at the farm gate	7716.41
Lactose	1047.02	8.0	8376.12		12396.66
Whey protein conc. 34%[34]	762.71	7.6	5796.63		8579.01
Nonfat Milk Powder	725.76	7.7	5588.35		8270.76
		kg milk / batch	24,974.90	*Total tons CO_2-eq / batch*	36.96

II. Dairy plant "black box"

The next step in the model infant formula lifecycle is transformation of the estimated 24,974.9 kg raw milk into four meta-product dairy ingredients: pasteurized milk, nonfat milk powder, whey protein concentrate and lactose. In a real dairy plant, the raw milk would undergo pasteurization, standardization, homogenization, and various separations and drying processes to make different dairy products with different fat and water contents [Figure 3]. These manufacturing systems are complex and many processes are shared among products (Feitz et al. 2007). Therefore, I considered this phase of the infant formula lifecycle as a "black box" to which raw milk, packaging and energy flow in, and the four requisite dairy ingredients come out. Hogaas Eide & Ohlsson (1998) compared a "black box" dairy to a detailed step-wise inventory of a dairy and determined that although a "black box" may overlook allocation among co-products, overall energy use can still be accurately accounted for. The detailed method of directly collecting energy usage from manufacturing machines in a dairy phase was beyond the scope of this study; therefore the "black box" model was appropriate.

Inputs considered were 24,974.9 kg raw milk, electricity, natural gas, and Kraft paper sacks for packaging the powdered ingredients. The outputs were fluid milk and the three

[34] Whey protein concentrate 34% is the actual ingredient required by the US Dairy Export Council formulation; here I use inherent whey protein content of milk and nonfat milk powder and add additional "whey" product to represent this compound.

packaged dry dairy ingredients for one batch of infant formula slurry (Table 2). The major GHG emissions from the "black box" dairy plant are from energy consumption. I calculated two separate estimates of GHG emissions from natural gas and electricity consumption for processing these ingredients at the plant. Estimate A used literature values for units of manufacturing electricity and natural gas required per ton liquid milk, nonfat milk powder, lactose powder, and whey protein powder produced. For example, making nonfat milk powder requires 1.4 GJ of electricity per ton produced (Feitz et al. 2007). I multiplied each of these ingredient-specific energy requirements by the tons of each ingredient needed for one batch to obtain the total energy and natural gas requirements for each ingredient [Table 3]. I also included an electricity requirement for "cleaning-in-place" processes (CIP) at the dairy (0.11 MWh/cleaning cycle), assuming that CIP would occur once per batch[36]. The background systems related to CIP such as manufacture of cleaning products (commonly ammonia and nitric acid) or disposal of "rinse milk" expelled by CIP were not included. Finally, I multiplied these batch energy amounts by the EIA emissions factors for CO_2-eq from electricity [Equation 3] and natural gas (53.06 kg CO_2-eq/MMBTU natural gas) and summed them to obtain a total estimate of CO_2-eq emitted by the processing and CIP in the "black box". I multiplied the resulting kg CO_2-eq by 1.04 to account for 4% estimated product waste[37] during processing CIP and quality control testing (Berlin et al. 2005). In total, Estimate A produced 5.2 tons CO_2-eq per batch.

Table 3: Tons CO_2-eq from energy use in a "black box" dairy plant for ingredients for one batch meta-product

Electricity	Amt. (kg)	Amt. (tons)	Electricity req. (GJ/ton)	Electricity (GJ/batch)	Electricity (MWh/batch)[38]	Emissions Factor (EIA)	Tons CO_2-eq
Fluid milk	5213.79	5.21	0.20	1.04	0.29	690.35 kg CO_2-eq/MWh	0.20
Lactose pw.	1047.02	1.05	2.20	2.30	0.64		0.44
Whey protein	762.71	0.76	2.20	1.68	0.47		0.32
Nonfat milk pw.	725.76	0.73	1.40	1.02	0.28		0.19
Cleaning	1 cleaning (CIP)/batch				0.11 MWh	690.35 kg CO_2-eq/MWh	0.07
Natural Gas[39]	Amt. (kg)	Amt. (tons)	Fuel req. (GJ/ton)	Fuel (GJ/batch)	Fuel (MMBtu[40]/batch)	Emissions Factor (EIA)	Tons CO_2-eq
Fluid milk	5213.79	11.47	0.46	5.28	5.00	53.06 kg CO_2/MMBtu	0.27
Lactose pw.	1047.02	2.30	13.30	30.64	29.04		1.54
Whey protein	762.71	1.68	13.30	22.32	21.15		1.12
Nonfat milk pw.	725.76	1.60	10.20	16.29	15.44		0.82
Accounting for 4% waste				*Tons CO_2-eq/batch*			5.16

[36]The FDA Pasteurized Milk Ordinance requires that inner surfaces of pasteurization equipment and pipes are sanitized at least once per day (IDF 2011c). Raw milk storage tanks and milk trucks also must be cleaned (Hospido et al. 2010). Cleaning processes altogether may represent up to half of the total energy use in a dairy plant (IDF 2011c).
[37]Product loss occurs in cleaning processes that "rinse" or "push" residues out of machinery, and by removal of samples from every batch for testing in quality control.
[38] 1 MWH = 3.6 GJ.
[39] Natural gas used for combustion in industrial boilers.
[40] 1 MMBTU = 1.055 GJ.

Instead of itemized ingredients, Estimate B was based on average values for annual energy and natural gas consumption in "dairy product" manufacturing facilities[41] as reported by the 2006 U.S. Manufacturing Energy Consumption Survey (MECS). I multiplied these energy requirements by the appropriate EIA emissions factors to obtain the kg GHG emissions per year at an average facility, and then divided by 365 to obtain the kg GHG emissions per day. Next, to estimate the GHG emissions per batch, I divided the daily CO_2-eq by six, assuming that one batch would require about four hours and the plant would be running constantly[42]. In total, Estimate B emitted 4.9 tons CO_2-eq per batch. These two estimates were less than 3% different; therefore, I selected the CO_2-eq value from Estimate A because it was further detailed and did not require an assumption of daily operation time.

Finally, I estimated the GHG emissions from production of enough Kraft paper sacks[43] to package the three dry dairy product outputs. Fluid milk output packaging was not included. Based on the amounts of each dry ingredient required per batch [Table 2] I estimated 2,535.9 kg of dry ingredients would need packaging. I assumed each sack could hold 25 kg and weighed 100 grams (0.1 kg). Therefore, I estimated 101.4 sacks were needed per batch, or 10.1 kg of total sack material. I located an estimate of GHG emissions per kg of Kraft paper sacks from the EcoInvent v2.0 LCA database: 1.7 kg CO_2-eq per kg Kraft sack (as in Roos, Sundberg & Hansson 2010). Multiplying this emissions factor by the 10.1 kg of sacks required I obtained 0.012 tons CO_2-eq from packaging. This was added to the tons CO_2-eq from Estimate A's energy use and totaled at 5.18 tons GHG from the "black box"

III. Infant formula factory

The third stage of the model system is the infant formula factory. Material inputs to the model factory were 2,535.9 kg of dry dairy ingredients and 5,213.8 kg liquid milk from the "black box", 1224.7 kg palm kernel oil, composite cans (primary packaging), and cardboard boxes (secondary packaging). Other material inputs to infant formula manufacturing such as vitamins and minerals were excluded for lack of data. Energy-related inputs were electricity, natural gas, steam, and compressed air. The output was one batch of packaged infant formula meta-product (4,536 kg). Infant formula is manufactured by mixing ingredients with a dilutent, homogenizing the wet slurry mix, evaporating to remove some moisture content[44], agitating for standardization, spray-drying to powder and finally packaging in canisters and cartons (PBM 2010) [Figure 5, 6]. This series of manufacturing processes consumes various types of energy. Specific

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[41] North American Industry Classification System (NAICS): code 3115.

[42] By personal communication with P. Cole of GEA, one batch of infant formula requires about 3 to 4 hours and the machinery must run 24 hours to be efficient. Due to lack of dairy plant specific data, I assumed the same for the dairy plant (3.29.2011).

[43] From information in a "Virtual Tour" video on the website of PBM Nutritionals describing their manufacturing process (2010).

[44] Evaporators are commonly used to partially dry mixes before spray drying to save cost (Sorensen et al. 1992).

information on design of infant formula plants is proprietary and each plant is likely unique. Therefore I created a model manufacturing process to evaporate 9,072 kg mixed wet "slurry" at 50% solids to a dried batch of 4,536 kg final meta-product (P. Cole: GEA, personal communication, 3.29.2011). Other factory activities such as software control systems and quality control testing were excluded from this model. Product sequencing in formula factories is significant for cleaning-in-place (CIP) electricity use and waste (Berlin & Sonesson 2006); for simplicity I assumed the model infant formula factory only produced one type of product.

I obtained data from GEA Process Engineering, Inc. for four energy processes for producing one batch of formula: natural gas (0.024m^3/lb.), steam at 6 bar (0.05 kg/lb.)), compressed air (0.3 m^3 /lb.), and electricity (0.08 kWh /lb.)). I then multiplied each of these energy consumption values by 10,000 lb.[45] to determine the total amount required per batch, and by 1.04 to account for 4% product loss (Berlin et al. 2005). I used the EIA emissions factors for electricity and natural gas and Natural Resources Canada's Office of Energy Efficiency emissions factors for steam (240 kg CO_2-eq/ton) and compressed air (0.103 kg CO_2-eq / normal m^3). I also added 0.11 MWh electricity consumed per CIP process, assuming that the factory equipment was cleaned once per batch. The total GHG-emissions from energy consumption by the infant formula factory were 1.6 tons CO_2-eq / batch [Table 4][46].

Table 4: CO_2-eq from energy use in model infant formula factory per batch of meta-product (4,536 kg or 10,000 lb.)

	Energy input / lb. produced		Energy input / batch (10,000 lb.)		Energy input / batch (converted)		Emissions factor		CO_2-eq (tons/ batch)
Natural Gas	0.024	m^3	8474.4	cu feet[47]	8.70	MMBTU	53.06	kg CO_2/ MM Btu	0.46
Steam (6 bar)	0.05	kg	545	kg	0.55	tons steam	240	kg CO_2/ton[48]	0.13
Compressed Air	0.28	m^3	2900	m^3[49]			0.10	kg CO_2 / m^3	0.29
Electricity	0.0759 kWh		788	kWh	0.79	MWh	680.35 kg CO_2-eq / MWh		0.54
Cleaning			110	kWh / CIP	0.11	MWh	680.35 kg CO_2-eq / MWh		0.07
					Account for 4% waste		Tons CO_2-eq/batch		1.55

Beyond energy use in-situ, the Infant formula factory stage also implicates background systems of oil and packaging production. One batch of meta-product requires about 1,224.7 kg of oil blend (p. 11). Individual brands of infant formula use multiple oil sources including palm oil, sunflower oil, and soybean oil (substituted as needed by market availability). For the meta-product, I used palm kernel oil to represent the oil

[45] 10,000 lb = 4,536 kg batch infant formula. I use lb in this stage because the emissions factors from GEA were reported in lbs.

[46] Unlike for the Dairy Plant, the CBECS estimate for energy use by a "dairy product" manufacturing plant was very dissimilar from this itemized factory model estimate. I chose to use the itemized GEA data for greater specificity.

[47] 1 cubic meter = 35.31 cu. Feet; and 1027 BTU/ft2; and 1 MMBTU = 10^6 BTU

[48] Natural Resources Canada (2008)

[49] ibid.

mixes used by real manufacturers because the U.S. National Renewable Energy Laboratory (NREL) Lifecycle Inventory Database supplies data for the carbon dioxide and methane emissions for agricultural production and refinement of palm kernel oil [Table 5]. To produce one kg of palm kernel oil, 2.3E-02 kg methane and 6.3E-01 kg $_{CO2}$ are emitted. I multiplied these separate GHG emissions factors by their appropriate global warming potential (GWP) coefficients to determine 1.2 kg CO_2-eq/kg oil; then, I multiplied this combined factor by 1,224.7 kg of oil needed per batch (p.11). 1.5 tons CO_2-eq are emitted in producing palm kernel oil for one meta-product batch of infant formula.

Table 5: Tons CO_2-eq from production of 1,224.7 kg palm kernel oil per batch meta-product

Output GHG for 1 kg Palm kernel oil, processed, at plant (NREL)					
Methane Carbon dioxide	2.297E-02 6.310E-01	kg kg	x 25 GWP x 1 GWP	5.7E-01 6.3E-01	
			Sum	1.2 1224.7	CO_2-eq (kg/ kg oil) oil needed (kg / batch)
				1.48	Tons CO_2-eq / batch

Finally, I assumed the infant formula was packaged in 15-oz. "composite cans[50]" (primary) and cardboard shipping boxes (secondary). Although other packaging systems do exist such as plastic canisters and single serving "to-go" pouches I assumed all composite cans for the model lifecycle because they comprise over 80% of the infant formula market (D. Trader: Sonoco, personal communication, 3.5.2011). Data specific to infant formula packaging was not available; therefore, I used GHG emissions factors for composite *coffee* cans from a 2008 LCA by Franklin Associates[51] to represent the infant formula packaging. Assuming that each coffee canister holds 15-oz. and that one batch of meta-product is 4,536 kg, I estimated about 10,667 canisters to package the entire batch[52]. The coffee LCA reported an emissions factor of 0.16 kg CO_2-eq per 15-oz. canister. Multiplying this factor by the total 10,667 canisters resulted in about 1.7 tons CO_2-eq for primary packaging for one batch. For the secondary packaging, I downloaded data for CO_2, CH_4 and N_2O emissions per 1000 kg of cardboard shipping cartons from the European Commission Joint Research Centre for Life Cycle Thinking and Assessment database[53] (2002). Assuming that twelve 15-oz. cans could be packaged per 0.1 kg cardboard carton, I estimated about 889 cardboard cartons, or 88.9 kg of cardboard cartons were needed per batch and normalized the GHG outputs by GWP coefficients. Total formula packaging emitted 1.8 tons CO_2-eq per batch. Overall, I estimated that the model infant formula factory emitted about 4.4 tons CO_2-eq to manufacture one dry batch of 4,536 kg infant formula meta-product.

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[50] A paperboard cylinder lined with aluminum.
[51] Franklin Associates is a premier private LCA consulting firm.
[52] 15 oz. = 0.4252 kg
[53] Process data set: corrugated board boxes; technology mix: production mix, at plant; 16.6 % primary and 83.4 % recycled fibre. European paper production and energy supply conditions.

Table 6: Tons CO_2-eq from production of 10,667 canisters and 89 kg cardboard cartons per batch

Primary: composite coffee canister (15 oz.)	CO_2-eq (lb./canister)	CO_2-eq (kg/canister)	No. canisters	CO_2-eq (kg/10,667 canisters)	CO_2-eq (tons/10,667 canisters)
Fiberboard steel composite canister	0.3564	0.16	10666.84	1724.41	1.72
Secondary: cardboard cartons (0.1 kg)	**GHG output (kg/1000 kg boxes)**		**CO_2-eq (kg/kg box)**	**CO_2-eq (kg/89 kg boxes)**	**CO_2-eq (tons/89 kg boxes)**
Cardboard boxes	*1.68*	*CH_4*	*0.04*	3.74	0.0037
	1096.46	*CO_2*	*1.10*	97.58	0.0976
	0.04	*N_2O*	*0.01*	1.12	0.0011
				tonsCO_2-eq/batch	1.83

IV. Consumer

In LCAs of food products the home stage is consistently cited as the most uncertain because consumer food preparation and wastage are highly varied (Sonesson & Berlin 2008). However, the consumer stage of food lifecycles may be significant for GHG emissions due to energy consumption by home appliances, especially for cooking. For example, a 2010 LCA study of Knorr dry soup products attributed one third of the total lifecycle GHG emissions to home cooking (Canals et al.). The home activities included in the Consumer phase of this model infant formula lifecycle were boiling water for formula preparation[54], sanitizing bottles in the dishwasher, and refrigerating prepared servings. The dishwasher was assumed to sanitize bottles and utensils instead of boiling water. Dry infant formula meta-product packaged in 15-oz. composite canisters, and plastic baby bottles. Other activities (e.g. hand-washing) were excluded, as was production of capital goods such as kitchen appliances.

To simplify the estimation of home energy use I divided the large manufacturing "batch" into smaller units of consumption of infant formula per infant per year [Table 7]. According to a 2010 report by the Washington State Department of Health on WIC-approved infant formulas, I estimated that one infant in one year should theoretically consume about 48.4 kg of powdered infant formula [Table 7]. According to Jones (2006), American households waste up to 14% of purchased food (2010). Because infant formula may be an expensive product for consumers it is uncertain to what degree infant formula would be wasted. However, according to the U.S. Department of Agriculture any leftover prepared infant formula must be discarded within one hour after use (2007). Also, open formula canisters must be discarded after a few days because the product degrades in air. In reality, wastage of infant formula by discarding uneaten formula is highly likely to occur. I therefore assumed the 14% food waste estimated by Jones and multiplied the 48.4 kg powdered formula per infant per year by 1.14 to account for waste. With this adjustment I estimated the average infant formula consumer would purchase about 55 kg

[54] Where water and sanitation are secure, boiling may not be essential. However, due to the high risk of illness from contamination of infant formula, for this model I assumed that water must be raised to 100 degrees Celsius for safety.

of powdered infant formula per infant per year. The total manufacturing batch size of 4,536 kg would therefore yield one year's supply of infant formula for about 82 infants[55].

Table 7: Powdered infant formula consumption required per infant per year

	0-3 months		4-5 months		6-11 months (with foods)	
SIMILAC	*12.4 oz *9 cans/month =*	446.4	*12.4oz *10 cans/month=*	248	*12.4 * 7 cans/month =*	520.8
	plus 3 cans / month	148.8	*plus 3 cans / month*	74.4	*plus 3 cans / month*	223.2
TOTAL / time period (oz.):		595.2		322.4		744
GOODSTART	*12 oz. * 10 cans/month =*	480	*12 oz.*11 cans/month=*	264	*12oz. *8 cans/month=*	576
	plus 3 cans / month	144	*plus 3 cans /month*	72	*plus 3 cans /month*	216
TOTAL / time period (oz.):		624		336		792
Average Similac & Goodstart (oz):		609.6		329.2		768
Average Similac & Goodstart (kg):		17.3		9.3		21.8
					Total (kg/infant-yr)	48.39
					Accounting for 14% waste	55.16
					Infant-yrs / batch	82.23

Assuming all infant formula was prepared in single 8 oz. servings in private home settings[56], I next estimated the energy requirements for heating water, sanitizing baby bottles, and refrigerating formula prepared ahead of time. Energy consumption for boiling water will differ by appliance used such as stove-top kettle versus electric hot water heater (Busser et al. 2009). Data on electricity consumption for home kitchen appliances were difficult to locate. I calculated four separate estimates of energy consumption for food and water heating to gain a better sense of the energy required. The first estimate was a theoretical calculation of the energy required to bring 236.56 g water from 20 °C to 100 °C using the specific heat of water (4.186 J/g°C). I then multiplied this energy requirement per 8 oz. serving times the EIA electricity factor and by 1719, the number of total 8 fluid oz. servings that one infant would consume in one year[57]. This theoretical heating energy estimate was used as a lower bound for comparison but not included in the final estimate because it did not account for appliance inefficiency. The second and third estimates were literature values obtained from a Danish study by Weidema et al (1995) for food preparation: boiling food on the stove (3.3 MJ electricity/kg); and microwaving food (0.8 MJ electricity/kg). When multiplied by the 235.56 g water per 8 fluid oz. serving of formula, by the EIA electricity emissions factor and by 1,719 servings per year, boiling and microwaving emitted 2.58E-01 and 6.15E-02 tons of CO_2-eq per year, respectively. Boiling food on the stove was the upper bound as it required the most energy input. The fourth estimate for energy consumption in water heating was based on a value reported in a UK newspaper article for boiling one cup of water in an electric kettle (0.0135 kWh /cup[58]) and yielded 3.65 E-02 tons CO_2-eq

[55] (4,536 kg / batch) / (55 kg / 1 infant-year) = 82.23 infant-years per batch.

[56] As opposed to bulk preparation in institutions such as child care facilities. Pre-preparation is generally not recommended.

[57] Number of 8-oz servings of formula per infant per year: [(55kg/year) / (0.032kgformula/serving)] = 1718.75 servings / year.

[58] The article calculated the energy requirement to boil one cup of tea. One cup of water = 8 fluid oz.

emitted per infant-year (Aldred 2008). Due to uncertainty in the variable methods of heating water I averaged the three estimates, as some consumers likely won't boil their water at all while others may use energy-intensive appliances [Table 8]. The average GHG emissions per infant per year for heating water for formula preparation was 1.19E-01 tons CO_2-eq.

Table 8: Tons CO_2-eq for consumer water heating for preparation of powdered infant formula per infant-year

Heating method	Energy/ 8oz serving	MWh / 8oz serving	Emissions Factor (EIA)	CO_2-eq (kg/ 8oz.)	CO_2-eq (ton /8oz)	CO_2-eq (ton/year)
Boil food (Weidema 1995):			689.35 kg CO_2-eq/ MWh			
3.5 MJ electricity/ kg	0.83 MJ/8oz	2.21E-04		1.50E-01	1.50E-04	2.58E-01
Microwave food (Weidema et al. 1995)						
0.8 MJ electricity/kg	0.19 MJ/8oz	5.26E-05		3.58E-02	3.58E-05	6.15E-02
Microwave water heating (Aldred 2008)						
0.03125 MJ electricity/ cup	0.03 kWh/8oz	3.13E-05		2.13E-02	2.13E-05	3.65E-02
				Average (tons CO_2-eq /infant-year)		1.19E-01

Data for dishwasher energy consumption was obtained from the U.S. Department of Energy (DOE) "Energy Savers" program (2011). I assumed a dishwasher would be run for one hour per day and that baby bottles would comprise 5% of the dish load. The DOE reports that a dishwasher ranges from 1,200-2,400 wattage depending on the drying cycle involved. I multiplied the average wattage (1,800 watts) times one hour per day and 365 days per year to obtain a yearly energy estimate. Then, I multiplied the energy requirement by the EIA emissions factor for electricity GHG emissions and by 0.05 to allocate 5% of the energy use to the infant formula, resulting in 2.23E-02 tons CO_2eq per infant per year.

For refrigeration I assumed that a pre-prepared 8 oz. bottle would be refrigerated for a total of 24 hours once every two days (182 days per year) and that the refrigerator would be actively running during that entire time period[59]. I found multiple estimates of refrigerator energy consumption in the literature and was unable to discern which would be most credible or relevant to U.S. households; therefore I calculated an average of three separate estimates: 7.1E-06 MWh/day/8 oz. serving (Steiner et al. 2005); 1.2E-06 MWh/day/8 oz. serving (Weidema et al. 1995); and 2.4E-06 MWh/day/8 oz. serving[60] (Carlsson-Kanyama & Faist 2000). I multiplied each energy estimate by the EIA electricity emissions factor and 182 days and averaged the three estimates to obtain a total estimate of 2.2E-02 tons CO_2-eq per infant per year. Given these many assumptions I estimated that the three energy consuming home processes collectively emitted about 0.14 tons CO_2-eq per infant-year. It is reasonable that refrigeration energy use is smallest

[59] This is likely an overestimation as refrigerators may shut on and off as needed to maintain a specified temperature.
[60] Each estimate is calculated from energy usage per item volume, such as 0.017MJ per liter per day (Weidema et al. 1995).

because one serving of infant formula is a small percentage of the total refrigerator volume and this activity was assumed to occur half as frequently as dishwashing. Water heating is the activity that occurs the most frequently throughout the consumer year; therefore it makes sense that the CO_2-eq associated with water heating are the greatest of the three home activities.

Table 9: Comparison of CO2-eq from energy consumption by home activity

Home energy activity:	tons CO_2-eq /infant-year
Water heating (ave.)	1.19E-01
Dishwasher use	2.23E-02
Refrigeration (ave.)	4.40E-04
Tons CO_2-eq/year:	*0.14*

Consumers also require baby bottles in order to serve prepared formula to infants[61]. High quality GHG data for plastics production are readily available for download from various LCA databases; therefore I included this background input in the consumer phase. I directly measured a 5 fluid oz. polypropylene (PP) baby bottle and divided the total mass by 5 to determine the amount of plastic required per unit volume: about 6.8 grams PP/oz. I assumed one infant would require four bottles in one year to enable multiple feedings per day without extensive washing burdens between feedings. Based on the 8 fluid oz. serving size used in the home energy estimations, 0.22 kg of PP were required for four 8 oz. bottles per infant per year[62]. I selected data on carbon dioxide, methane and nitrous oxide emissions per kg of PP granulate from the European Commission Joint Research Centre for Life Cycle Thinking and Assessment database (2002). These values are for raw production of PP; they do not include manufacturing processes for making the bottles nor packaging and shipping of the bottles to retail stores. Multiplying these PP production GHG emissions factors by the estimated 0.22 kg PP needed for four bottles, the annual CO_2-eq per infant per year was 4.3E-04 tons [Table 10].

Table 10: Tons CO_2-eq for 4 polypropylene (PP) baby bottles per infant per year

GHG: 1 kg PP at plant:	CO_2-eq (kg / kg PP)	CO_2-eq (tons / kg PP)	CO_2-eq (tons / kg PP)	
CO_2	1.6700	/1000	1.67E-03	
CH_4	0.0118	*25 GWP / 1000	2.96E-04	
N_2O	4.82E-13	*298 GWP / 1000	1.44E-13	(tons CO_2-eq/ 4 bottles)
		Tons CO_2-eq/kg:	1.97E-03	4.28E-04

Finally, I combined the CO_2-eq estimates for water heating, dishwashing, refrigeration and bottle production per infant per year into one measure (5.8E-02) and multiplied that total by 227 to represent the number of infants that the one batch of infant formula meta-product (4,536 kg) could supply with 20 kg of formula for one whole year. The overall

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[61] Infant formula is now available in liquid to go packs, eliminating home energy use but likely causing greater GHG emissions due to increased raw material consumption and packaging.

[62] (0.0068 kg PP/fl.oz. measured bottle) * (8oz. / serving-size bottle) * (4 bottles) = 0.22 kg PP per four 8 oz. bottles.

potential consumer GHG emissions from one batch of infant formula meta-product were 11.6 tons CO_2-eq per year.

V. Waste

Several of the stages in the infant formula lifecycle produce waste products; however this model lifecycle only accounted for post-consumer waste from infant formula composite canister packaging[63]. Due to variable recycling capabilities by U.S. region I assumed 100% of composite can packaging was disposed of in a landfill[64]. Transportation emissions by municipal solid waste trucks from consumer to landfill were excluded due to lack of quality data on cargo load or distances travelled by municipal solid waste trucks. For the entire batch of infant formula (4,536 kg) I estimated that 10,667 15-oz. composite canisters were required[65]. Each canister is comprised of an aluminum and paperboard body cylinder, a low-density polyethylene (LDPE) lid, a high-density polyethylene (HDPE) scoop, and a thin aluminum and LDPE seal. To determine the relative amounts of each raw material per canister I directly measured each component of a 12.7 oz. canister of infant formula and normalized the values to a 15-oz. size [Table 11]. The Franklin Associates study used in the Infant formula factory stage of the model lifecycle provided the relative amounts of aluminum, paper and plastic in two canister components that were made of mixed materials- the seal and the canister body. I multiplied the amounts of each raw material present in one canister by 10,667 canisters, and then multiplied by emissions factors for landfill disposal of raw materials as reported by the U.S. Environmental Protection Agency (EPA) Waste Reduction Model (WARM 2010) [Table 12]. Interestingly, these WARM emissions values are not significantly different among types of waste. Based on these assumptions, the Waste phase GHGs were 0.06 tons CO_2-eq per batch of infant formula packaging (10,667 composite canisters holding 4,536 kg of powdered meta-product).

Table 11: Raw materials for one 15-oz. composite canister

Direct measurement: 12.7 oz. canister:	Normalized for 15 oz. canister:
54.07 g composite canister	63.86
1% aluminum foil: 0.5407 g	0.64
99% cardboard: 53.5293 g	63.22
1.00 g seal	1.18
90% LDPE : 0.90 g	1.06
10% aluminum : 0.10 g	0.12
8.00 g scoop (HDPE)	9.45
6.46 g lid (LDPE)	7.63
Total kg material / 15oz. canister	82.12
Total mass (kg/10,666 canisters)	858.40

[63] Disposal of secondary packaging (cardboard cartons) was excluded; they may be re-used by the retail sector or recycled.

[64] According to direct communication with the Orange County Solid Waste Management Department, composite cans may not be recycled in Orange County, NC. However, direct experience suggests otherwise.

[65] 1 kg = 35.274 oz. Number of 15-oz canisters needed = (4536 kg / batch) * (35.274 oz./kg) * (1 can/15 oz.) = 10,66 canisters.

Table 12: Tons CO2-eq for 10,667 15-oz. composite canisters using EPA WARM model

Canister component:	waste (kg/batch)	waste (ton/batch)	CO_2-eq (ton/ton waste)	CO_2-eq (ton/batch)
Canister (aluminum)	6.81	0.01	0.04	2.64E-04
Canister (cardboard)	674.36	0.67	0.08	5.09E-02
Seal (LDPE)	11.34	0.01	0.04	4.40E-04
Seal (aluminum)	1.26	0.00	0.04	4.89E-05
Scoop (HDPE)	100.79	0.10	0.04	3.91E-03
Lid (LDPE)	81.39	0.08	0.04	3.16E-03
			(tons CO_2-eq/batch):	0.06

VI. Transportation

Although transportation necessarily occurs between each stage of the infant formula lifecycle, for this model transportation was limited to three "legs": 1) farm to factory by refrigerated truck, 2) manufacturing[66] to retail by truck; and 3) retail to consumer by passenger vehicle[67]. Each leg was counted twice: first with the appropriate cargo load, and again for "backhaul" with zero cargo[68]. I assumed that all goods remained within the U.S. geopolitical boundary and traveled by road (excluding rail and water transport)[69]. Because I had the exact coordinate locations of the U.S. infant formula factories from the U.S. EPA Facility Registry System (FRS), I conducted an ArcGIS analysis to estimate the distances from these facilities both to the farm and to the retail site [Figure 7][70]. I plotted the infant formula factories in a GIS frame of the continental U.S. along with data points for major U.S. cities and shading for the top ten major dairy producing states[71]. To estimate the distance from dairy farm to factory I used one major U.S. city in each of the top ten dairy-producing states to represent the milk transport origin from all dairy farms in that state, plotted the distance from each selected city to each factory, and averaged the distances. This analysis for "leg 1" resulted in an average distance of 1,665 km from farm to factory [597.8 - 2,732.2 km, standard deviation]. Similarly, for "leg 2" I used 100 major U.S. cities in all 50 states to represent points of sale and plotted the distances to each factory, resulting in an average distance of 1,721 km from manufacturing to retail [1540.1 – 1902.0 km, standard deviation]. All manufacturing and all cities were weighted equally.

To translate these distance estimates into GHG emissions I multiplied the distance traveled and/or the cargo carried by an emissions factor for the type of vehicle. For the

[66] The Dairy plant and Factory stages were merged for simplicity.

[67] This approach omits multiple sub-legs. For example, refrigerated milk trucks collect milk from multiple farms before either distributing a full load to a "trans-shipment depot" or directly to a dairy plant (Foster et al 2006).

[68] E.g. the milk truck arrives full at the factory and dispenses all milk, then returns empty to the dairy farms to refill.

[69] The U.S. is a major exporter of infant formula. Future studies should investigate the GHG emission from foreign trade flows.

[70] This method skips the separate journey from the "black box" Dairy Plant to the Formula Factory. Data was not available to separate out these sub-legs; therefore, the Dairy Plant is considered here to be co-located with the Formula Factory.

[71] California, Wisconsin, New York, Idaho, Pennsylvania, Minnesota, Texas, New Mexico, Michigan, Washington (USDA ERS 2009).

refrigerated milk truck, I selected an emissions factor from FAO of 0.016 tons CO_2 per ton of milk transported (2010). The cargo was the 24.97 tons of raw milk estimated in stage I (Dairy farm) for delivery to the Dairy plant. I assumed that the refrigerated milk truck could hold up to 30 tons; therefore, only one refrigerated milk truck was needed to transport the raw milk required per batch of meta-product. Distance traveled could not be applied to this emission factor. The forward journey of "leg 1" emitted about 0.4 tons CO_2-eq /year and the backhaul emitted 0.02 tons CO_2-eq /year.

For the smaller cargo truck to transport the infant formula ingredients from the factory to the cities (representative of retail sites) I calculated GHG emissions from diesel transportation data in the U.S. National Renewable Energy Laboratory LCI Database: 0.08 kg CO_2,eq / ton-km [Table 13]. This estimate was based on LCA data from Franklin Associates and the GREET model[72]. I assumed that one truck could hold 100 boxes with 12 canisters per box. For the entire batch size, 889 boxes were needed and therefore nine trucks[73,74]. The canisters themselves weighed 15 oz. each and each box also weighed 0.1 kg, therefore the total cargo per batch of infant formula was 4.6 tons. I also assumed that the truck had to return along the same path with empty cargo[75]. From these assumptions the forward transportation of leg 2 emitted 5.7 tons CO_2-eq per batch transported, and the backhaul transportation of leg 2 emitted 1.2 tons CO_2-eq.

Table 13: Example calculation of a transportation emissions factor using IPCC global warming potentials

NREL LCI: Franklin Associates; Center for Transportation Research, Argonne; GREET V. 1.6					100-yr GWP	CO_2-eq (kg/ton*km)
Input	Diesel, at refinery	US	L	0.0272		
Output	Carbon dioxide, fossil		kg	0.0799	x1	7.99E-02
Output	*Carbon monoxide, fossil*		*kg*	[illegible]		
Output	Methane, fossil		kg	1.29E-06	x25	3.22E-05
Output	*Nitrogen oxides*		*kg*	*0.00085*		
Output	*Dinitrogen monoxide*		*kg*	*1.99E-06*		
Output	*Particulates, < 2.5 um, and > 10um*		*kg*	*9.10E-06*		
Output	*Sulfur oxides*		*kg*	[illegible]		
Output	*VOC, volatile organic compounds*		*kg*	[illegible]		
	Transport, combination truck, diesel powered	*US*	*tkm*	*1*		
					kg CO_2-eq / ton*km	0.080

For "leg 3" from consumer to retail I selected an average distance of 6 km from home to retail site from a 2006 LCA study by Dutilh et al. entitled "Energy Consumption in the Food Chain". The US EPA estimates 5.5 tons CO_2-eq per consumer vehicle travelling an average of 12,000 miles per year (2005). Dividing this by the 12,000 miles to determine the CO2-eq per mile, I then converted to kilometers to form a passenger vehicle

[72] *GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*, Argonne National Laboratory.
[73] (4536 kg batch size + 88.9 kg boxes) = 4624.9 kg cargo = 4.6 tons cargo.
[74] (4536 kg formula / batch) * (35.27 oz. / kg) * (1 canister / 15 oz.) * (1 box / 12 canisters) * (1 truck / 100 boxes) = ~9 trucks
[75] In reality, truck shipments likely have their own complex and interconnected system like the dairy plant. Future studies should more carefully investigate the distances travelled by trucks that can be allocated to the product of interest.

emissions factor of 0.29 kg CO2-eq / km driven. I next assumed that a consumer would take one individual shopping trip per three canisters of formula purchased throughout the year (about one trip per week). For 55 kg of powdered formula per infant per year, this translates to 130 canisters and thus about 43 trips[76]. However, within each of these grocery trips the consumer is likely to purchase other items as well; therefore, I assumed the formula would be 5% of the total items purchased by the consumer on each of the 43 retail trips for infant formula purchases per infant per year. Finally, I multiplied the tons CO_2-eq per 43 trips in one passenger vehicle per year by 82, the number of years'-worth of formula provided by the entire batch size (4,536 kg). Because there is no cargo requirement for the passenger vehicle emissions factor of 0.28 kg CO_2-eq per km, the backhaul produced the same emissions as the forward trip: about 0.31 tons formula per year. In total, the GHG emissions from all transportation legs of the model lifecycle were 7.2 tons CO_2-eq per batch size distributed. Because so many sub-legs were excluded from this model, the true emissions associated with transportation to distribute infant formula throughout the lifecycle may be more.

Table 14: CO2-eq emitted by three transportation legs in the infant formula lifecycle

		Distance (km)	Cargo (t / batch)	Emissions factor		T CO_2-eq/batch
Leg 1	Proxy d farm to dairy plant/factory		24.97	0.016	CO2 (t / t milk)	0.40
	Backhaul (empty load)			0.016	CO2 (t / t milk)	0.02
Leg 2	Proxy d dairy plant/factory to retail	1,721	4.62	0.080	CO2-eq (kg t⁻¹km)	5.72
	Backhaul (empty load)	1,721		0.080	CO2-eq (kg t⁻¹km)	1.24
Leg 3	Proxy d from retail to home	6.0	1 passenger	0.28	CO2e (kg /km)	0.31
	Backhaul (empty load)	6.0	1 passenger	0.28	CO2e (kg /km)	0.31
				Total (tons CO_2-eq batch)		7.99

[76] (55 kg /year/infant = 1945.8 oz.; 1945.8 oz. / 15 oz. can = 129.7 cans = ~130 cans. Trips: 130/3 is ~ 43 trips.

holistic framework that includes not only physical impacts on the biosphere but also impacts to the anthrosphere such as human health, societal development and economic trade-offs. In the case of infant formula, promoting breastfeeding over formula feeding has positive benefits on all of these parameters.

Although this LCA only examined GHG emissions, future studies should assess other environmental impacts associated with dairy production and the larger infant formula lifecycle. For example, refrigerated milk transport may be a significant source of stratospheric ozone damaging substances, and manure management on dairy farms may contribute to eutrophication. Four of the five major infant formula companies in the U.S. hold permits with the U.S. Environmental Protection Agency (EPA) for air and water emissions[89]; therefore, future LCA studies could easily quantify these impacts. Less tangible categories accepted by LCA protocol include "changes in the landscape", "risk of accidents", "ecotoxicity", and "human health"; future studies of the lifecycle of infant formula should address these and other environmental and human impacts to strengthen environmental arguments for breastfeeding.

The corporate sector should also take initiative to analyze and report their environmental impacts. In 2010, Knorr food products became the first brand to conduct a lifecycle assessment of greenhouse gases at their global portfolio level. Major infant formula companies such as Abbott, Mead Johnson and Nestle should follow suit, if they are not already doing so privately. Where LCAs are being conducted privately or by consulting firms there should be third party and public participation and results should be made publicly available whenever possible such as through voluntary reporting programs like the Carbon Disclosure Project. Finally, change can occur within the organizational structure of an industry regardless of whether the product or process becomes "green"; industries are made up of individuals who can all take steps to reduce the environmental impact of their daily work activities (Townsend 1998).

V. *Evidence-based public health advocacy for breastfeeding*

While the infant formula industry continuously strives towards better nutritional quality, companies must also compete for consumer attention and be responsive to consumer demands. Increased single-serving-size and other convenience packaging may save time for the busy parent, but they carry heavier environmental consequences due to increased processing and packaging materials. There may be environmental implications of nutritional advancements, as well[90]. For example, osteopontin is one compound in human milk that is not present in equal quantities in cow's-milk based formulas (Nyhetsarkiv 2010). Adding this compound to formula to more closely mimic human

[89] I could not locate PBM Nutritionals in the EPA permit system; however, quantitative emissions information for Abbot Laboratories Ross Products Division, Mead Johnson, and Nestle are all publicly available.
[90] It is unclear how much these nutritional additives actually improve the nutritional quality of the formula; changes may also be made for marketing purposes.

milk may be important for infant health. On the other hand, it would implicate another "milk concentration factor" similar to those for whey protein and lactose, thereby compounding the environmental effect of the raw milk required to produce formula. There are interesting trade-offs in the infant formula sector between desiring the highest quality nutritional product for infant growth and the unrealistic environmental and economic costs of processing these micro-ingredients. As public health navigates the interdependent relationships between humans and their environment, is it more advantageous to produce higher quality infant formulas at a cost to the environment, or to promote breastfeeding? While breastfeeding provides health benefits that are proven to be fundamentally out of reach for formula, this study suggests that breastfeeding also avoids environmental impact to climate change that infant formula is necessarily bound to.

One emergent trend in consumer marketing of food products is "ecolabeling". The general consensus in the field, however, is that marketing certifications and "environmental product declarations" (EPDs) are not currently feasible (Canals et al. 2010). As the consumer food market continues to develop these measures public health efforts can adopt the same approach in labeling health behaviors as "green" or "ecofriendly". For infant feeding, choosing breastfeeding is "the carbon neutral choice".

CONCLUSION

This study was a partial lifecycle assessment of the total greenhouse gas emissions from all stages in a model U.S. infant formula lifecycle from cradle to grave. Overall, this model determined that 14.7 kg CO_2-eq are emitted per kg infant formula consumed, equivalent to 4.0 kg carbon per kg infant formula consumed. This is seven times greater than the greenhouse gas emissions of fluid milk consumption. For one year's consumption of infant formula, 808.5 kg CO_2-eq are emitted per infant. In comparison, the average American household emits about 12.4 tons of carbon dioxide from all household operations each year, according to 2003 data (Hinkle). Off-setting these emissions per infant per year would cost families about $8.

Milk production at the dairy farm was the greatest contributor to the total lifecycle emissions (55.4%). This agrees with the existing literature on GHG emissions of dairy products. The second greatest contributor in the lifecycle was the consumer (17.4%); however, this phase is also the most uncertain due to high variability in consumer behavior. Transportation was 12.0% and manufacturing and packaging together comprised 15% of the total GHG emissions.

Despite the uncertainties and limitations of the model it is evident that infant formula is a significant source of greenhouse gas emissions because it is a condensed milk product. Future research should address other environmental impacts of infant formula such as to water pollution. Ironically, parents who do not breastfeed not only limit the health potential of their children but also contribute to the climate change problem these children will have to face in the future. Public health may benefit from greater understanding of the environmental consequences of infant formula to strengthen evidence-based advocacy for breastfeeding.

APPENDIX A: FIGURES

Figure 1: Four Stages of ISO Lifecycle Assessment

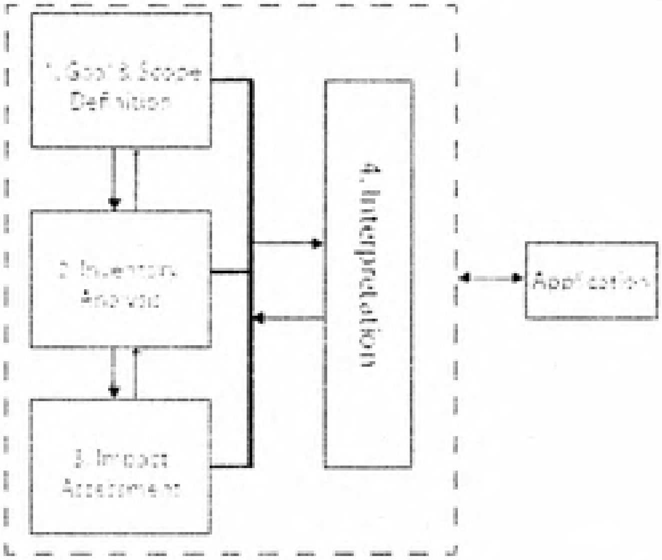

Figure 2: Lifecycle production system of powdered cows-milk-based infant formula meta-product

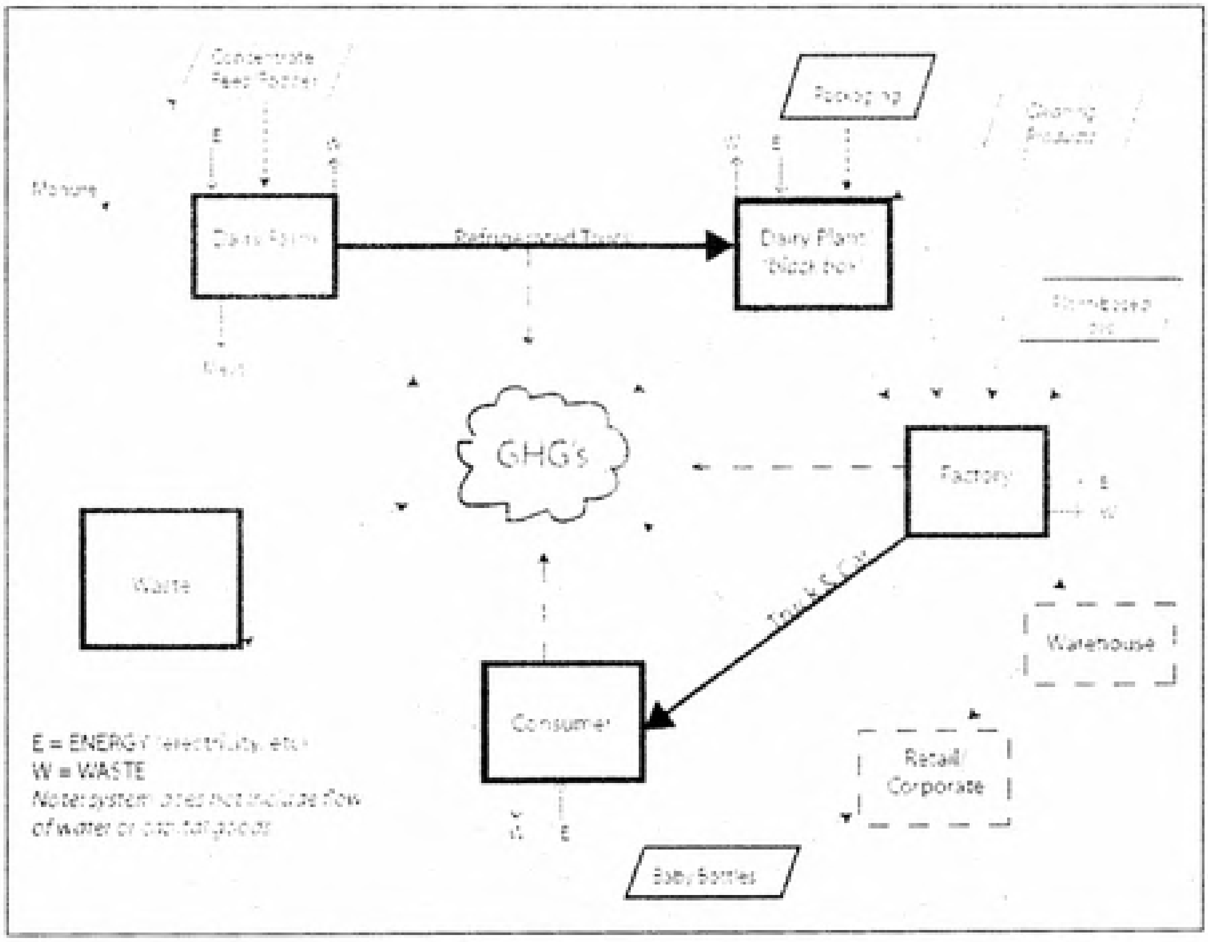

Figure 3: Detailed system for "black box" dairy stage

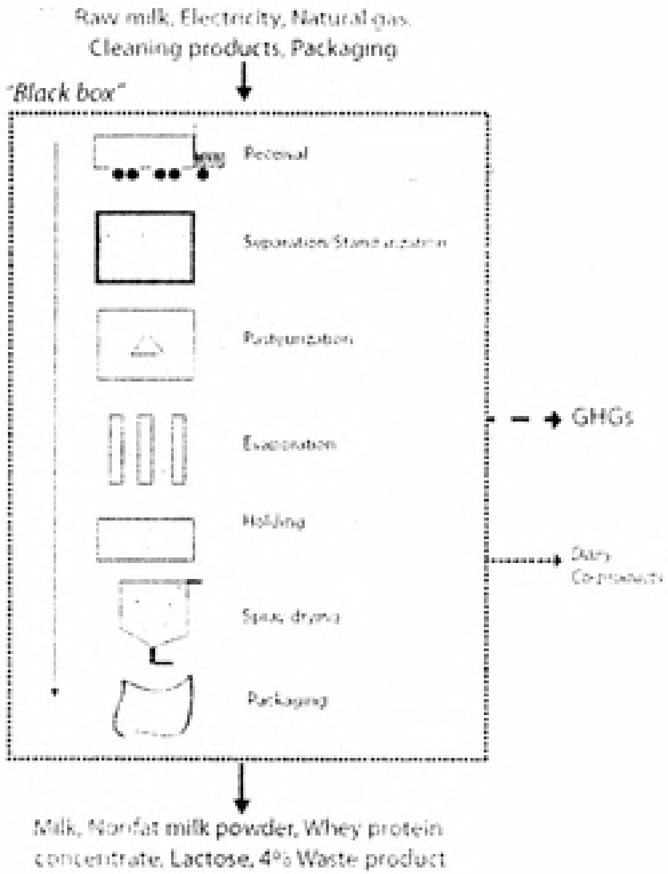

Figure 4: Powdered infant formula factory schema (Sorenson H, Jorgensen E, Westergaard V, 1992)

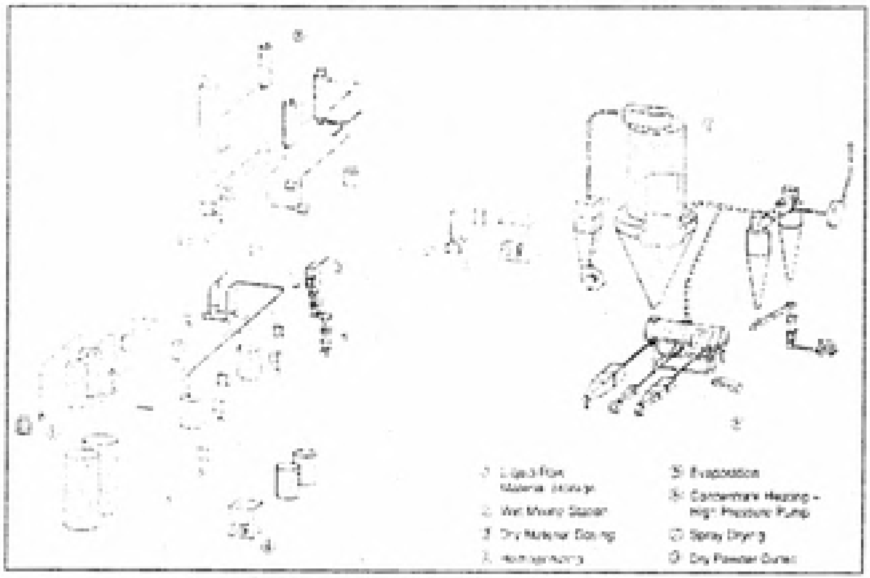

Figure 1: Detailed system for infant formula factory stage

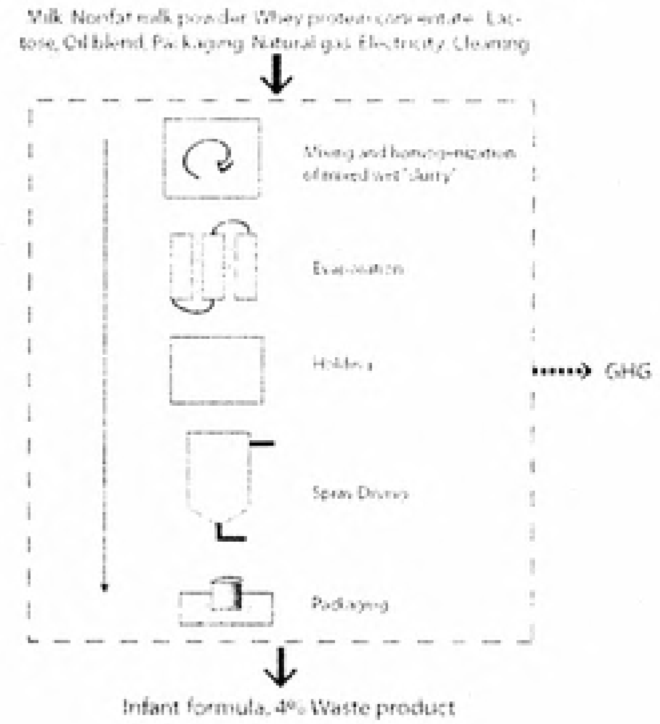

Figure 6: GIS analysis for transportation distances

APPENDIX B: TABLES & EQUATIONS

Equation 1: Carbon dioxide equivalent (CO_2-eq)

$$TotalCO2-eq=\sum(m_{CO2})+(m_{CH4}\times 25)+(m_{N2O}\times 298)$$

Equation 2: Simplified algorithm

$$GHG_{LCA}=GHG_{milk}-GHG_{plant}-GHG_{factory}-GHG_{consumer}-GHG_{waste}-\sum_{i=1}^{j}GHG_{transport}$$

$$GHG_{milk}=\sum_{i}^{j}(GHG-em_{ingredient}\times m_{dairy\,product})$$

$$GHG_{plant}=(\varepsilon/m_{product}\times m_{product})-GHG_{packaging}$$

$$GHG_{factory}=(\varepsilon/m_{product}\times m_{product})-GHG_{packaging}$$

$$GHG_{consumer}=(\varepsilon_{fridge}\times m_{user})-(\varepsilon_{cooking}\times hours)-(\varepsilon_{dishwash}\times hours)-GHG_{packaging}$$

$$GHG_{waste}=GHG_{waste}\times m_{waste}$$

$$GHG_{transport}=(GHG_{transport}\times m_{cargo}\times d_{i})-(GHG_{transport}\times m_{backhaul}\times d_{i})$$

Equation 3: Example CO2-eq calculation for MMBTU natural gas

$$kgCO_2eq=(0.784MMBTU)*\left(kgCO_2/MMBTU\right)=41kgCO_2eq=0.04tonsCO_2eq$$

Equation 4: Electricity CO_2-eq (EIA 2007)

$$kgCO_2-eq_{electricity}=\left(676.76kgCO_2-eq/MWh\right)+\left[\left(0.0182kgCO_2-eq/MWh\right)*25\right]+\left[\left(0.0108kgCO_2-eq/MWh\right)*298\right]*MWh$$
$$kgCO_2-eq_{electricity}=679.344*MWh$$

Equation 6: Example milk-solids concentration factor (Feitz et al. 2007)

$$Whey\,ProteinConcentrate.=95.4\%milksolids;$$
$$RawMilk=12.5\%milksolids;$$
$$\therefore 95.4/12.5=7.6"concenrationfactor"$$

APPENDIX C: DATA QUALITY ANALYSIS

Highest quality data (A): must meet 2 of the 3 following conditions:

- *From the United States*
- *Within the past five years (2005-2011)*
- *Peer-reviewed journal, academic institution or government source*

Sub-optimal data (B): *from other locations, older dates or unknown credibility*

REFRENCE	LOCATION	YEAR	QUALITY
1. Cross-Sector: Electricity & Natural Gas Admissions Factors			
U.S. Energy Information Administration (EIA): Appendix F: Electricity Emissions Factors, in Voluntary Reporting of Greenhouse Gases. U.S. Department of Energy.	USA	2007	A
U.S. Energy Information Administration (EIA): Voluntary Reporting of Greenhouse Gases Program. U.S. Department of Energy.	USA	2011	A
2. Milk Production			
Feitz AJ et al.: Generation of an industry-specific physico-chemical allocation matrix: application in the dairy industry and implications for systems analysis. Int J LCA..	Australia	2007	A
Jacobson R: Calculating Milk Equivalents: Milkfat or Total solids Basis. Dairy Markets and Policy Issues and Options: P-2. Cornell University Program on Dairy Markets and Policy.	USA	1992	A
Lloyd BB: US Whey Products and Child Nutrition. Applications Monograph Child Nutrition. U.S. Dairy Export Council.	USA	2002	A
University of Arkansas, Michigan Technological University (UA & MTU): Fluid Milk Carbon Footprint Study: Executive Summary. Innovation Center for US Dairy.	USA	2010	A

Walstra P et al.: Dairy Technology: Principles of Milk Properties and Processes. Marcel Dekker, Inc. New York, NY.	USA	1997	A
3. Dairy Plant			
Berlin J et al.: A life cycle based method to minimize environmental impact of dairy production through product sequencing. J Cleaner Prod. (*Cleaning & product waste)*	Sweden	2005	A
EcoInvent v2.0 database (as in Roos E, Sundberg C, Hansson PA. 2010. Uncertainties in the carbon footprint of food products: a case study on table potatoes. Int J LCA.	Europe	2010	A
Feitz AJ et al: Generation of an industry-specific physico-chemical allocation matrix: application in the dairy industry and implications for systems analysis. Int J LCA.	Australia	2007	A
Hogaas Eide & Ohlsson: A Comparison of Two Different Approaches to Inventory Analysis of Dairies. Int J LCA. *("black box" method)*	Norway	1998	B
4. Factory			
Berlin & Sonesson: Minimising environmental impact by sequencing cultured dairy products: two case studies. J Cleaner Prod.	Sweden	2006	A
Food and Agriculture Organization of the United Nations (FAO): Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. FAO Animal Production and Health Division, International Dairy Federation (IDF).	Global	2010	A
Franklin Associates. Peer Reviewed Final Report: LCI Summary for Eight Coffee Packaging Systems. Prepared for the Plastics Division of the American Chemistry Council. Franklin Associates; Eastern Research Group, INC. Prairie Village, Kansas.	USA	2008	A
Natural Resources Canada: Appendix B- CO2 Emissions Factors. Office of Energy Efficiency,	Canada	2008	A

Natural Resources Canada.			
PBM Nutritionals: Virtual Tour (video). Available: http://www.pbmnutritionals.com [accessed 12.10.2010]	USA	2010	A
5. Consumer			
Aldred J: Keep your kettle in check. The Guardian: guardian.co.uk: Green Living Blog.	UK	2008	B
Jones TW: Food Loss and the American household. Biocycle.	USA	2006	A
Washington State Department of Health: Can Sizes, Yields, and Maximum Amounts of WIC Approved Formulas. Washington State Department of Health DOH Pub #960-148.	USA	2010	A
Foster C. et al.: Environmental Impacts of Food Production and Consumption: A Report to the Department for Environment Food and Rural Affairs (DEFRA). Manchester Business School, DEFRA, London.	UK	2006	A
U.S. Department of Energy (DOE): Estimating Appliance and Home Electronic Energy Use. Energy Savers. US DOE: Energy Efficiency & Renewable Energy.	USA	2011	A
Weidema et al.: Life cycle screening of food products - two examples and some methodological proposals, Danish Academy of Technical Services, 266 Lundtoftevej. DK-2800 Lyngby, Denmark, pp. 194.	Denmark	1995	B
Büsser S et al.: LCA of Packed Food Products: the function of flexible packaging; coffee, spinach and butter, ESU-services Ltd. im Auftrag von Flexible Packaging Europe, Düsseldorf, DE and Uster, CH.	Europe	2005	B
Carlsson-Kanyama & Faist: Energy Use in the Food Sector: a Data Survey. Swedish Environmental Protection Agency, AFR Report 291, Stockholm.	Sweden	2000	B
European Commission Joint Research Centre (EU JRC): Process data set: Polypropylene	Europe	(data from	B

granulate (PP); production mix, at plant; Plastics Europe, 1999. LCA Tools, Services and Data. European Commission DG Joint Research Centre Institute for Environment and Sustainability.		1999)	
6. Waste			
Franklin Associates: Peer Reviewed Final Report: LCI Summary for Eight Coffee Packaging Systems. Prepared for the Plastics Division of the American Chemistry Council. Franklin Associates; Eastern Research Group, INC. Prairie Village, Kansas.	USA	2008	A
U.S. Environmental Protection Agency. Waste Reduction Model (WARM).	USA	2010	A
7. Transportation			
ArcGIS 10 Software. 2010. ESRI.	N/A	2010	A
US Environmental Protection Agency (EPA): Emissions Facts; Greenhouse Gas Emissions from a Typical Passenger Vehicle. EPA Office of Transportation and Airy Quality.	USA	2005	A
Dutilh & Kramer: Energy Consumption in the Food Chain. Ambio.	Netherlands	2000	B
U.S. National Renewable Energy Laboratory (NREL). 2001. Transport, single unit truck, diesel powered; Franklin Associates. US Life Cycle Inventory Database.	USA	2001	A
Food and Agriculture Organization of the United Nations (FAO): Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. FAO Animal Production and Health Division, International Dairy Federation (IDF).	Global	2010	A

RESULTS:

Highest Quality (A): 24 sources (77%)

Sub-Optimal Quality (B): 7 sources (23%)

APPENDIX D: LITERATURE REVIEW: LCAs OF MILK

Dairy products have long figured in the practice of lifecycle assessments: as early as 1985 a Swedish study compared environmental impacts of milk packaging systems (Lundholm & Sundstrom). Numerous LCAs have been conducted for liquid milk; however, secondary dairy products such as yogurt are less prevalent in the literature. No studies of powdered milk products have been conducted beyond a 1997 screening LCA by Blonk et al.[91]. In attempting to conduct the first lifecycle assessment of powdered infant formula it was important to first understand the LCA practice and methodology that has been successfully employed for the dairy sector. While numerous reviews have been conducted of *results* of dairy LCAs, no reviews have specifically focused on the methodological choices employed by these studies. A review of the available literature on LCAs of milk suggests that there is no one method to follow: LCA in practice is a creative and heuristic process as much as it is a standardized protocol.

METHODOLOGY

Research Questions:

1. What stages of the dairy production system are the environmental "hotspots" for greenhouse gas emissions, and what is the range of values for carbon dioxide equivalents (CO_2-eq) of one kilogram of milk?
2. What lifecycle assessment methodologies are followed? How are allocation methods, functional units, and system boundaries defined?
3. What are the challenges to conducting LCAs for dairy products and how are they addressed?

Inclusion criteria:

1. Followed lifecycle assessment methodology
2. Conducted at least after 1997[92]
3. Occurred in an Annex I nation or region[93]
4. Published in a peer-reviewed journal or by a government institution[94]
5. Reported a value related to GHG emissions or CO_2-eq of fluid milk[95]

In the first stage of the review, the International Journal of Life Cycle Assessment[96] was searched for three terms inclusive: [lifecycle assessment], [milk] and [dairy]. This

[91] Screening LCAs are simplified analyses in reduced detail, often used to compare materials.
[92] The date of first publication of the International Standards Organization 14040 series: Environmental Management: *"Life Cycle Assessment- Principles and framework"*.
[93] UNFCC- because of the FAO study that showed GWP for 1 kg milk is up to 7 times higher in the developing world
[94] Several PhD theses were excluded.
[95] Studies of milk packaging systems and other dairy products (e.g. yogurt, cheese) were not considered. An exception was made for a comparative LCA of margarine and butter that reported a GWP value for fluid milk.

search yielded 29 results. Titles were then reviewed to identify potential studies for review. Of these, 19 abstracts were reviewed to determine relevancy. Seven articles which met inclusion criteria were reviewed in full. In the second phase of the review, the "snowballing" method was used to peruse references contained within selected studies to identify additional studies, and so on (Greenhalgh 2005). This method is considered useful for identifying high quality sources in obscure locations and served particularly useful for this review as the studies came from diverse geographical regions and institutions. Some studies were unavailable due to proprietary terms of use or language barriers. A total of 25 studies were reviewed in full, including nineteen independent peer-reviewed journal articles and six reports from government and/or academic institutions. Four of the reviewed studies were literature reviews themselves.

REVIEW

I. Greenhouse gases:

All reviewed studies that included the agricultural stage within their system boundaries reported that this primary milk production at the farm was the largest source of greenhouse gas emissions (GHG), often reported as an aggregate measure of different GHGs called "global warming potential" (GWP)[97]. Emissions of methane due to enteric fermentation were consistently cited as the greatest percentage of GWP in the dairy lifecycle, ranging from 48% to over 95%, depending on the system boundaries. Analysis of global warming potential was an initial criterion for inclusion in the review; however, some studies did not report a value for this measure[98]. Of the 16 studies that did quantify GWP, the average result was 1.3 kilograms of carbon dioxide equivalent per kilogram of milk. For the studies originating in Europe, the average was slightly lower at 1.2 kilograms. One of the four reviews included in this literature review was a 2010 report of the Food and Agriculture Organization of the United Nations (FAO) that analyzed GWP for global milk production. According to FAO, the GWP of one kilogram of "fat and protein corrected milk"[99] ranges from 1.3 to 7.5 kilograms carbon dioxide equivalents, with the lowest values in industrialized regions such as North America and Europe and the highest values in developing regions such as sub-Saharan Africa and South Asia. Therefore, the average GWP obtained in this literature review is in agreement with the range of estimates produced by the FAO.

II. LCA in practice:

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[96] Founded in 1996, the Int. Journal of Lifecycle Assessment is the first journal exclusively devoted to LCA practice.

[97] This use of "GWP" differs from the IPCC use. In LCAs GWP refers to an aggregated measure of environmental impact calculated by combining GHGs into CO_2 eq using coefficients set by the IPCC. For the IPCC, GWP refers to the coefficients themselves (e.g. methane has a GWP of 25 because it has 25 times the greenhouse effect of carbon dioxide).

[98] A few studies showed results in graphs but did not report values in tables or text, perhaps due to industry confidentiality.

[99] Fat-and-protein-corrected milk is a constructed variable to enable comparison of milk systems among diverse regions with differing milk production capacity and nutritional composition.

While the International Standards Organization (ISO) is the foremost authority on LCA practice, its series of standards and protocol is general and may not fulfill needs of researchers on the ground, especially related to current operational models and justifications for modifications and assumptions. Various secondary protocols are therefore used in addition to the ISO framework to improve operability and accessibility. Of the 25 reviewed studies, 19 followed ISO guidelines to some degree and all studies used more than one LCA resource. Before the ISO series was published the only standardized protocol available was a methodology produced by the Society for Environmental Toxicology and Chemistry (SETAC) in 1993. Two of the reviewed studies cited SETAC methodology[100]. For the specific environmental impact category of global warming potential (GWP), the Intergovernmental Panel on Climate Change (IPCC) has a well-respected protocol aimed at directing national governments in their efforts to report and reduce greenhouse gas emissions in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). Seven of the reviewed studies cited IPCC methodology. Beyond these institutional methodologies, 23 of the studies employed the previously mentioned secondary protocols such as the popular "Handbook on Life Cycle Assessment" published by Guinée in 2002 or "The Hitchhiker's Guide to LCA" published by Baumann & Tillman in 2004.

Figure 2: LCA methodologies followed in reviewed LCAs of milk

Choice of system boundary in LCA practice is directly related to research goals. For example, LCAs exploring total environmental impact of milk might construct comprehensive system boundaries from "cradle to grave", whereas a study comparing dairy processing technologies might employ a narrower "gate to gate" boundary[101]. Twelve of the reviewed studies followed milk production from cradle to farm gate: the point at which raw milk was ready to leave the dairy. Other system boundaries included

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[100] Haas et al. 2001; Hogaas Eide 1998

[101] Comparing two products or processes enables omission of other stages. For example, Sonesson & Berlin ignored the agricultural stage because they set their system boundary at the arrival of equal amounts of raw milk at the dairy plant (2002).

milk ready for sale at retail or end-of-life milk as consumer waste. Almost all studies excluded capital goods such as manufacture of farm equipment or building construction, as well as employee activities such as commuting to work or waste from cafeterias[102]. The definition of system boundaries is related to the distinction between "attributional" and "consequential" LCAs. Attributional studies examine an existing product lifecycle to identify current "hotspots" of environmental impact, while consequential studies analyze future changes to the lifecycle that could reduce impacts. Two reviewed studies were self-defined as consequential and seven included scenario analyses of potential system changes[103].

Functional units in LCA practice enable reporting of results in a way that is meaningful to the intended audience. For dairy products they may be at the product level, such as a one-gallon glass bottle of milk, or the functional level, such as one week's supply of milk for a household (Horne 2009). The choice of functional unit is somewhat subjective and may vary widely. Seventeen of the reviewed studies used a mass based functional unit and five used a volume based unit. Because nutritional content of dairy products varies by breed of cow, feeding practice, and region, some LCAs use quality-corrected functional units to enable better comparison among milk systems. Six of the reviewed studies employed such units, either as "Energy corrected milk" (ECM) or "Fat and Protein Corrected Milk" (FPCM)[104]. Hospido et al created a unique functional unit comprised of a certain volume of milk plus a certain mass of fodder and rinse milk.

Milk production is a multi-functional process. Therefore, special consideration must be taken to accurately allocate environmental burdens among milk, meat, and other co-products of each sub-system[105]. Allocation for milk can be a complicated process as dairy cows and meat cows use different amounts of land, water, feed, and electricity[106]. Although the ISO standards recommend avoiding allocation wherever possible, all studies reviewed included some type of allocation and some included multiple types. The most popular method was economic allocation (12 studies), followed by physical allocation such as by mass or weight. Other methods included "biological causality" and government regulatory emissions limits[107]. Feitz et al. suggest a "physico-chemical" allocation method based on milk solids percentages in dairy products. There is disagreement in the field over which allocation method is most appropriate. Cederberg &

[102] Hogaas Eide did assess energy and water use for employee offices, social rooms, cafeteria and laundry (1998).
[103] E.g. Sonesson & Berlin constructed a mathematical model of the milk supply chain to examine resource use and environmental emissions from alternative actions using Material Flow Accounting (MFA) and Substance Flow Analysis (SFA).
[104] E.g. [FPCM (kg) = raw milk (kg) * (0.337 + 0.116 * Fat content (%) + 0.06 * Protein content (%)] (FAO 2010)
[105] Hides are usually considered an extremely minor co-product and are not addressed. Other multi-output elements of milk production include generation of fodder ingredients such as protein meal from crops which also yield vegetable oils.
[106] Milk uses more electricity than meat because modern milking systems are highly dependent on electricity for milking and feeding equipment, manure handling, and ventilation, but meat uses more land (Cederberg & Stadig).
[107] Hogaas Eide used "biological oxygen demand allowances" (BO) as permitted by the Norwegian Pollution Control Authority (e.g. kg BOD allowed for 1 metric ton of cream produced) (1998).

Stadig compared four different allocation methods in their 2003 study, *System Expansion and Allocation in Life Cycle Assessments of Milk and Beef Production*: no allocation; economic allocation by yearly income per dairy cow; cause-effect physical allocation by fodder inputs, and system expansion merging milk and beef systems. This analysis found that allocation choice affects results and may not be representative of the true relationships between co-products. For example, economic allocation was found to favor beef, whereas system expansion showed that meat actually benefits from the parallel milk system because milk cows displace meat cows; therefore, the meat system can be carried out with fewer animals than it would alone. This insight is especially significant in Europe where about 50% of beef cows come from the dairy system (Cederberg & Stadig 2003). Economic allocation for milk is also affected by variable production levels, supply and demand, and government price supports. Overall, choice of allocation method is the most significant challenge facing the development of LCA practice for dairy products.

Figure 3: Allocation methods in reviewed LCAs of milk

CHALLENGES AND STRATEGIES

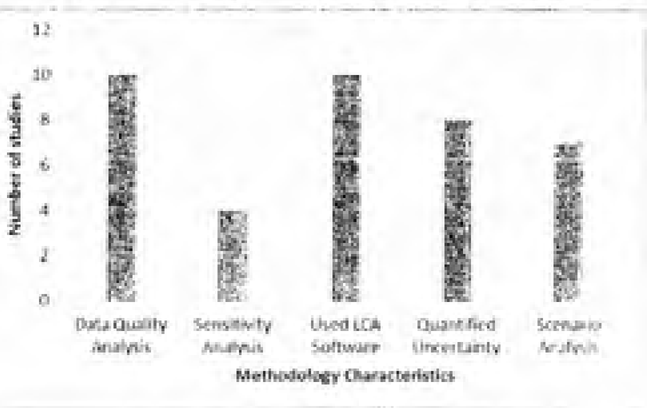
This review of 25 LCAs of milk production illuminated myriad challenges to successful LCA practice. One significant limitation is availability of quality and relevant data. The reviewed LCAs employed a mixture of government, industry/corporate, and literature data, with nine studies conducting some direct data collection and six studies using proprietary databases[108]. The ISO requires that formal LCAs undertake a data quality assessment to assess the credibility of the results. Of the 25 reviewed studies, 10 conducted a formal data quality analysis and two acknowledged a heuristic method in estimating and aggregating data[109]. Another challenge is the potential for uncertainty in one emissions factor or variable in a lifecycle inventory to significantly affect the results. It is good practice to conduct a quantitative sensitivity analysis where this may be the case; however, only four of the reviewed studies did so. While nearly all articles discussed uncertainty qualitatively, only eight authors chose to quantify uncertainty and the methodology was not always transparent. For example, Hospido et al reported an "overall uncertainty" of 13-17% from "standard deviations shown at the inventory tables" but did not elaborate on how they aggregated the individual uncertainties into one range

[108] E.g. EcoInvent.
[109] Berlin et al. 2005; Berlin & Sonesson 2008

(2003). Three of the studies which quantified uncertainty conducted a Monte Carlo analysis[110].

In reviewing the available literature on LCAs of milk, it is evident that no two studies can be directly compared as each LCA follows a uniquely designed lifecycle system based on somewhat subjective methodology choices. Dairy production systems vary among regions, including milk productivity per cow and average electricity mixes[111]. As the agricultural phase is the most significant for emissions of greenhouse gases, variations in agricultural practice limit applicability of LCA results to that particular context. For example, spreading manure on-farm in a closed-loop system has different environmental impacts than storing manure in a liquid or slurry system. In addition, given the importance of feed digestibility for enteric fermentation, different feed mixes and practices[112] limit comparability of enteric fermentation values among regions.

Figure 4: Data Management in Reviewed LCAs of Milk



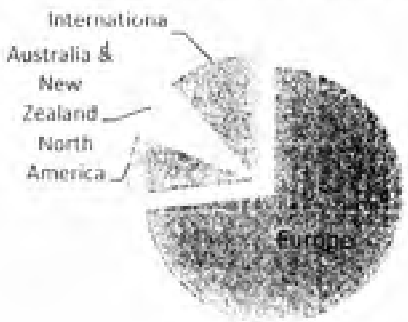
CONCLUSION

This review of methodological elements in 25 LCA studies of milk production reveals that LCA in practice is variable and subjective. A wide array of methodological choices is available to researchers, from system boundaries to functional units. FAO came to the same conclusion in their global review of LCAs for milk, stating "while more information has become available in recent years, it is still largely fragmented and not based on a consistent or comparable set of methodologies" (2010). However, the limitations of LCA practice have not overcome its ability and future potential to provide important information on the environmental impact of the dairy practice. Best practices in conducting an LCA of milk products should uphold transparency and justification of methodological choices, assumptions, and data sources.

[110] Basset-Mens 2005; FAO 2010; UA & MTU 2010.
[111] E.g. northern European countries use more hydropower whereas Australia uses primarily coal.
[112] E.g. mixed concentrate fodder transported to the farm vs. in-situ grazing.

Out of 25 reviewed LCAs, only one was produced in the U.S. and only two in North America. Recent efforts to reverse this imbalance include the U.S. National Renewable Energy Laboratory (NREL) Life Cycle Inventory Initiative. Partnering with non-profits, research and university institutions, corporations, and diverse government bodies, NREL collects and maintains lifecycle inventory databases and software to support domestic LCA practice. Although NREL has a few datasets for raw agricultural products, data on food products is nonexistent. There are some consulting firms that conduct LCAs for private industries, though these results are not always accessible to the public. Rarity of quantitative literature on the environmental impacts of the U.S. food production system requires researchers to "transplant" data and emissions factors from European sources, thereby limiting accuracy (Scholz 2008). The Innovation Center for U.S. Dairy has recently initiated several efforts to assess report and reduce the environmental impact of the U.S. dairy industry. It seems that non-governmental institutions are leading the way in producing quantitative LCA information on food products. Academic, research, and not-for-profit institutions in the U.S. should continue to increase use of LCAs to assess environmental impact of food products and further unite and evolve the methodology.

Figure 5: Geographic Distribution of Reviewed LCAs of Milk



Appendix D Sources

Basset-Mens C, Kelliher FM, Ledgard S, Cox N. 2009. Uncertainty of global warming potential for milk production on a New Zealand farm and its implications for decision making. Int J LCA 14:630-638

Baumann H, Tillman AM (2004) The Hitchhiker's Guide to LCA. Studentlitteratur AB. 544 pp.

Berlin J, Sonesson U, Tillman A. 2005. A life cycle based method to minimize environmental impact of dairy production through product sequencing. J Cleaner Prod 15: 347-356.

Berlin J, Sonesson U, Tillman M. 2008. *Product Chain Actors' Potential for Greening the Product Life Cycle: The Case of the Swedish Post-farm Milk Chain. J Industrial Ecology 12: 95-110.*

Berlin J, Sonesson U. 2006. *Minimising environmental impact by sequencing cultured dairy products: two case studies. J Cleaner Prod 16: 483-498.*

Blonk H, LaFleur M, Van Zeijts. 1997. *Towards an environmental information infrastructure for the Dutch Food Industry: exploring the environmental information conversion of five food commodities, Appendix 3: screening LCA on milkpowder. Amsterdam,The Netherlands: IVAM Environmental Research and Centre for Agriculture and Environment.*

Casey JW, Holden NM. 2005. *Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86: 97-114.*

Castanheira EG, Dias AC, Arroja L, Amaro R. 2010. *The environmental performance of milk production on a typical Portuguese dairy farm. Agricultural Systems 103: 498-507.*

Cederberg C, Mattson B. 2000. *Life Cycle Assessment of milk production- a comparison of conventional and organic farming. J Cleaner Prod 8: 49-60.*

Cederberg C, Stadig M. 2003. *System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production. LCA Case Studies. Int J LCA 8: 350-356.*

de Boer IJM. 2003. *Environmental Impact Assessment of conventional and organic milk production- a review. Livestock Production Science 80: 69-77.*

Feitz AJ, Lundie S, Dennien G, Morain M, Jones M. 2007. *Generation of an industry-specific physico-chemical allocation matrix: application in the dairy industry and implications for systems analysis. Int J LCA 12: 109-117.*

Food and Agriculture Organization of the United Nations (FAO). 2010. *Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. FAO Animal Production and Health Division, International Dairy Federation (IDF). 98 pp.*

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

Greenhalgh, T., & Peacock, R. (2005). *Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources. British Medical Journal, 331(7524). 1064.*

Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R.

van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

Haas G, Wetterich F, Kopke U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agricultural Ecosystems and Environment 83: 43-53

Hogaas Eide M, Ohlsson T. 1998. A Comparison of Two Different Approaches to Inventory Analysis of Dairies. Int J LCA 3: 209-215.

Hogaas Eide M. 2002. Life Cycle Assessment of Industrial Milk Production. Int J LCA 7: 115-126.

Horne R, Grant T, Verghese K. Lifecycle Assessment: Principles, Practice, and Prospects.

Hospido A, Moreira MT, Feijoo G. 2003. Simplified life cycle assessment of Galician milk production. Int Dairy J 13: 783-796.

Houghton, J.T. (1997). IPCC guidelines for national greenhouse gas inventories. Bracknell, UK, IPCC WGI Technical Support Unit.

International Organization for Standardization (ISO). 2006. Environmental management: life cycle assessment; principles and framework (2nd Ed.). Geneva, Switzerland: ISO.

Lindfors LG, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen OJ, Ronning A, Ekvall T, Finnveden G. 1995. Nordic guidelines on life-cycle assessment. Nord 1995:20. Copenhagen, Nordic Council of Ministers.

Lundholm MP, Sundstrom G. 1985. Tetra brik aseptic environmental profile: Resource and environmental impact of tetra brik aseptic carton and of refillable glass bottles. Malmo, Sweden: Tetra Pak. 173 pp.

Nilsson K et al. 2008. A sustainable dairy sector: global, regional and life cycle facts and figures on greenhouse gas emissions. No. 08.7798.48. Delft CE; Commissioned by US Dairy Center.

Scholz, AJ. 2008. Research assumptions, methodologies and analytical results for a low-carbon diet calculator for public education. Bon Appetit Management Company; Ecotrust.

Sevenster M, de Jong F. 2008. A Sustainable Dairy Sector: global, regional and life cycle facts and figures on greenhouse-gas emissions. CE Delft, Delft, the Netherlands.

Sonesson U, Berlin J. 2008. Minimizing environmental impact by sequencing cultured dairy products: two case studies. J Cleaner Prod 16: 483-498.

Thomassen MA, Dalgaard R, Heijungs R, de Boer I. 2008. Attributional and consequential LCA of milk production. Int J LCA 13: 339-349.

Thomassen MA, Van Calker KJ, Smits MCJ, Iepema GL, de Boer IJM. 2008. Life cycle assessment of milk production systems in the Netherlands. Agricultural Systems 96: 95-107.

University of Arkansas, Michigan Technological University. 2010. Fluid Milk Carbon Footprint Study: Executive Summary. Innovation Center for US Dairy. 11 pp.

Verge XPC, Dyer JA, Desjardins RL, Worth D. 2006. Greenhouse gas emissions from the Canadian dairy industry in 2001. Agricultural Systems 94: 683-693.

Williams, A.G., Sandars, D.L. & Audsley, E. 2007. Sustainability and environmental burdens of milk and beef production. In: Pullar, D and Lewin, L. British Cattle Conference, Weston, Shropshire, Holsworthy, Devon: British Cattle Breeders Club, 40-47.

REFERENCES

Aldred J. 2008. Keep your kettle in check. The Guardian: guardian.co.uk: Green Living Blog. Available here: http://www.guardian.co.uk/environment/green-living-blog [accessed 4.1.2011].

ArcGIS 10 Software. 2010. ESRI.

Bala A, Raugei M, Benveniste G, Gazulla C, Fullana-i-Palmer P. 2010. Simplified Tools for global warming potential evaluation: when "good enough" is best. Int J LCA 15:489-498.

Berlin J, Sonesson U, Tillman A. 2005. A life cycle based method to minimize environmental impact of dairy production through product sequencing. J Cleaner Prod 15: 347-356.

Berlin J, Sonesson U. 2006. Minimising environmental impact by sequencing cultured dairy products: two case studies. J Cleaner Prod 16: 483-498.

Blonk H, LaFleur M, Van Zeijts. 1997. Towards an environmental information infrastructure for the Dutch Food Industry: exploring the environmental information conversion of five food commodities, Appendix 3: screening LCA on milkpowder. Amsterdam, the Netherlands: IVAM Environmental Research Centre for Agriculture and Environment.

Büsser S, Steiner R, Jungbluth N. 2008. LCA of Packed Food Products: the function of flexible packaging: coffee, spinach and butter, ESU-services Ltd. im Auftrag von Flexible Packaging Europe, Düsseldorf, DE and Uster, CH.

Canals, LC; Sim, S; Garcia-Suarez, T; Neuer, G; Herstein, K; Kerr, C; Rigarlsford, G; King, H. Estimating the Greenhouse Gas Footprint of Knorr. LCA for Food Products. IJLCA. 2010.

CarbonFund. 2011. Take Action Now - Offset Your Carbon Footprint: Custom Carbon Calculator. Available: http://www.carbonfund.org/Calculators/ [accessed 4.4.2011]

Carlsson-Kanyama A, Faist M. 2000. Energy Use in the Food Sector: a Data Survey. Swedish Environmental Protection Agency, AFR Report 291, Stockholm.

Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 7 Apr, 2011].

Casey JW, Holden NM. 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86: 97-114.

Cederberg C, Mattson B. 2000. Life Cycle Assessment of milk production- a comparison of conventional and organic farming. J Cleaner Prod 8: 49-60.

Cederberg C. Stadig M. 2003. System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production. LCA Case Studies. Int J LCA 8: 350-356.

Datamonitor. 2010. Market Volume by Category for 1999-2013 in Millions of Kilograms. Export from Interactive Consumer Database. [accessed 11.15.2010].

Dutilh CE, Kramer KL. 2000. Energy Consumption in the Food Chain. Ambio: 29(2). 98-101.

Euromonitor. 2010. Baby Food- USA. Sector Data: Baby Food Brand Shares 2005-2008. Retrieved 10.12.2011 from the Euromonitor Global Market Information Database.

European Commission- Joint Research Centre (EU JRC). 2010. Process data set: Polypropylene granulate (PP); production mix, at plant; Plastics Europe, 1999. LCA Tools, Services and Data. European Commission DG Joint Research Centre Institute for Environment and Sustainability.

Feitz AJ, Lundie S, Dennien G, Morain M, Jones M. 2007. Generation of an industry-specific physico-chemical allocation matrix: application in the dairy industry and implications for systems analysis. Int J LCA 12: 109-117.

Food and Agriculture Organization of the United Nations (FAO). 2009. Food and Agricultural Commodities Production. FAO Stat. Available: http://faostat.fao.org/site/339/default.aspx [accessed 3.5.2011].

Food and Agriculture Organization of the United Nations (FAO). 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. FAO Animal Production and Health Division, International Dairy Federation (IDF). 98 pp.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, R. Prinn, Raga G, Schulz M, Van Dorland R. 2007. Changes in Atmospheric Constituents and in Radiative Forcing, in *Climate Change 2007:The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

Franklin Associates. 2008. Peer Reviewed Final Report: LCI Summary for Eight Coffee Packaging Systems. Prepared for the Plastics Division of the American Chemistry Council. Franklin Associates; Eastern Research Group, INC. Prairie Village, Kansas. Available: http://www.americanchemistry.com/s_plastics/sec_content.asp?CID=1593&DID=8456 [accessed 2.10.2011].

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, Koning A, vanOers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, deBruijn H, vanDuin R, Huijbregts MAJ. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

Hinkle Charitable Foundation. Report 5: How do we individually contribute to global warming? Available: http://www.thehcf.org/emaila5.html [accessed 4.28.2011]

Hockerman E. News Release: Dairy Industry Sets Goal to Reduce Greenhouse Gas Emissions and Drive Innovation. April 14, 2009. Innovation Center for U.S. Dairy.

Hofstetter P. 1998. Perspectives in Life Cycle Impact Assessment. Kluwer Academic Publishers. 1-484.

Hogaas Eide M, Ohlsson T. 1998. A Comparison of Two Different Approaches to Inventory Analysis of Dairies. Int J LCA 3: 209-215.

Horne R, Grant T, Verghese K. Lifecycle Assessment: Principles, Practice, and Prospects.

Hospido A, Davis J, Berlin J, Sonesson U. 2010. LCA for Food Products: a review of methodological issues affecting LCA of novel food products. Int J LCA 15:44-52.

Innovation Center for US Dairy (IDF). 2011a. Dairy Farm Smart. Available: http://www.usdairy.com/Sustainability/GHGReduction/Projects/Pages/DairyFarmSmart.aspx [accessed 1.20.2011].

Innovation Center for US Dairy. 2011b. Cows of the Future. Available: http://www.usdairy.com/Sustainability/GHGReduction/Projects/Pages/CowoftheFuture.aspx\ [accessed 1.20.2011].

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

International Dairy Federation (IDF). 2009b. Environmental/Ecological Impact of the Dairy Sector. Bulletin of the International Dairy Federation, Brussels, Belgium.http://www.idf-lca-guide.org/Public/en/LCA+Guide/Introduction.

International Dairy Foods Association (IDFA). 2008a. Nutrition Listening Sessions Continue; IDFA Urges Members to Participate. Available: http://www.idfa.org/key-issues/category/nutrition--health/child-nutrition-act/details/2927/ [accessed 10.20.2010].

International Organization for Standardization (ISO). 2006. Environmental management: life cycle assessment; principles and framework (2^{nd} Ed.). Geneva, Switzerland: ISO.

Jacobson R. 1992. Calculating Milk Equivalents: Milkfat or Total solids Basis. Dairy Markets and Policy Issues and Options: P-2. Cornell University Program on Dairy Markets and Policy. 4pp.

Jones TW. 2006. Food Loss and the American household. Biocycle 47:28-38.

Kessler DA, Shahala DE. 1996. Infant Formula Act of 1980. FR Doc. 96-17058.

Liu E. 2008. Peoples Republic of China, Dairy and Products: Opportunity Knocks for High Value US Ingredients. USDA Foreign Agricultural Service, GAIN Report.

Lloyd BB. 2002. US Whey Products and Child Nutrition. Applications Monograph Child Nutrition. U.S. Dairy Export Council. Arlington, VA.

Mead Johnson Nutritionals (MJN). 2009. Grow with us: Mead Johnson Nutrition Annual Report 2009. 14 pp.

Miller FD. 1983. *Out of the mouths of babes: the infant formula controversy*. Bowling Green, Ohio: Social Philosophy & Policy Center.

Mintel International Group Limited. 2010. Baby Food and Drink: US.

Natural Resources Canada. 2008. Appendix B- CO2 Emissions Factors. Office of Energy Efficiency, Natural Resources Canada. Available: http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/csi/appendix-b.cfm?attr=0 [accessed 3.4.2011].

New additive brings infant formula closer to breast milk. 1995. Consumers' Research Magazine78: 7.

Nyhetsarkiv 2010. Merjeritekniskt Forum. Arla Foods Ingredients Begins Production of New Infant Nutrition Protein. Available: http://www.mejeritekniskforum.org/nyhetsarkiv_2010.htm [accessed 2.10.2011].

O'Connor NR. 2009. Infant Formula. *Am Fam Physician* 79: 565-570.

PBM Nutritionals. 2010. Virtual Tour (video). Available: http://www.pbmnutritionals.com/pbm-virtual-tour.aspx [accessed 12.10.2010].

Radford A. 1991. The ecological impact of bottle feeding. Baby Milk Action, UK.

Roos E, Sundberg C, Hansson PA. 2010. Uncertainties in the carbon footprint of food products: a case study on table potatoes. Int J LCA 15: 478-488.

Scientific Applications International Corporation (SAIC). 2006. Life Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, United States Environmental Protection Agency (U.S. EPA), Cincinnati, Ohio.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O. 2007. Agriculture. in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, UK and New York, NY, USA.

Sorensen H, Jorgensen E, Westergaard V. 1992. Production of powdered baby foods. Reprint from Scandinavian Dairy Information 4: 6pp.