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Green Cheese: LCA of Energy Intensity and GHG Emissions of Integrated Dairy/Bio-fuels Systems in Wisconsin

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Abstract. The objective of this study was to estimate the effects of dairy diets, manure-handling methods, and interactions with the bio-fuels industry on the net energy intensity, greenhouse gas (GHG)¹ emissions, and land use for milk production in Wisconsin. Five dairy diets supplemented with varying amounts of co-products from corn ethanol and soybean biodiesel production were modeled in two manure management scenarios: with and without on-farm biogas generation. The diets were characterized by different inclusion of soybean meal (SBM)² and dry distillers grains with solubles

¹ GHG emissions accounted for in this study were: CH₄, N₂O, NO_x, and CO₂.

² SBM is the residue left by soybeans after both oil extraction with solvents and oil extraction by mechanical expelling.

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(DDGS)³, balanced with different types forages. A partial life cycle assessment (LCA) of milk production from cradle to farm gate was performed. Milk production was used as the primary output for this analysis, since the dairy industry will remain the primary agricultural enterprise in Wisconsin for the foreseeable future. The boundaries of the milk production system were expanded to include bio-fuels production. The production of bio-fuels (corn ethanol and biodiesel) was scaled to meet the dietary requirements of each selected dairy ration. The choice of dairy ration had a substantial effect on GHG emissions and net energy intensity per energy corrected milk (ECM)⁴ produced. Land use for the integrated dairy and bio-fuels production systems ranged from 1.68 m²/kg ECM to 2.01 m²/kg ECM. Accounting for bio-fuels credits but without biogas generation, net energy intensity ranged from 0.83 MJ/kg ECM to 1.34 MJ/kg ECM, and GHG emissions ranged from 0.69 kg CO₂-eq⁵/kg ECM to 0.80 kg CO₂-eq/kg ECM, depending on the diet. The average effects of including anaerobic digesters for on-farm biogas generation were reductions in GHG emissions by 0.24 kg CO₂-eq/kg ECM, and in net energy intensity by 2.84 MJ/kg ECM.

Keywords. Milk production, environmental impact, carbon footprint, methane emission, life cycle assessment, system expansion, bio-energy

³ DDGS are the residue left by corn after drying, enzymatic treatment, and fermentation.

⁴ In this study, ECM was milk corrected for its energy content to a standard of 4.0% fat, 3.3% protein and 4.85% lactose, based on heat combustion of those components. It was calculated by dividing the energy for specific milk fat, protein, and lactose content by the energy value of milk with the standard fat, protein, and lactose content. The energy value of 1 kg of milk with 4.0% fat, 3.3% protein and 4.85% lactose is: $(0.0929 \times 4.00) + (0.0547 \times 3.30) + (0.0395 \times 4.85) = 0.7436$ Mcal.

⁵ CO₂-eq. = carbon dioxide equivalent.

Introduction

The energy crisis, oil prices, and climate change have positioned bio-energy development as one of the top priorities in many country's agendas. The sustainability of bio-energy feedstock supply depends on mutually beneficial integration with existing agricultural and forestry industries. There are a number of well known management practices that can reduce the undesirable environmental consequences of milk production including; optimizing dairy diets, wisely managing waste, adopting optimal cropping patterns and conservative field operations, and choosing energy efficient on-farm equipment and settings. Our work is focused on identifying synergies that reduce greenhouse gas (GHG) emissions, reduce the use of fossil fuels, reduce other environmental impacts, and improve profitability of integrated dairy and bio-fuels production systems.

A recent Life Cycle Assessment (LCA) by the Food and Agriculture Organization of the United Nations (FAO) estimated that GHG emissions from milk production at the farm gate range from 1.3 to 7.5 kg CO₂-eq per kg of fat and protein-corrected milk (FAO, 2010). An analysis by the International Dairy Federation (IDF) concluded that about 80% of the GHG emissions from producing dairy products originate from on-farm sources; mainly emissions from soils (crop production), from cows and from manure. The range of GHG emissions reported in the IDF study was from 0.40 to 1.81 kg CO₂-eq/kg milk while the energy intensity ranged from 1.31 to 6.57 MJ/kg milk (IDF, 2009). The average estimates from these studies are quite different. The variation within each study of about five to one from the lowest to highest estimate depends on the type of dairy production system and geographic region

There is general agreement about the major contributions to the total GHG emissions from dairy production with enteric methane produced during rumination and methane emissions from manure as the largest single contributor (about 52% of total emissions), nitrous oxide (between 27 and 38% of total emissions) emitted from soils producing dairy feeds. The third largest is carbon dioxide (between 10 and 21% of total emissions) emitted from manure and cows (FAO, 2010).

Significant research has been done aiming to reduce GHG emissions from the dairy sector. Several studies have evaluated adjustments in dairy diets compositions to optimize nutrient cycling (Arriaga et al., 2009; Brito and Broderick, 2006; Misselbrook et al., 2005; Powell et al., 2006; Powell et al., 2001; Reijs, 2007; Wattiaux and Karg, 2004a), or to reduce enteric methane emissions of cows (Giger-Reverdin et al., 2003; Johnson et al., 2007; Johnson and Johnson, 1995; Martin et al., 2008). Others have investigated reduction of methane volatilization from slurry manure through manure management practices (Monteny et al., 2006). These studies have shown that these methods of reducing GHG emissions can be very technically and economically challenging.

Wisconsin, ranking as the second largest state in dairy cows and milk production (USDA-NASS, 2010a), has identified a number of regionally specific best management conservation practices and technical standards. In 1997 the Wisconsin Department of Agriculture, Trade, and Consumer Protection (DATCP) published a compilation of conservation practices to address manure storage, nutrient management, and other environmental issues. More recently, *Wisconsin's Strategy for Reducing Global Warming* includes proposals to: increase the capture and use of animal methane for electricity or heat; reduce current methane emissions; reduce the application of nitrogen and the overall use of chemical fertilizers; the mandated adoption of nutrient management practices; and increase the availability and use of renewable biomass and bio-fuels for electricity, heat, and transportation (WI Global Warming Task Force, 2008).

The composition of the dairy diet plays an important role in GHG emissions, both directly (affecting enteric emissions from cows), indirectly by changing the quantities or types of crops grown, and synergistically by interacting with bio-fuels production. In Wisconsin, a valuable supplement for dairy cows is dry distillers grains with solubles (DDGS), a co-product from corn ethanol. Wisconsin has an installed capacity to produce of 1.9 billion liters of ethanol and more than 1 billion kg of dried distillers grains with solubles (DDGS) per year (Kaufman et al., 2010). Soybean meal (SBM), a co-product from soy oil production, is another common component in dairy diets. Estimates are that about 15% of the gasoline use in Wisconsin could be replaced by ethanol based on maximum allowable DDGS consumption by the state's 1.2 million dairy cows. Alternately with maximum allowable SBM consumption by the state's dairy herd, biodiesel from soy oil could replace approximately 6% of the petroleum diesel (Hermans et al., 2006). According to Sinistore (2008), replacement of SBM for DDGS, which don't need transportation from out-of-state crushing facilities, could save even more GHG emissions and energy.

The use of manure as a fertilizer can displace synthetic fertilizers that require high fossil fuel energy inputs, however, Wisconsin regulations limit manure application according to crops requirements for phosphorus, which often creates the need to apply synthetic nitrogen fertilizers to supply feed crop demands. Dairy manure can also displace fossil fuels if it is processed in anaerobic digesters to generate biogas, which combustion can yield heat or electricity. The use of biogas from anaerobic digesters can reduce GHG emissions from fossil fuels that otherwise would have been used.

There have been numerous studies of the environmental impact of bio-fuels production with varying estimates of energy intensity and GHG emissions (Bremer et al., 2010; Farrell et al., 2006; Patzek, 2004-2006; Pimentel and Patzek, 2005). There have also been several studies that have resulted in varying estimates GHG emissions of milk production (Del Prado et al., 2010; Rotz et al., 2010). There are also a few LCA studies that have included system boundaries beyond dairy production to related systems (Baker and Babcock, 2008; Bremer et al., 2010; Hermans et al., 2006; Sinistore, 2008). Some of the variation in the estimates of the environmental impact of both bio-fuels and dairy production can be attributed to differences in system boundaries and allocation methods used for co-products. Co-products allocation strategies can have an enormous influence on the results of an LCA. The International Organization for Standardization recommends "expanding the product system [boundaries] to include additional functions related to the co-products" (ISO, 2006) as the most accurate method of dealing with co-products. This systems expansion method avoids arbitrary allocation decisions based on mass balance, energy content or economic value.

The objective of this study was to estimate the effects of nine different dairy diets and two manure management practices on energy intensity, GHG emissions, and land use of Wisconsin dairy production systems, considering synergies with corn ethanol, soy biodiesel, and biogas production. This study develops a LCA of milk production applying a system expansion approach to account for the interactions that exist between the dairy and bio-fuels sectors in the state of Wisconsin.

Methods

LCA framework

The functional unit of this study was chosen as one kg of energy corrected milk (ECM) to 4.0% fat and 3.3% protein produced by dairy cows. The boundaries of the system were: milk production "from cradle to farm gate" in Wisconsin. Included in the boundaries are: crops production for dairy feed, for corn ethanol, and for soy biodiesel production, off-farm production

of nutrient and energy inputs for crops, and the corn to ethanol and the soybean to biodiesel conversion process (Figure 1). The time frame of the analysis was one year. This was a midpoint category assessment, which impact categories, indicators, and characterization factors of this study are shown in Table 1.

Table 1. Impact categories, indicators and characterization factors of the LCA.

Impact Categories	Inventory Parameters / Indicators	Characterization factors (a)	Unit
Resources	Energy use		MJ
	Land use		m ²
Climate Change & Global Warming Potential (GWP)	Carbon dioxide (CO ₂)	1	kg CO ₂ -eq
	Nitrous oxide (N ₂ O)	298	kg CO ₂ -eq
	Methane (CH ₄)	25	kg CO ₂ -eq

(a) Characterization factors of GWP for 100 years time horizon (Forster et al., 2007)

Life cycle inventory data were obtained from literature, our own calculations using the Green Cheese model (described below), and databases accessed through GaBi 4 Professional© (PE International GmbH and LBP-Univ.Stuttgart., 1989) platform: US-LCI (NREL), Professional, Extension XII-Renewable Materials, Ecoinvent 2.0 US.

GaBi 4 Professional© is a tool to create life cycle balances in modular units formed by plans, processes and flows. Existing GaBi plans utilized were: nitrogen fertilizer, phosphorus fertilizer, diesel, gasoline, natural gas, liquefied petroleum gas (LPG), and cotton production, all from the US-LCI database (NREL). A process and its respective plan for electricity generation were created in GaBi based on Wisconsin net electricity generation in January, 2010 (EIA, 2010) (Table 26). The impact assessment method used for calculating CO₂-eq emissions in GaBi processes was the *CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) (updated 03/01/2008)* (CML, 2001), accessed from PE-GaBi 2006.

The Green Cheese model

The Green Cheese model is a system expansion LCA of integrated dairy and bio-fuels production systems. The process modules of the Green Cheese model used in this study were: (1) milk production: including, dairy herd structure and animal nutrition; (2) manure handling and storage: including biogas generation; (3) crop production for dairy feeds and ethanol and biodiesel feedstock production; and (4) corn/ethanol and soybean/biodiesel conversion.

The decision tree for the model begins with a presumed volume of milk production, either from a specific dairy herd, or from a group of herds in Wisconsin using similar management practices. The user defines the management practices, including the characteristics of the herd, the components of the diet fed to cows, and manure management practices. This information is used to calculate the crops that need to be grown to supply this ration and the manure volume produced by the herd. The dietary requirements are used to calculate the inputs and outputs for crop production. The crop production model prioritizes the use of dairy manure and calculates the additional purchased fertilizers required to obtain typical crop yields in Wisconsin. In scenarios that used DDGS or SBM as a feed component, the model calculates the volume of corn grain and soy that would be grown and converted to ethanol or biodiesel to supply these

co-products. Bio-fuels production module calculates the inputs and outputs for the volume of fuel production corresponding to the specified volume of co-product. Nutrients (nitrogen (N), phosphorus (P), potassium (K), and carbon (C)), GHG, and energy flows are estimated within each module and are interconnected throughout the model.

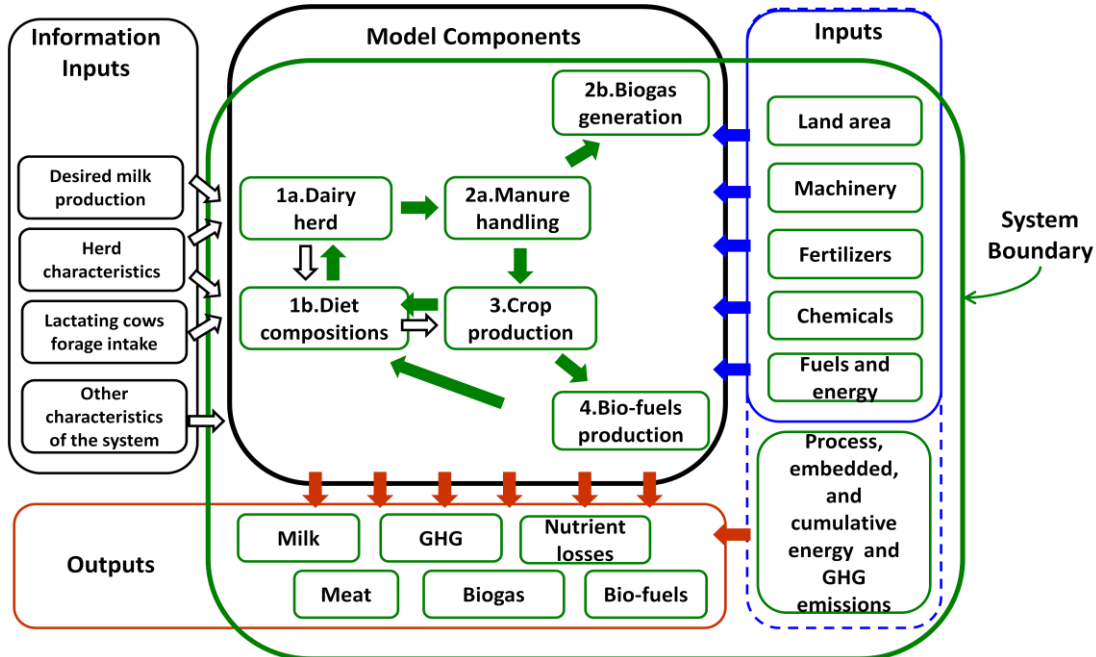


Figure 1. Green Cheese Model Components and Boundaries.

It was assumed that the CO₂ originated from C content in plants was emitted through plant decomposition, animal digestion and respiration, and manure, and was re-captured by plants within the time frame of the LCA. In other words, CO₂ released during waste processing of the agricultural product was assumed to be canceled out by CO₂ fixed in biomass. The CH₄ originated from C content in plants was accounted as “new” GHG (Guinée et al., 2009). For this analysis we assumed a “steady state” condition in which there was no change in the carbon content of soils as it might occur if there was a change in crop management practices.

The results of five different dairy diets characterized by different inclusion of SBM and DDGS and different forages, and two manure management practices (with and without anaerobic digesters) were selected for this analysis.

Green Cheese Module 1: Milk production, dairy herd structure and nutrition

In this module, we calculated:

- The herd structure to produce the desired amount of milk,
- Energy consumption in housing and milking operations,
- Dairy diet composition,
- GHGs released by the animals,
- Nutrient flows from feed to milk and manure, and
- Co-product meat yields from culled cows.

Dairy herd structure, milk production, and energy for housing and milking

Using input values listed in Table 2, the number of lactating cows that would be needed to produce the assumed amounts of milk, and the herd composition necessary to support those amounts were determined. We assumed that all heifers needed to maintain the herd size were raised as replacements on the farm.

Table 2. Inputs for milk production and dairy herd structure.

<i>Inputs</i>	<i>Values used in this study</i>
Desired milk production	10,000 kg/day
Milk protein	3.0%
Milk fat	3.5%
Milk lactose	4.85%
Body weight of non-pregnant adult dairy cows	650 kg
Daily milk production per cow	35 kg
Dry period	62 days (AgSource, 2009)
Calving interval	14 months (AgSource, 2009)
Annual adult replacement rate ⁶	35.8% (AgSource, 2009)
Annual mortality rate for weaned heifers	1.8% (USDA, 2007)
Annual mortality rate for unweaned heifers	7.8% (USDA, 2007)
Abortions	Neglected
New born female:male ratio	0.467 (Del Rio et al., 2007)
Milk intake by calves up to 30 days old	4 kg milk per calf per day
Electricity for housing and milking ⁷	0.062 MJ/kg milk (ECW, 2005)

Input values of milk characteristics were used to calculate the functional unit of this LCA, calculated as:

$$\text{ECM (kg)} = \text{kg milk} \times ((0.0929 \times \text{milk fat \%}) + (0.0547 \times \text{milk protein \%}) + (0.0395 \times \text{milk lactose\%})) / 0.7436 \quad [\text{equation 2-15 from the NRC (2001)}] \quad [1]$$

Starting from the 10,000 kg of milk produced with the composition and herd characteristics listed in Table 2, discounting milk fed to calves (35.5 kg), and correcting to fat, protein and lactose contents, the final ECM delivered at the farm gate was calculated as 9,122 kg:

$$\text{ECM (kg)} = (10,000 - 35.5) \times ((0.0929 \times 3.5) + (0.0547 \times 3.0) + (0.0395 \times 4.85)) / 0.7436 = 9,122$$

⁶ Includes mortality and culling.

⁷ Includes energy for space heating, ventilation, lighting, milking, milk cooling, and water heating.

Dairy diets

Young stock and non-pregnant non-lactating animals

Diets for young stock and non-lactating animals were formulated to supply maintenance and growth requirements. It was assumed that the animals achieved their mature weight at 21 months old. The additional gestational nutritional requirements for pregnancy were calculated separately. For nutrition purposes, non-lactating animals were divided into three categories: heifers from 1 to 11 months old; heifers from 12 to 21 months old; and heifers older than 21 months old and dry cows. Diets for each category of non-lactating animals were formulated following the Nutrient Requirements for Dairy Cattle (NRC) (NRC, 2001) in order to meet the energy and protein requirements for maintenance and growth. Dry matter intake (DMI) was predicted on the basis of NRC (2001) equations. The dairy diets were representative of good management practices in Wisconsin⁸. The characteristics of the diets for young stock and non-lactating cows are given in Table 3.

The diets of growing heifers between 1 and 21 months old were formulated in two parts: one for heifers from 1 to 11 months old (based on an average diet for heifers at 6 months of age), and one for heifers from 12 to 21 months old (based on an average diet for heifers at 16 months old). We assumed that all animals were fed both harvested alfalfa silage (mature) and harvested corn silage, in different proportions according to their categories. Growing heifers from 1 to 11 months old were also supplemented with concentrate, while animals older than 11 months old did not receive any concentrate.

For growing heifers from 1 to 21 months old, we calculated: the size-scaled shrunk body weight, the maintenance and net growth energy and protein requirement, the retained energy (RE), and DMI requirement for both maintenance and weight gain. We assumed that calves up to 1 month old would not receive solid feed (therefore they were not accounted for in feed consumption).

Table 3. Young stock and non-lactating animals diet composition and dry matter intake.

Diet / Animal Category	Heifers from 1 to 11 months old	Heifers from 12 to 21 months old	Heifers older than 21 months and Dry cows
	kg dry matter/animal/day		
Dry matter intake	4.97	12.0	7.25
Feed ingredients	% of dry matter intake		
Alfalfa silage (mature)	39.8	55.0	55.0
Corn silage	35.0	45.0	45.0
Corn grain (ground, dry)	9.2	-	-
Soybean meal	5.6	-	-
Dry distillers grains with solubles	10.4	-	-

Lactating animals

Diets for lactating animals were formulated to meet cows' energy, rumen undegradable protein (RUP) and rumen degradable protein (RDP) requirements for both maintenance and milk

⁸ Louis Armentano, personal communication.

production according to NRC (2001) recommendations and feed composition library. The additional gestational nutritional requirements for pregnancy were calculated separately.

Feed used in the diets were alfalfa and corn silage, corn grain, SBM and DDGS. Five different diets were formulated to feed lactating cows yielding the same amounts of milk. The diets used in this analysis included:

- One diet with equal amounts of corn silage and alfalfa silage (in a dry matter basis), and equal amounts of DDGS and SBM (in a dry matter basis) (Diet CADS);
- Two diets with more corn silage than alfalfa silage dry matter content: one maximizing DDGS (Diet CSDG), and one maximizing SBM (Diet CSSB); and
- Two diets with more alfalfa silage than corn silage dry matter content: one maximizing DDGS (Diet ASDG), and one maximizing SBM (Diet ASSB).

Details of these diets are shown in Table 4; more details are shown in Table 16 in the appendix⁹.

In order to formulate the diets, we estimated the DMI, total digestible nutrients at a maintenance level of intake (TDN_{1x}), total digestible nutrients at a production level of intake (TDN_p), digestible energy (DE), metabolizable energy (ME), net energy for lactation (NE_L), rumen undegradable protein (RUP), and rumen degradable protein (RDP) required for the maintenance and milk production of lactating cows. Using information provided by the user about the DMI of each ingredient of the “forage portion of the diet, we calculated the DMI, TDN_p, DE, ME, and NE_L in this (“forage portion of the diet”). Based on nutrient composition of the feeds regarding the crude protein (CP), RUP and RDP values of each ingredient of the diet (NRC (2001) Table 15-2b), we calculated the amount of these components present in the “forage portion of the diet”. Then we calculated the estimated TDN_p, and DE, ME, NE_L, and DMI to be supplied by the concentrate blend formulated to meet either the RUP or RDP requirement, whichever required more protein. A target of 17% of CP in the final diet for lactating cows was used to predict the amounts of DMI, CP, RUP, and RDP required, and the amounts and percentages of CP, RUP, and RDP needed in the concentrate. Next, we calculated how much CP, RUP, and RDP was present in the protein blend supplied by the SBM and DDGS fraction, and the relationship between RUP and the required CP, the ratio RUP:DM, RDP, CP, and the amount of corn needed in the concentrate to be fulfilled by corn grain.

Table 4. Selected diets for lactating animals.

DIETS	CADS	CSDG	CSSB	ASDG	ASSB
% of dry matter intake from corn silage	29	36	36	22	22
% of dry matter intake from alfalfa silage	29	22	22	36	36
Feed Ingredients	kg dry matter intake/lactating cow/day				
Alfalfa silage (immature)¹⁰	6.5	5.0	5.0	8.0	8.0
Corn silage¹¹	6.5	8.0	8.0	5.0	5.0
Cottonseed (whole)	2.0	2.0	2.0	2.0	2.0

⁹ Tables 20 through 30 are in the Appendix section.

¹⁰ For alfalfa silage, it was assumed: 23.2% CP and 36.7% NDF, on a dry matter basis.

¹¹ For corn silage, it was assumed: 8.8% CP and 45% NDF, on a dry matter basis.

Corn grain (ground, dry)	6.1	3.0	5.6	6.1	6.6
SBM¹²	0.6	-	1.5	-	0.8
DDGS¹³	0.6	4.1	-	1.3	-
Total	22.2	22.1	22.1	22.4	22.3

Diet CSDG had 18.7% DDGS of DMI, which is not typical of Wisconsin dairy diets, but was assumed as a possible scenario near the upper limit of DDGS fraction in a dairy diet.

Pregnancies

The energy required to support pregnancies was calculated separately, and the values are shown in Table 5.

Table 5. Dry matter intake and diet composition for pregnancies.

kg dry matter intake/pregnancy	
Dry matter intake	215.9
Feed ingredients	% of dry matter intake
Alfalfa silage (mature)	55.0
Corn silage	45.0

GHG emissions from the herd

Enteric methane emissions have been considered to be best estimated by dynamic mechanistic models (Bannink et al., 2006; Benchaar et al., 1998; Dijkstra et al., 2008; Ellis et al., 2008; Kebreab et al., 2008; Mills et al., 2003). The complexity of chemical and microbiological transformations accounted for in these models require highly detailed information about the diet compositions, feed digestibility, and the dynamics of the digestion process itself. Most farm level estimates of enteric emissions have been calculated using empirical approximations. Among several empirical regression equations in the literature, the equation from Moe and Tyrrell (1979) has been evaluated as one of the best predictors of methane emissions from dairy cattle in non-dynamic-mechanistic models (Ellis et al., 2010; Wilkerson et al., 1995). Other empirical methods are not sensitive to changes in diets composition because they are based on only body weight, milk yield or DMI, and therefore are not suitable for studying the effect of diet on emissions. The method used by Chianese et al. (2009) and Rotz et al. (2010), equation Mits3 from Mills et al. (2003), accounts for differences using starch content and digestibility of the dairy ration. However, Shaver (2008) concluded that more translational research on assays to assess the starch digestibility of corn silage is needed before these estimates can be used with confidence.

¹² For SBM, it was assumed: 53.8% CP and 9.8% NDF, on a dry matter basis.

¹³ For DDGS, it was assumed: 29.7% CP and 38.8% NDF, on a dry matter basis.

We used the method presented by Moe and Tyrrell (1979) for estimating enteric methane emissions (equation [A1]¹⁴). This empirical equation accounts for the chemical composition of the diet (nonstructural carbohydrate, hemicellulose and cellulose fractions) and was expected to be sensitive to the changes in diet composition we were interested in investigating.

Nutrient flows from feed to milk and manure

Nutrients intakes for each diet were calculated from feed compositions described in table 15-2b from the NRC (2001), and DMI. The calculation methods used for the outputs of N, P, and K in milk and manure are described in Table 6.

Table 6. Nutrients from dairy herd: nitrogen, phosphorus, potassium, and carbon in milk and manure.

Nutrient output	Calculation method
N, P, and K in milk	Equations [A2], [A3], and [A4]
N, P, and K in manure from the lactating herd	Difference between nutrients intakes and nutrients in milk
N, P, and K in manure from heifers from 1 to 21 months old	Equations [A5], [A6], and [A7]
N, P, and K in manure from heifers older than 21 months old and dry cows	Same as intake (assuming there was no accumulation in the animals' bodies)
P and K in manure related to pregnancies	Equations [A8] and [A9]
N in manure related to pregnancies	N intake minus the amount of N in the fetus; N in the fetus: 16% of CP in the fetus; CP in the fetus: Equation [A10]
Nutrients in manure from calves up to 30 days old	Neglected

Meat co-product

Meat from culled adult dairy cows that was suitable for human consumption was considered a co-product of milk production. The meat co-product was valued based on its nutritional (protein and fat) content. The mass of the meat and its characteristics are given in Table 7.

Table 6. Meat production and characteristics.

<i>Inputs</i>	<i>Values used in this study</i>
Culled animal meat for human consumption (% of adult animals per year)	19.3% (35.8% (total) - 5.6% (mortality) - 10.9% (injury/sick/other) = 19.3%) based on AgSource (2009)
Number of culled adult cows for human consumption	Number of lactating cows x culled animals proper for human consumption = (286*0.193/365=0.15)

¹⁴ Equations starting with the letter A are given in the appendix.

Boneless meat production	195 kg per culled adult cow (Cederberg and Stadig, 2003)
Meat protein	20.7% (Franco et al., 2009; Minchin et al., 2009)
Meat fat	6.5% (Franco et al., 2009; Minchin et al., 2009)

Green Cheese Module 2: Manure handling and biogas generation

In this module, we calculated:

- Volume and composition of manure and bedding,
- Energy consumption due to manure handling and corresponding GHG emissions,
- Biogas production and net energy generation,
- Gaseous emissions from manure in housing, treatment and storage,
- Avoided energy and GHG emissions due to displacement of natural gas production and combustion, and
- Remaining manure nutrient content.

The manure management options and the values used for the analysis presented in this study are given in Table 8. Two manure treatment options, with and without anaerobic digesters, were simulated to evaluate the impacts of manure management and biogas generation on GHG emissions and the net energy intensity of milk production.

Table 8. Manure handling inputs.

<i>Inputs</i>	<i>Values used in this study</i>
Housing type	Free-stall barn
Bedding material	Chopped straw, 90% dry matter
Exposed manure surface in housing	3.5 m ² / animal older than 21 months; 2.35 m ² / animal younger than 21 months (Rotz and Jouke, 2005)
% manure collection	100% manure collected from all herd
Manure collection method	Alley scraper
Dry matter of manure after collection	8% (slurry)
Manure storage facility	Lined ¹⁵ , uncovered manure pond loaded from the bottom, with crust formation on surface
Manure pond depth	4.5 m
Manure storage capacity (time period)	180 days
Manure transportation to crop field	240HP truck with 9,500 gallon tank
Broadcast cycle time	0.212 h, including travel and application
External temperature	Table 23

¹⁵ Manure pond lined with concrete or high-density polyethylene (HDPE).

Amount and composition of manure and bedding

The methods used to calculate manure volume and composition are given in Table 9.

Table 9. Manure excretion and bedding material to be handled.

Animal category	Calculation method		
	Gross manure production	Manure dry matter	Bedding (kg/animal/day) (a)
Lactating cows	Equation [A11] (b)	Equation [A15]	1.755
Heifers up to 21 months old	Equation [A12]	17% (ASAE, 2005)	0.892
Heifers older than 21 months old and dry cows	Equation [A13]	Equation [A16]	1.755
Pregnancies	Equation [A13]	Equation [A16]	-
Calves	Equation [A14]	4% (ASAE, 2005)	0.154

(a) assuming 2.7 kg of chopped straw per 1,000 kg animal weight (MWPS-7, 2000)

(b) The excretion of manure by the lactating cows could have been underestimated by the equation [A11], as reported by Aguerre et al. (2010).

Energy consumption for manure handling

To estimate the electricity and fuel consumptions in each stage of the manure handling operations, we used a survey conducted on 19 Wisconsin dairy farms (Sanford, 2009), and motion studies conducted in the Great Lakes Region (Hadrich et al., 2009; Harrigan, 2009) (equation [A17]). The values used in this study are shown in Table 10.

Table 10. Energy consumption in manure handling operations.

Manure Handling Operations	Method	Electricity (kWh/metric ton of manure)	Diesel (L/metric ton of manure)
Collection	Alley Scraper	0.454	-
Agitation	Pump	0.218	-
Transportation to Storage/Treatment	Pump	0.217	-
Treatment	Anaerobic digestion	0.0001	-
Application (including transportation)	Spread		0.432

Emissions from manure in housing, treatment and storage

Direct emissions from manure in housing, treatment and storage were calculated as shown in **Error! Reference source not found.**, and CO₂ emissions from fuel combustion during manure handling (including combustion of CH₄ from digested manure) were calculated as shown in Table 12 and Table 17. For scenarios with anaerobic digesters, it was assumed that all CH₄ from biogas was converted into CO₂ through combustion, and all CO₂ from biogas was

released. This CH₄ and CO₂ released from biogas reduced the total amount of volatile solids in manure, and therefore decreased CH₄ emissions from manure storage after digestion. The nutrients (N, P, K, and C) in manure leaving the storage were adjusted for losses through volatilization.

Biogas generation

The amount of biogas, its composition, and energy balance for anaerobic digestion were estimated using the values listed in Table 7. The energy content in the biogas produced was based on values presented in Table 17.

Table 7. Biogas production characteristics.

<i>Inputs</i>	<i>Values used in this study</i>
Biogas yield	0.268 m ³ /kg volatile solids (Berglund and Börjesson, 2006)
Volatile solids in manure	Values reported by the ASAE (2005)
Volatile solids in bedding	95.9% of total solids, for straw (Møller et al., 2004)
Biogas composition	65% CH ₄ and 35% CO ₂ (in volume)
Energy input/output ratio	28% (Berglund and Börjesson, 2006)

Anaerobic digestion of manure can reduce overall GHG emissions both by avoiding part of the direct CH₄ emissions (due to the conversion of CH₄ from manure volatile solids into CO₂) and by avoiding emissions from displaced fossil fuel combustion for either heat or power. In this study we assumed that the displaced fossil fuel would be natural gas because of its similarity to biogas, and because it can be used for either heat or (electric) power generation.

GHG credits for avoided natural gas production and combustion were calculated as the GHGs that would be emitted by the production and combustion of the amount of natural gas with the same energy content (MJ) as the biogas (Table 17 and Table 29).

Table 8. Emissions from manure.

Emissions from manure	Calculation method
CH ₄ from the barn	Equation [A18]
CH ₄ from storage	Equation [A19]
N ₂ O from the barn	3.3 x 10 ⁻⁶ kg N ₂ O per animal/day (Wheeler et al., 2008)
N ₂ O from storage	20.2 g N ₂ O/m ³ (Amon et al., 2006)
NO _x from storage	0.001 kg NO _x /kg N (De Vries et al., 2003)
N ₂ from storage	0.015 kg N ₂ /kg N (De Vries et al., 2003)
NH ₃ from the barn	NH ₃ -N = 5.2% of N intake (Harper et al., 2009)
NH ₃ from storage	NH ₃ -N = 2.4% of N intake (Harper et al., 2009)
N ₂ O indirect from NH ₃	0.01 kg N ₂ O-N/ kg NH ₃ -N (IPCC, 2006b)
N ₂ O indirect from NO _x	0.01 kg N ₂ O-N/ kg NO _x -N (IPCC, 2006b)

Green Cheese Module 3: Crop production for dairy feed, corn ethanol and soy biodiesel feedstock production

Values estimated in this module were:

- Land area, and nutrients required for crop production,
- Energy consumption for on-farm operations (manure and fertilizer application, field operations),
- Embedded energy in off-farm inputs (chemicals, electricity and fuels), and
- GHG emissions from on-farm and off-farm activities.

Land area and nutrients required for crop production

The land area for crop production to meet dairy feed requirements was calculated from yields based on Wisconsin averages and on Texas data for cotton, as given in Table 13. The area used to produce the DDGS of the ration included all the corn that would generate the DDGS. We did not account for extra feed that would have to be produced to compensate losses in harvesting, transportation, storage, or feeding processes.

The N, P, and K inputs for crops were calculated based on recommendations to meet crops demands (Table 18). Our assumed fertilization strategy was to apply nutrients to just meet crop requirements, an optimistic, but attainable management strategy. It was assumed that N from manure applied to soils was 50% available to plants (Beegle, 2008). Crops requirements not met with manure nutrients were supplied by purchased fertilizers in the form of N, P, and K.

Chemicals, energy, fuels, and machinery used by crops for on-farm field operations were calculated based on Wisconsin data (when available), USA averages, or Texas data (for cotton), as shown in Table 21.

Agricultural lime (expressed here as CaCO_3) requirements for crops were assumed to be the sum of: lime required to supply calcium (Ca) removal in harvested material, lime required to neutralize the potential acidification rate of the crop ($50 \text{ g CaCO}_3/\text{kmol H}^+$, (Avila et al., 2005)), and lime required to neutralize the potential acidity from nitrification and mineralization of N fertilizers ($2.45 \text{ kg of CaCO}_3/\text{kg N fertilizer}$ (Sinistore, 2008)), minus the lime displaced due to the potential alkalinity of the manure ($1.12 \text{ kg of CaCO}_3/\text{kg N manure}$ (Sinistore, 2008)). The Ca removal in harvested material and the potential acidification rate of crops are shown in Table 20.

Table 9. Crop yields.

<i>Inputs (crops)</i>	<i>Values used in this study (yields at 0% moisture)</i>
Alfalfa silage	7,865 kg/ha (USDA-NASS, 2009)
Corn silage	13,097 kg/ha (USDA-NASS, 2009)
Corn grain	7,591 kg/ha (USDA-NASS, 2009)
Soybeans	2,386 kg/ha (USDA-NASS, 2009)
Cottonseed ¹⁶	1,031 kg/ha (USDA-NASS, 2010b)

¹⁶ Assuming that the cottonseed was imported from Texas, which is “probably the largest supplier of cottonseed used by Wisconsin producers.” Al Schultz, VitaPlus. 2010. Personal communication.

Energy consumption of cropping systems

On-farm energy (fuels and electricity) used for crop production including manure and fertilizer application, was calculated using data presented in Table 17 and Table 21. Off-farm embodied energy to produce chemicals, electricity, and fuels was calculated based on data in Table 29.

Emissions from crops (on-farm) and indirect GHG emissions from inputs for crop production (off-farm)

The calculation strategy for emissions from on-farm activities for crops production is presented in Table 14. GHG emissions from fuels combustion during on-farm operations, including manure and fertilizers applications, were calculated using factors from the literature on fuels combustion, shown in Table 17. Indirect GHG emissions from off-farm activities related to crops production were calculated based on the GHG emissions associated with chemicals (fertilizers, lime, herbicides, and pesticides), electricity, and fuels production, as shown in Table 29.

Table 10. Emissions from crops (on-farm).

Emissions from crops (on-farm)	Calculation method
CH ₄ from manure applied	Equation [A20] (a)
N ₂ O from manure and N fertilizer applied	1% N of available N (IPCC, 2006a)
NH ₃ from N fertilizer applied	10% of applied N (IPCC, 2006a)
NO _x from manure and N fertilizer applied	0.035 kg NO _x /kg N (De Vries et al., 2003)
NH ₃ from manure applied	Equation [A21] (a)
N ₂ O indirect from NH ₃	0.01 kg N ₂ O-N/ kg NH ₃ -N (IPCC, 2006a)
N ₂ O indirect from NO _x	0.01 kg N ₂ O-N/ kg NO _x -N (IPCC, 2006a)
CO ₂ from lime applied	0.44 kg CO ₂ /kg CaCO ₃ (IPCC, 2006a)
CH ₄ emitted from silage	Not accounted for.

(a) assuming 8 days after application.

Green Cheese Module 4: Bio-fuels production

Bio-fuels were accounted for as co-products of the milk production system, which boundaries were expanded to include bio-fuels production.

In this module, we calculated:

- Bio-fuels production volume and energy content,
- Energy consumption and GHG emissions due to bio-refining processes,
- Energy consumption and GHG emissions due to drying the distillers grains, and
- Avoided GHG emissions due to the displacement of fossil fuels production and combustion.

Bio-fuels production and accounting

Bio-fuels production volumes were scaled to the amounts of DDGS and SBM used to feed the dairy herd, and were calculated based on the information shown in Table 25. The energy

content of bio-fuels was calculated based on factors listed in Table 17. The energy consumption and GHG emissions attributed to the bio-refining processes were calculated based on factors listed in Table 25.

We assumed that the production of ethanol and biodiesel would displace the production of gasoline and petro-diesel, respectively. The GHG that would otherwise have been emitted by the production and use of the displaced fuels (gasoline and petro-diesel) with the same energy content (in MJ) of the bio-fuels that were yielded were credited to the bio-fuels (corn ethanol and soybean diesel). The energy that would otherwise have been used in the production of the displaced fuels (gasoline and petro-diesel) with the same energy content (in MJ) of the bio-fuels that were yielded was credited to the bio-fuels (corn ethanol and soybean diesel). These were calculated based on values shown in Table 17 and Table 29). The resulting factors for crediting GHG emissions due to avoided fossil fuel production and combustion are shown in Table 11.

Table 11. Factors for crediting greenhouse gas (GHG) emissions due to avoided fossil fuel production and combustion.

	Biodiesel	Ethanol
Credited GHG emissions	kg CO ₂ -eq/kg bio-fuel	
Due to avoided fossil fuel production	0.44	0.32
Due to avoided fossil fuel combustion	2.67	1.71

Allocation of co-products

Meat co-product

In this study, meat was valued based on the nutritional content (protein and fat) in boneless meat produced compared to the nutritional value of milk produced during the same time period. Only meat that was suitable for human consumption was accounted for as a co-product.

The same logic of ECM was used to obtain “milk corrected meat” (MCM) by multiplying the amount of meat produced by the calorific value of protein and fat content in meat in comparison to the calorific value of protein and fat content in ECM, as presented in equation 2:

$$\text{MCM (kg)} = \frac{(\text{kg boneless meat per culled cow} \times \text{number of culled cows which meat was proper for human consumption}) \times ((0.0929 \times \text{meat fat \%}) + (0.0547 \times \text{meat protein \%}))}{((0.0929 \times 4.0) + (0.0547 \times 3.3))} \quad [2]$$

This MCM approach to value meat in comparison to milk resulted in 98.99% of the system inputs and outputs being attributed to milk, and 1.01% to meat, as calculated below:

$$\text{ECM (kg)} / (\text{ECM (kg)} + \text{MCM (kg)}) = 9,122 / (9,122 + 92.64) = 98.99\%$$

Results and Discussion

Land use, net energy intensity, and GHG emissions of selected milk production systems in Wisconsin were estimated. Results were compared within five scenarios using diets supplemented with differing amounts of DDGS and SBM and with two different manure management practices: with and without on-farm biogas generation.

The results for net energy intensity and GHG emissions were either aggregated in the following sectors: dairy herd, manure, crops (on-farm), crops (off-farm), on-farm energy use, and bio-fuels. The results regarding land use were aggregated for the whole system.

All results were calculated per kg of ECM to 4.0% fat and 3.3% protein, and applied a factor of 98.99% (i.e. 98.99% of the inputs and outputs were attributed to milk, and 1.01% to meat, according to the MCM allocation criteria utilized).

Land use

The average land area needed to support the five production systems ranged from 1.68 m²/kg ECM to 2.01 m²/kg ECM (Table 12) or a difference of 17% from the lowest to the greatest value. Note that our results include the production of enough corn and soybeans to generate the DDGS and SBM in the diets and the associated bio-fuels produced from the corn and soy. These results were close to the USA average 1.62 m²/kg ECM reported by (Capper et al., 2009). Within diets with same forage characteristics, land use was greater when DDGS were included than when they were not (Diet CSDG versus Diet CSSB, and Diet ASDG versus Diet ASSB). The increment occurred because land was used to produce corn for the ethanol industry, from which DDGS are co-products.

There was no excess manure for any of the scenarios, indicating that the land base used to grow the crops to supply these dairy rations was capable of sustainably absorbing all of the manure produced by the dairy herd. Fertilizers in the forms of N, P, and K in varying amounts were purchased to supply crop requirements not met with manure nutrients.

Table 12. Land area used to produce feed for milk production and feedstock for bio-fuels; and purchased fertilizers, for selected diets.

Diets	CADS	CSDG	CSSB	ASDG	ASSB
	m²/kg ECM				
Land area	1.70	2.01	1.71	1.74	1.68
Purchased Fertilizer	kg active ingredient/1,000kg ECM				
Nitrogen	3.76	8.96	2.91	4.66	3.09
Phosphorus	1.34	1.86	1.30	1.41	1.24
Potassium	4.95	6.23	4.41	5.59	4.90

Within diets with the same forage compositions, those with more DDGS than SBM had greater need for purchased N, because corn crop required additional N fertilizer, and soybeans did not.

Energy intensity

We defined net energy intensity as the net energy from activities related to milk and bio-fuel production, calculated as the difference between the energy inputs (required energy) and energy outputs (supplied energy), and discounting the avoided energy use, as shown in equation 3. Negative values indicate net positive energy output from the system accounting for the energy content of the bio-fuels produced or for the avoided energy to produce fossil fuels.

$$\text{Net energy intensity (MJ/kg ECM)} = [\text{Energy input (E}_i) - \text{Energy output (E}_o) - \text{Avoided energy (E}_A)] / \text{kg ECM} \quad [3], \text{ where:}$$

E_i (MJ) = energy inputs to the system, including on-farm and off-farm inputs for crops production and for bio-fuels production

E_o (MJ) = energy generated in form of bio-fuel or biogas

E_A (MJ) = avoided energy use due to displacement of other fuels production

The average net energy intensity of milk production without the inclusion of bio-fuels ranged from 1.53 (Diet CSSB) to 1.95 (Diet CSDG) MJ/kg ECM (Table 17 and Figure 3), which is within the 1.31 to 6.57 MJ/kg milk range reported by the International Dairy Federation (IDF, 2009). Note that our results take into account the energy needed to produce enough corn and soybeans to generate the DDGS and SBM in the diets.

Accounting for energy from bio-fuels production and for energy credits due to displacement of fossil fuels, the subtotal net energy intensity ranged from 0.83 (Diet CSDG) to 1.34 (Diet ASSB) MJ/kg ECM. In a scenario including a diet with high DDGS, such as in Diet CSDG, that meant a decrease of 1.26 MJ/kg ECM (or of 60% of the energy intensity of milk production).

On average, the production of biogas contributed to 2.57 MJ/kg ECM and avoided 0.28 MJ/kg ECM due to the displacement of natural gas. The overall net energy intensity of milk production, including bio-fuels and biogas credits, ranged from -2.00 (Diet CSDG) to -1.52 (Diet ASSB) MJ/kg ECM. The inclusion of biogas generation thus made all of the scenarios net energy producers.

Table 13. Net energy intensity of milk production for selected diets, by sector.

Diets	CADS	CSDG	CSSB	ASDG	ASSB
Sector	MJ/kg ECM				
Dairy herd	0.07	0.07	0.07	0.07	0.07
Manure handling	0.01	0.01	0.01	0.01	0.01
Feed crops (on-farm)	0.70	0.83	0.67	0.73	0.69
Feed crops (off-farm)	0.83	1.19	0.78	0.90	0.79
SUBTOTAL a	1.61	2.10	1.53	1.72	1.56
Bio-fuels production	0.86	4.48	0.36	1.56	0.27
Bio-fuels	(1.02)	(4.82)	(0.61)	(1.69)	(0.42)
SUBTOTAL b	1.45	1.75	1.29	1.59	1.42

Fossil fuels displacement	(0.20)	(0.92)	(0.12)	(0.32)	(0.08)
SUBTOTAL c	1.26	0.83	1.17	1.27	1.34
From biogas	(2.57)	(2.56)	(2.56)	(2.58)	(2.57)
Natural gas displacement	(0.28)	(0.28)	(0.28)	(0.28)	(0.28)
TOTAL	(1.59)	(2.00)	(1.67)	(1.59)	(1.52)

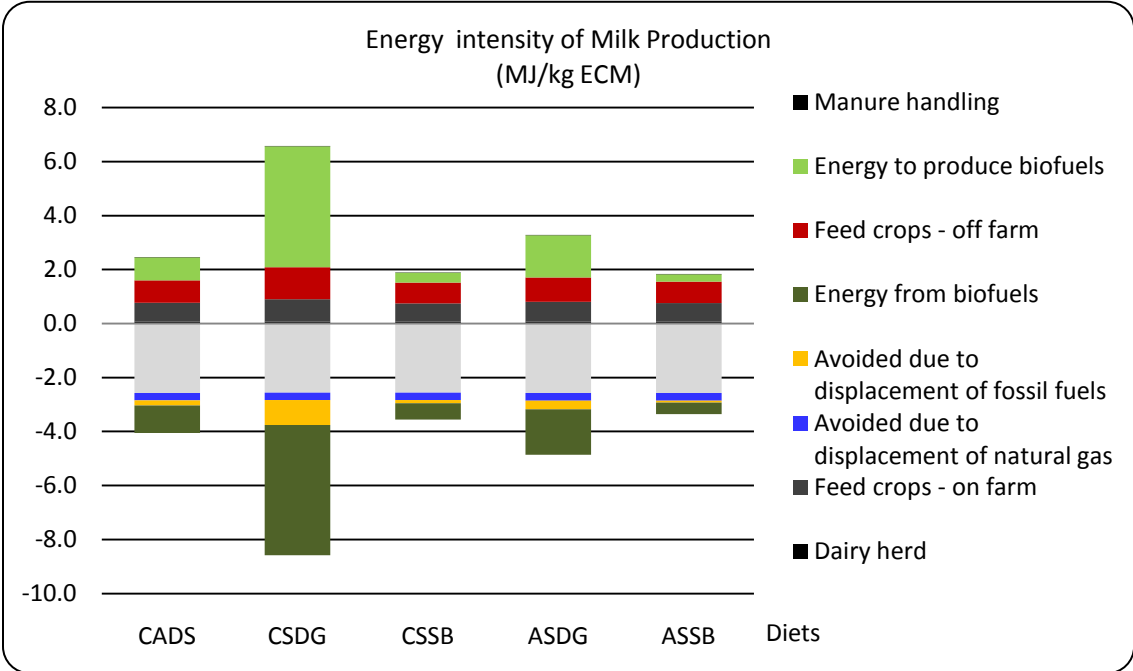


Figure 2. Net energy intensity of milk production for selected diets, by sector.

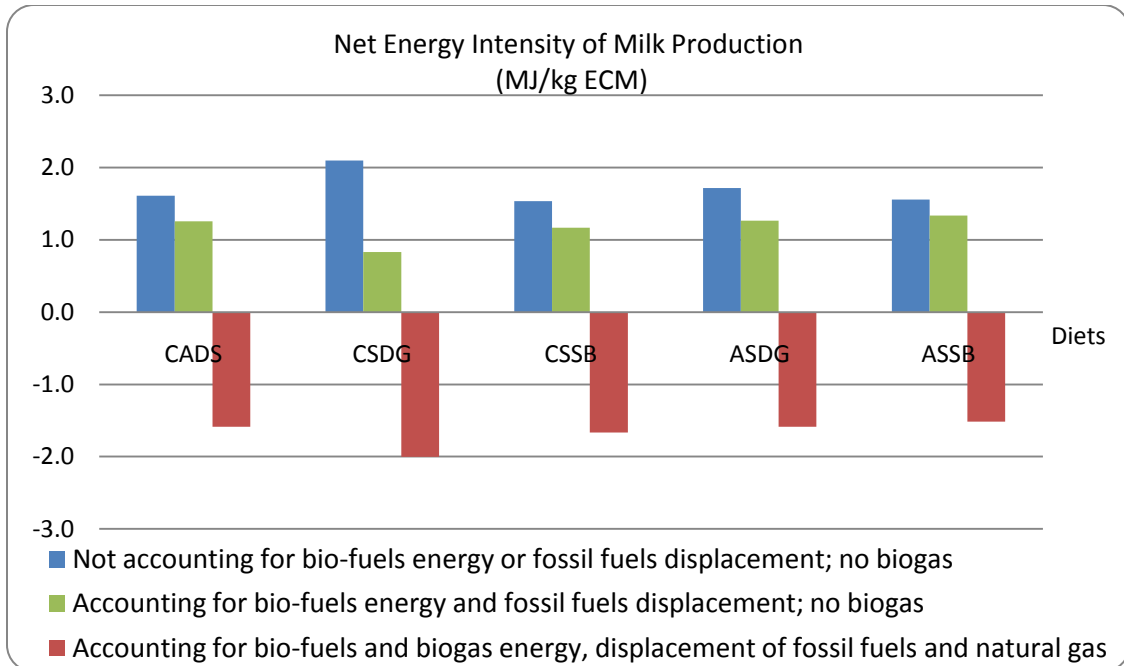


Figure 3. Net energy intensity of milk production for selected diets, according to distinct accounting criteria.

GHG Emissions

The largest single contributor to GHG emissions was enteric CH₄ (52% of total GHGs from milk production), ranging from 0.42 kg CO₂-eq/kg ECM (Diet ASSB) to 0.44 kg CO₂-eq/kg ECM (Diet CSDG), as shown in Figure 4. The difference between the scenarios was due to the difference in the diet compositions of the lactating herd.

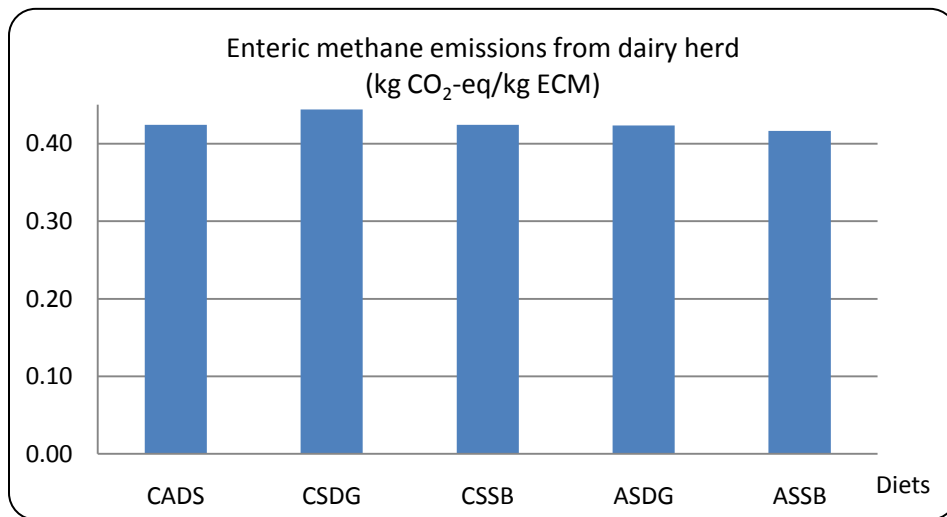


Figure 4. Enteric methane emissions from the dairy herd for selected diets.

A summary of the total GHG emissions from each scenario per sector is presented in Table 18. The average GHG emissions from milk production in the scenarios that did not include bio-fuels production ranged from 0.82 to 0.91 kg CO₂-eq/kg ECM. These numbers are higher than the highest figure reported by Rotz et al. (2010): 0.70 kg of CO₂-eq/kg ECM (to 3.5% fat and 3.1% protein concentrations), depending upon milk production level and the feeding and manure handling strategies used, and lower than the 1.35 kg of CO₂-eq/kg of milk reported by Capper et al. (2009). Each of these studies used different methodologies to compute GHG emissions. Note that our results account for the emissions related to the production of enough corn and soybeans to generate the DDGS and SBM in the diets.

The results were quite different when the system boundaries of the LCA were expanded to include bio-fuels production. Diets high in corn silage and DDGS had the lowest GHG emissions (Diet CSDG: 0.69 kg CO₂-eq/kg ECM), and diets with more alfalfa silage and no DDGS had the greatest emissions (Diet ASSB: 0.80 kg CO₂-eq/kg ECM). The average for all scenarios was 0.76 kg CO₂-eq/kg ECM accounting for bio-fuels, or 90% of the valued when bio-fuels production was not considered. The difference in GHG emissions was mainly due to the avoidance of fossil fuels production and combustion.

Table 14. Greenhouse gas (GHG) emissions from integrated milk and bio-fuels production for selected diets, by sector.

Diets	CADS	CSDG	CSSB	ASDG	ASSB
Sector	CO₂-eq/kg ECM				
Dairy herd	0.42	0.44	0.42	0.42	0.42
Manure	0.19	0.19	0.19	0.19	0.19
On-farm energy use	0.06	0.07	0.06	0.07	0.06
Feed crops (on-farm)	0.11	0.14	0.10	0.11	0.11
Feed crops (off-farm)	0.05	0.06	0.04	0.05	0.04
SUBTOTAL a	0.83	0.91	0.82	0.85	0.82
Bio-fuels	0.03	0.13	0.01	0.05	0.01
SUBTOTAL b	0.86	1.04	0.83	0.89	0.83
Fossil fuels displacement	(0.08)	(0.36)	(0.05)	(0.13)	(0.03)
TOTAL	0.78	0.69	0.78	0.77	0.80

Emissions related to biogas

The addition of anaerobic manure digestion resulted in total GHG emissions ranging from 0.45 (Diet CSDG) to 0.56 (Diet ASSB) kg CO₂-eq/kg ECM (Table 19 and Figure 5) or 71-75% of the value that accounted for liquid bio-fuels alone. The further reduction in emissions was due mainly to the avoided natural gas production and combustion (0.19 kg CO₂-eq/kg ECM), and secondarily to avoided CH₄ emissions from manure storage¹⁷ (0.05 kg CO₂-eq/kg ECM). The average effect of including anaerobic digesters for on-farm biogas generation reduced GHG

¹⁷ Production of CH₄ through anaerobic digestion decreased the amount of C left in manure, thus reduced CH₄ emissions from manure during storage post-digestion. It was assumed that the CO₂ emitted from the combustion of CH₄ in the biogas would have otherwise been emitted from the manure when it was exposed to the air.

emissions from milk production by 0.24 kg CO₂-eq/kg ECM, which was lower than the reduction of 0.32 kg CO₂-eq/kg ECM (to 3.5% fat and 3.1% protein) reported by Rotz et al. (2010).

Table 15. Greenhouse gas (GHG) emissions from integrated milk and bio-fuels production for selected diets including biogas generation, by sector.

Diets	CADS	CSDG	CSSB	ASDG	ASSB
Sector	CO₂-eq/kg ECM				
Dairy herd	0.42	0.44	0.42	0.42	0.42
Manure (with biogas)	0.14	0.14	0.14	0.14	0.14
On-farm energy use	0.06	0.07	0.06	0.07	0.06
Feed crops (on-farm)	0.11	0.14	0.10	0.11	0.11
Feed crops (off-farm)	0.05	0.06	0.04	0.05	0.04
SUBTOTAL a	0.78	0.86	0.77	0.79	0.77
Bio-fuels	0.03	0.13	0.01	0.05	0.01
SUBTOTAL b	0.80	0.99	0.78	0.84	0.78
Fossil fuels displacement	(0.08)	(0.36)	(0.05)	(0.13)	(0.03)
SUBTOTAL c	0.73	0.63	0.73	0.71	0.74
Natural gas displacement	(0.19)	(0.18)	(0.18)	(0.19)	(0.19)
TOTAL	0.54	0.45	0.55	0.53	0.56

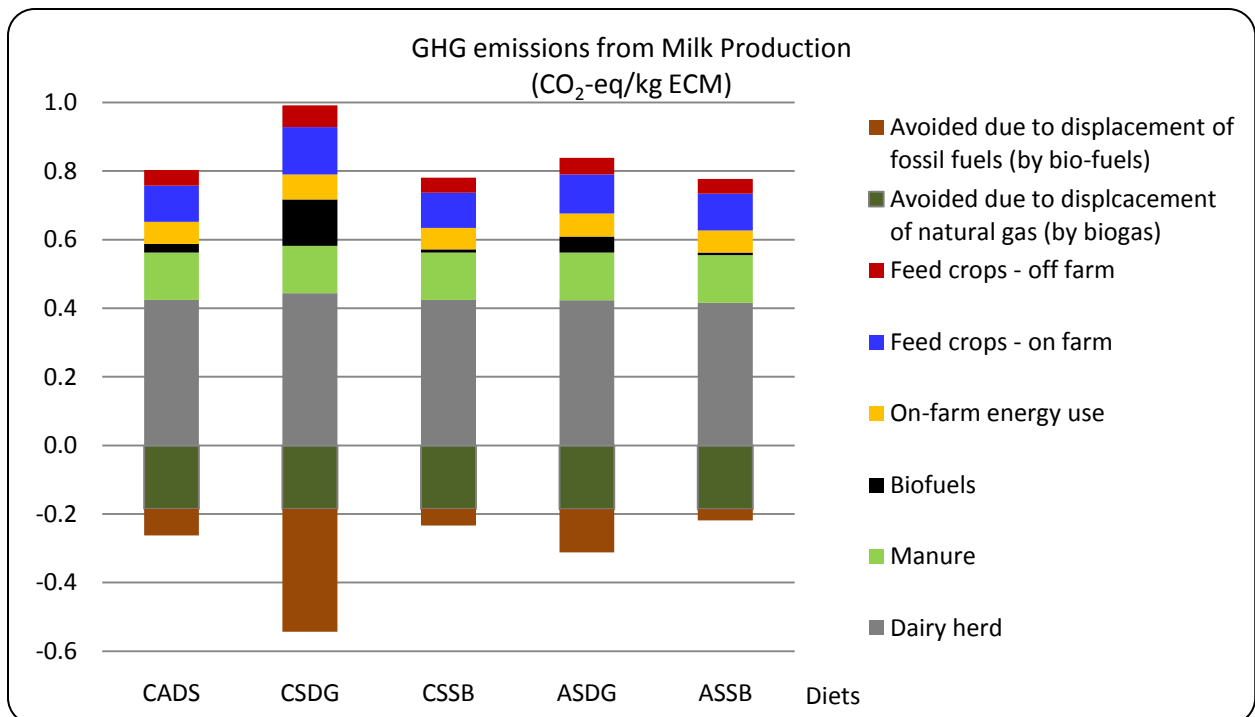


Figure 4. GHG emissions from milk production for selected diets, by sector.

The net GHG emissions for all scenarios are presented in Figure 6. When the system generated bio-fuels and biogas, less fossil fuels were used and overall GHG emissions were smaller. The least GHG emission resulted from scenarios that included DDGS in the diets and used anaerobic digesters. The reduction in overall GHG emissions resulted from the avoidance of fossil fuels production and combustion when the system generates bio-fuels and biogas.

The effect of the DDGS fraction in the diet can be assessed by comparing the first to the second bars for each scenario in Figure 6. Diets CSSB and ASSB had no DDGS in the lactating cows' ration. The effect of biogas generation can be assessed by comparing the second to the third bars for each scenario in Figure 6. Diets CSDG and ASDG were high in DDGS but showed large differences in overall GHG emissions. These differences highlight the influence that the forage fraction of the diets could have on the final results.

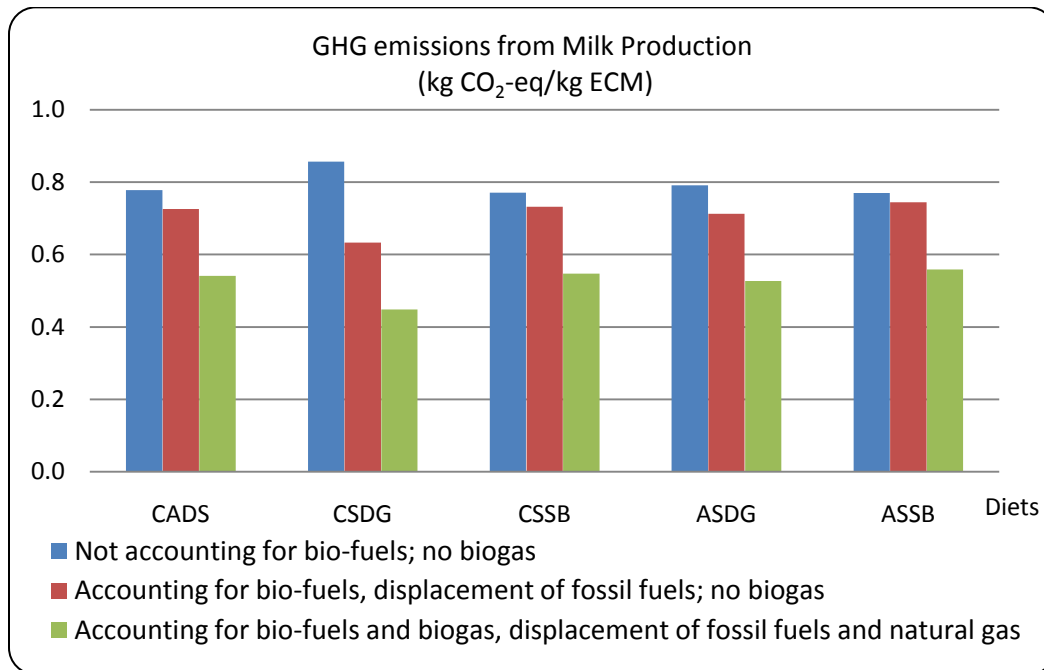


Figure 5. GHG emissions from milk production for selected diets, according to distinct accounting criteria.

Combined aspects

In Figures 7, 8, and 9, the results are presented in relation to scenario CADS, which results were reported as being 100%.

When evaluating the three aspects (land, GHG, and energy) combined, without accounting for bio-fuels, scenarios with more DDGS (Diets CSDG and ASDG) used more land, emitted more GHG, and had higher net energy intensity per kg of ECM when compared to other diets within the same group in terms of forage (Figure 7).

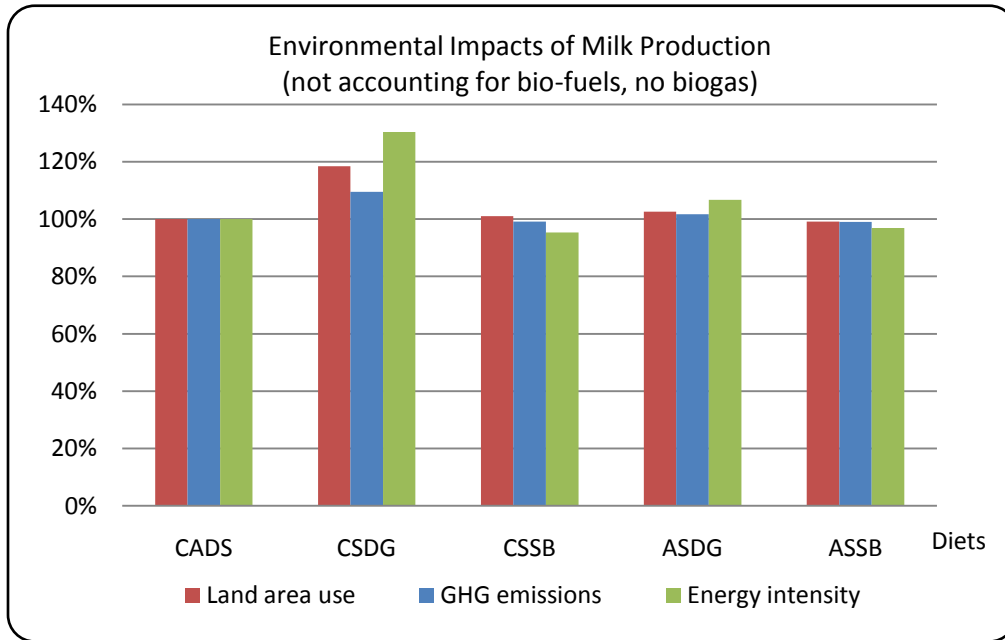


Figure 6. Land use, GHG emissions, and net energy intensity of milk production for selected diets, not accounting for bio-fuels. All values presented in relation to Diet CADS (100%).

However, when accounting for bio-fuels production and the correspondent displacement of fossil fuels, scenarios with more DDGS (Diets CSDG and ASDG) emitted less GHG and had lower net energy intensity per kg of ECM when compared to other diets within the same group in terms of forage (Diets CSSB and ASSB) (Figure 8).

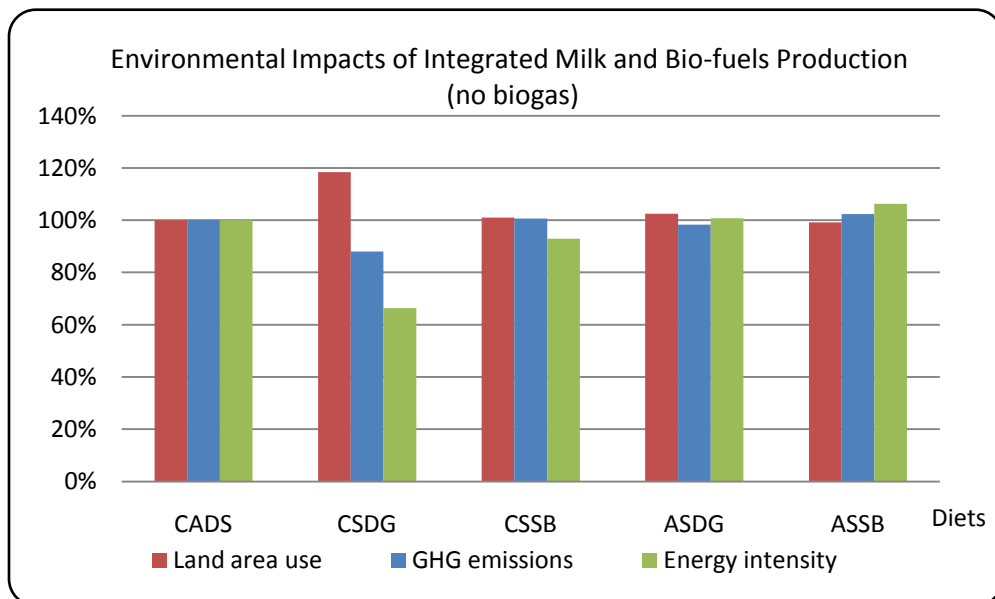


Figure 7. Land use, GHG emissions, and net energy intensity of milk production for selected diets, accounting for bio-fuels. All values presented in relation to Diet CADS (100%).

Finally, when anaerobic digestion for manure treatment was implemented, the effects of biogas generation on GHG emissions and especially on net energy intensity were highly positive (Figure 9).

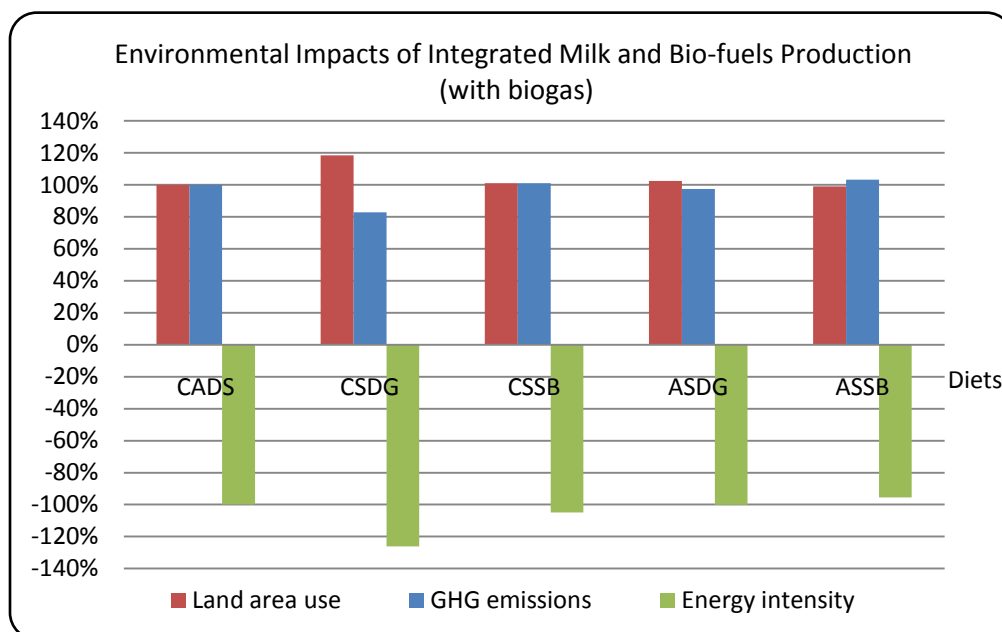


Figure 8. Land use, GHG emissions, and net energy intensity of milk production for selected diets, accounting for bio-fuels, and including biogas generation. All values presented in relation to Diet CADS (100%).

Discussion of results and methods comparison

The difference of 6.6% in enteric CH₄ emissions among the selected diets emphasizes the need for both the implementation of diets that might result in less CH₄ emissions, and the development of more accurate methods to estimate those emissions. Assessments of environmental impacts of milk production that do not account for diet compositions probably overlook this key factor in the system.

The energy related to equipment and buildings that were used for bio-fuels production was accounted for. We did not account for energy related to equipment or buildings used for milk production or the GHG emissions related to machinery that was used on field operations for cropping, as these have a small influence on the total life cycle of milk production.

We did not account for extra feed that would have to be produced to compensate for eventual losses in harvesting, transportation, storage, or feeding processes.

We did not account for the effects of anaerobic digestion of manure on NH₃ or N₂O volatilization after manure application to soils. We might have overestimated N₂O emissions (Chantigny et al., 2007) and NH₃ emissions from digested manure applied (Chantigny et al., 2009).

We assumed that the GHG emissions from ethanol and biodiesel combustion would offset the GHG uptake by the feedstock used to produce them. Data suggests that the combustion of

biodiesel from soybeans can increase NO_x emissions by up to 15% (EPA, 2002), which, according to our calculations, would mean that there would be a 4% decrease in the GHG credits attributed to each kg of biodiesel produced. Due to the uncertainty regarding NO_x emissions from biodiesel combustion, and the minor effect it had on this study (0.01 to 0.12% increase in total GHG emissions), the estimated 15% increase in NO_x emissions due to biodiesel combustion was disregarded.

We treated bio-fuels as co-products of the milk production systems. We assumed that ethanol, biodiesel, and biogas would displace the production and combustion of the fossil fuels: gasoline, petro-diesel, and natural gas, respectively. The biogas substitution fuel we chose was natural gas because it is the most similar primary fossil energy source. Most biogas is used to produce electricity at the point of production and our initial estimates were that in this use scenario the credits would be slightly smaller than those claimed for natural gas substitution.

We did not do a complete analysis of the fuels transport, delivery, and end-use conditions of each fuel. This implies that these parts of the fuel cycle would be comparable when transportation fuels are blended with fossil fuels. A more complete analysis would likely affect these estimates and this work is continuing.

The significance of biogas in GHG emissions and net energy intensity in this study reflected in reductions of 30-35% in CO₂-eq/kg ECM and 213-240% in MJ/kg ECM. Despite the existing incentives and the many potential benefits of anaerobic digesters, only 0.2% dairy farms in Wisconsin have implemented this technology. A major obstacle for on-farm generation of biogas is the high capital cost of implementing anaerobic digesters. Another weakness of using dairy manure as an energy source is its low energy potential (25-38 m³ of biogas per ton) in comparison to other feedstocks¹⁸. Co-digestion¹⁹ and the optimization of added-value co-products (both the liquid effluent and the dewatered digested solids) play a key role in the overall outcome of anaerobic digestion systems (Kramer, 2008).

Methodologies to assess GHG emissions and energy intensity differ not only in what items are accounted for (boundaries) and how (reference values, equations etc.), but also in how they refer to the product being assessed. An example is the fraction of the impacts allocated to milk: 91.7% and 92.2% based on economic value used by Rotz et al. (2010), 85% based on biological cause-effect (cited by Cederberg and Stadig (2003), or 98.9% based on energy and protein value of MCM in our study. Another example is the variation in the functional unit of milk production, which was one kg of ECM to 3.5% fat and 3.1% protein concentrations reported by Rotz et al. (2010), and one kg of ECM to 4.0% fat and 3.3% protein concentrations in FAO's study (FAO, 2010) and in ours. For comparison: one kg of ECM to 3.5% fat and 3.1% protein concentrations is equivalent to 0.92 kg of ECM to 4.0% fat and 3.3% protein. While the allocation factor is highly scenario-related, the functional unit should be standardized to allow comparisons among studies.

The system expansion method reduces ambiguities produced by allocation decisions at the level of feedstock production and produces a more robust estimate of the influence of integrated dairy/bio-fuels systems on GHG emissions. These results can provide a more accurate allocation estimate for studies that do not use the systems expansion approach. The system expansion method allows for a more accurate estimate of total GHG emissions and moves the discussion of the allocation of GHG credits between the dairy and bio-fuels industries to a higher level.

¹⁸ Source: <http://www.biogas-energy.com/site/BiogasEnergy.pdf>.

¹⁹ Biogas production may be significantly increased by the co-digestion of two or more types of feedstock, preferably with high biogas potential generation.

Conclusions

Five different diets were analyzed using the Green Cheese system expansion model to estimate and compare the environmental footprint of each diet, using two different manure management practices (with and without biogas generation). We analyzed the results when accounting for or not accounting for bio-fuels credits on avoiding fossil fuels production and combustion.

The minimum GHG emissions and net energy intensity per kg of ECM occurred in the system that maximized feeding of DDGS (and ethanol production) and used anaerobic digestion on the farm. This scenario also resulted in the largest required land area illustrating the tradeoffs that need to be considered. It is likely that the dairy industry will continue to dominate agricultural activities in Wisconsin for the foreseeable future. The emerging bio-fuels industry will need to be integrated into existing agricultural systems in Wisconsin and throughout the world. System models will help farmers and policy makers identify synergies between dairy production systems and renewable energy development.

This research is continuing to further improve the accuracy of our estimates, expand the boundaries of our system and explore the most appropriate methods for accounting and allocation.

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Appendix

Abbreviations

BW = body weight
Ca = calcium
CaCO₃ = lime
CO₂-eq. = carbon dioxide equivalent
CH₄ = methane
CP = crude protein
DDGS = dry distillers grains with solubles
DMI = dry matter intake
ECM = energy corrected milk
GHG = greenhouse gas
K = potassium
LCA = life cycle assessment
LCI = life cycle inventory
LPG = liquefied petroleum gas
MCM = milk corrected meat
N = nitrogen
N₂O = nitrous oxide
NO_x = nitric oxide and nitrogen oxide
P = phosphorus
RUP = rumen undegradable protein
RDP = rumen degradable protein
SBM = soybean meal

Equations

Emissions from the dairy herd

- [A1] CH₄ emissions due to enteric fermentation (Mcal) = 0.814 + 0.122 x soluble residue(kg) + 0.415 x hemicellulose (kg) + 0.633 x cellulose (kg) (Moe and Tyrrell, 1979)

Nutrients in milk

- [A2] N in milk (kg) = (milk protein / 6.38) + MUN (kg), where:
 - MUN (mg/dL) = 0.0148 x N intake (g/d) + 2.16 (Wattiaux and Karg, 2004b)
 - MUN (kg) = MUN (mg/dL) * 1,000,000
- [A3] P in milk (kg) = 0.9 x milk (kg) / 1000 (NRC, 2001)
- [A4] K in milk (kg) = 1.5 x milk (kg) / 1000 (NRC, 2001)

Nutrients in manure

From heifers from 1 to 21 months old:

- [A5] N in manure (kg) = ((DMI (kg) x dietary CP (g/g DM) x 78.39) + 51.4) / 1000 [equation 16 from Nennich et al. (2005)]
- [A6] P in manure (kg) = (DMI (kg) x dietary P (g/g DM) x 622.03) / 1000 [equation 21 from Nennich et al. (2005)]
- [A7] K in manure (kg) = K in urine + K in feces = (0.038 x BW (kg) / 1000) + (6.1 x DMI (kg) / 1000) (NRC, 2001)

From pregnancies:

- P and K contents in manure related to pregnancies were calculated as the difference between the intakes of those nutrients and their contents in the fetuses/calves, based on (House and Bell, 1993):
 - [A8] P in the fetus (kg): $0.01842 \times \text{EXP}((0.05454 - 0.00007 \times 280) \times 280)$
 - [A9] K in the fetus (kg): $-140.23 + (0.823 \times 280)$
- [A10] CP in the fetus (g): $(0.461 \times 280^2) - (138.8 \times 280) + 10,895$ (Bell et al., 1995)

Manure excretion

- [A11] Manure from lactating cows (kg) = $(\text{DMI (kg)} \times 2.63 + 9.4)$ [equation 2 from Nennich et al. (2005)]
- [A12] Manure from heifers up to 21 months old (kg) = $(\text{DMI (kg)} \times 4.158) - (\text{BW (kg)} \times 0.0246)$ [equation 14 from Nennich et al. (2005)]
- [A13] Manure from heifers older than 21 months old and dry cows (kg) = $((0.00711 \times \text{BW (kg)}) + (32.4 \times \text{CP intake (\%)}) + (25.9 \times \text{NDF intake (\%)}) + 8.05)$ (Wilkerson et al., 1997)
 - For pregnancies: $(32.4 \times \text{CP intake (\%)}) + (25.9 \times \text{NDF intake (\%)}) + 8.05$ [adapted from Wilkerson et al. (1997)]
- [A14] Manure from calves (kg) = $\text{calf body weight (kg)} \times 0.0811$ [equation 18 from Nennich et al. (2005)]

Manure dry matter

- [A15] Manure dry matter from lactating cows (kg) = $(\text{DMI (kg)} \times 0.356) + 0.8$ (Nennich et al., 2005)
- [A16] Manure dry matter from heifers older than 21 months old, dry cows, and pregnancies (kg) = $(\text{DMI (kg)} \times 0.178) + 2.733$ [equation 10 from ASAE (2005)]

Manure handling

- [A17] Diesel consumption (L) = $0.223 \times T \times \text{PTo}$ (ASAE, 2006), where:
 - PTo is the maximum power in kW/h
 - T is the total operation time of the tractor in hours

Emissions from manure and fertilizers

- [A18] CH₄ emissions from the barn area (kg CH₄): $\max(0.0, 0.13 \times T) \times \text{Abarn} / 1000$ [equation 10.48 from Rotz et al. (2009)], where:
 - T = temperature (°C)

Tables

Table 16. Characteristics of lactating cows' diets. Not including pregnancy requirements

Diets	CADS	CSDG	CSSB	ASDG	ASSB
% of dry matter intake					
CP	16.2	17.4	16.6	16.7	17.1
RUP	4.62	5.75	5.00	4.58	4.58
RDP	11.6	11.6	11.6	12.1	12.5
NDF	32.3	37.7	32.2	32.5	30.9
NSC or NFC	41.1	33.5	41.3	39.8	41.6
Ether extract	4.78	5.86	4.56	4.99	4.54
% of dietary crude protein					
From corn sources	36.5	57.6	33.5	37.6	27.7
kg dry matter intake/non-pregnant lactating cow/day					
Cellulose	4.04	4.50	4.01	4.10	3.95
Hemicellulose	2.23	2.85	2.28	2.19	2.00
NSC or NFC	9.14	7.42	9.13	8.90	9.29

CP = crude protein

RUP = rumen undegradable protein

RDP = rumen degradable protein

NDF= neutral detergent fiber

NSC = nonstructural carbohydrates; NFC = non fiber carbohydrates.

NSC or NFC = 1- (NDF+CP+Fat+Ash)

Table 17. Fuels densities and CO₂ emissions from combustion.

Fuels	kg	Liters	MJ	kg CO ₂ -eq emitted/L combusted
Methane	0.68	1,000	37.8	1.87 x 10 ⁻³
Gasoline	0.74	1	34.7	2.17 (b)
Liquefied petroleum gas	0.54	1	26.9	1.76 (b)
Natural Gas	0.88	1,000	38.2	2.45 x 10 ⁻³ (b)
Ethanol (from corn)	0.79	1	21.5 (a)	1.94
Biodiesel (from soybeans)	0.88	1	33.2 (a)	2.48
Petro-diesel	0.84	1	38.4	2.73 (b)

(a) assuming 5,130 kcal/L ethanol; and 9,000 kcal/kg biodiesel (Pimentel and Patzek, 2005)

(b) based on the US-LCI database (NREL)

Table 18. Nutrient inputs for crops.

Crops	Alfalfa silage	Corn silage	Corn grain	Soybeans	Cotton
Nutrients	kg/ton DM feed				
Nitrogen (N)	0	7.15 (b)	16.1 (b)	0	18.5 (c)
Phosphorus (P)	2.84 (a)	2.25 (a)	3.51 (a)	6.69 (a)	9.24 (d)
Potassium (K)	24.9 (a)	9.84 (a)	5.09 (a)	22.3 (a)	12.8 (e)

Sources:

(a) Laboski et al. (2006)

(b) USDA-NRCS (1992)

(c) TAES (2001)

(d) TAES (2006)

(e) TAES (2000)

Table 19. Potential acidification rate of crops.

Crops	Alfalfa	Corn for silage	Corn for grain	Soybeans
	kmol H ⁺ /ha			
Potential acidification rate (a)	14.5	4.5	0.8	3.3

(a) based on Avila et al. (2005)

Table 20. Lime requirements to supply calcium removal in harvested material and to neutralize the potential acidification rate of crops.

Crops	Alfalfa	Corn for silage	Corn for grain	Soybeans
Lime requirements				
to supply calcium removal in harvested material (g CaCO₃/kg DM) (a)	64	13	2	35
to neutralize the potential acidification rate of crop (g CaCO₃/ha) (b)	725	225	40	165

(a) based on Schulte et al. (2005)

(b) assuming 50 g of CaCO₃/kmol H⁺ (Avila et al., 2005)

Table 21. Inputs of chemicals, fuel and energy for on-farm field operations.

Chemicals and Energy inputs	per ton DM	Harvested alfalfa silage (immature)	Harvested alfalfa silage (mature)	Harvested corn silage	Corn grain	Soybeans	Cotton
Seed	kg	0.9 (a)	0.9 (a)	1.7 (a)	1.78 (d)	15.7 (e)	3.17 (h)
Herbicides	kg	0.42 (c)	0.42 (c)	n/a	0.32 (c)	0.35 (c)	0.55 (f)
Pesticides	kg	0.1 (a)	0.1 (a)	0.3 (a)	0.28 (d)	n/a	0.12 (f)
Lime	kg	(i)	(i)	(i)	(i)	(i)	0.006 (g)
Diesel	L	25 (a)	17 (a)	19 (a)	7.62 (d)	19.7 (c)	2.7 (h)
Gasoline	L	n/a	n/a	n/a	1.69 (d)	1.1 (c)	n/a
LPG	L	n/a	n/a	n/a	2.54 (d)	0.26 (c)	27 (h)
Electricity	kW h	n/a	n/a	n/a	4.52 (d)	0.32 (c)	34.7 (h)
Natural gas	m ³	n/a	n/a	n/a	1.71 (d)	n/a	0.0007 (h)
Machinery	kg	5.5 (a)	3 (a)	5.5 (a)	1.18 (d)	8.38 (b)	n/a

(a) alfalfa silage and corn silage, USA (Rotz et al., 2010)

(b) soybeans, USA (Pimentel and Patzek, 2005)

(c) alfalfa, corn and soybeans in WI (Kim and Dale, 2003)

(d) corn in WI (Kraatz et al., 2009)

(e) soybeans in WI (Pradhan et al., 2009)

(f) cotton in Texas (USDA-NASS, 2008)

(g) cotton, USA from US-LCI database (NREL) using GaBi platform

(h) cotton, USA (USDA-ERS, 2001)

(i) calculated based on

Table 19 and Table 20, and on amounts of manure and N fertilizer applied (see text)

Table 22. Wisconsin electricity matrix.

Resource	% share (a)
Coal	61.1%
Nuclear	20.3%
Natural gas	11.4%
Biomass	3.71%
Hydropower	2.05%
Wind	1.32%
Fuel oil	0.12%

(a) Based on EIA (2010)

Table 23. Average monthly temperatures in Wisconsin.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Temperature (°F) (a)	13.2	19.0	30.1	43.2	55.5	64.5	69.1	66.9	58.1	46.7	32.4	19.0

(a) Wisconsin 1971-2000 NCDC Normals (WSCO)

Table 24. Seed production and seeding frequency.

Crops	Alfalfa	Corn	Soybeans	Cotton
Energy to produce (MJ/kg seed) (a)	133	53.4	12.9	33
Years of crop yield per seeding event	3	1	1	1

(a) based on West and Marland (2002)

Table 29. Off-farm energy and greenhouse gas (GHG) emissions associated with chemicals and energy production.

	Energy to produce	GHG emissions due to production
Seeds (general)	See Table 28	0.3 g CO ₂ -eq/kg (e)
Nitrogen fertilizer (N)	41.2 MJ/kg (a)	1,968 g CO ₂ -eq/kg (a)
Phosphorus fertilizer (P)	6.38 MJ/kg (a)	394 g CO ₂ -eq/kg (a)
Potassium fertilizer (K)	7.50 MJ/kg (b)	533 g CO ₂ -eq/kg (b)
Herbicides	267 MJ/kg (f)	17,242 g CO ₂ -eq/kg (f)
Pesticides	287 MJ/kg (f)	18,534 g CO ₂ -eq/kg (b)
Agricultural lime	1.47 MJ/kg (b)	42.1 g CO ₂ -eq/kg (b)
Diesel	7.73 MJ/L (a)	11.7 g CO ₂ -eq/MJ (a)
Gasoline	6.59 MJ/L (a)	11.6 g CO ₂ -eq/MJ (a)
LPG	1.90 MJ/L (a)	8.12 g CO ₂ -eq/MJ (a)
Electricity	10.9 MJ/kWh (a, c)	207 g CO ₂ -eq/MJ (a)
Natural gas	4.12 MJ/m ³ (a)	7.01 g CO ₂ -eq/MJ (a)
Machinery manufacture	45.9 MJ/kg (d)	3,540 g CO ₂ -eq/kg (e)
Corn ethanol	21.6 MJ/kg (g) + 3.71 MJ/kg (h)	0.763 g CO ₂ -eq/kg (i)
Soy biodiesel	17.1 MJ/kg (j)	0.4 g CO ₂ -eq/kg (k)

(a) based on the US-LCI database (NREL) using GaBi platform

(b) Source: Kim and Dale (2003)

(c) based on Wisconsin electricity net generation in January, 2010 (EIA, 2010) shown in Table 22 and calculated using the US-LCI database (NREL) in GaBi platform

(d) Source: Patzek (2004-2006)

(e) Source: Rotz et al. (2010)

(f) Source: West and Marland (2002)

(g) assuming 4,075 kcal/L ethanol from corn (including energy related to: corn transport, water, stainless steel, steel, cement, steam, electricity, distillation from 95% ethanol to 99%, and sewage effluent), based on Pimentel and Patzek (2005)

(h) assuming 10,500 Btu/gal ethanol for drying distillers grains (EPA, 2007)

- (i) assuming 1.7 million kg CO₂-eq for grain feedstock transport and 85.6 million kg CO₂-eq for refining 145 million L of corn ethanol, based on Kaufman et al. (2010); assuming drying of dry distillers grains with solubles is included in refining
- (j) assuming 4,078 kcal/kg biodiesel from soybeans (including energy related to: electricity, steam, cleanup water, space heat, direct heat, losses, stainless steel, steel and cement), based on Pimentel and Patzek (2005)
- (k) based on Sheehan et al. (1998)

Table 25. Bio-fuels and co-products yields.

	Soybean Biodiesel	Corn Ethanol
Bio-fuel yield	0.18 kg biodiesel/kg soybeans (a)	0.34 kg ethanol/kg corn (c)
Co-product yield	0.79 kg SBM/kg soybeans (b)	0.26 kg DDGS/kg corn (d)

- (a) assuming 1,000 kg biodiesel/5,556 kg soybeans (Pimentel and Patzek, 2005)
- (b) assuming 47.16 lb soybean meal/bu soybeans (Wang et al., 2010)
- (c) assuming 0.435 L ethanol/kg corn (Patzek, 2004-2006)
- (d) assuming 14.51 lb dried distillers grains with solubles/bu corn (Wang et al., 2010)