International Dairy Journal 31 (2013) S65–S77

Contents lists available at SciVerse ScienceDirect

International Dairy Journal

journal homepage: www.elsevier.com/locate/idairyj

Dairy farm greenhouse gas impacts: A parsimonious model for a farmer's decision support tool

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A R T I C L E I N F O

Article history:
Received 18 November 2011
Received in revised form
15 May 2012
Accepted 18 September 2012

A B S T R A C T

This study presents an analysis of the cradle to farm gate greenhouse gas footprint of milk. Compared with the detailed model, we aim to accurately represent the variations in carbon footprint across farms, while being more parsimonious in terms of data needs. The simplified model strongly reduces the farm-specific data requirement from 162 animal-rations in the detailed survey to 12 feed rations for lactating cows, while explaining 91% of the variability in feed print and 98% of the variability in total footprint across 531 farms. The additional 95% confidence interval on an individual farm footprint is less than 10%. Feed efficiency and manure management are key determinants of the footprint per kg milk. A 15% reduction in the average footprint can be achieved by a 10% reduction for the 50th percentile of the best farms and by a higher and targeted reduction for the less efficient farms.

1. Introduction

Consumers and retailers are becoming increasingly aware of their impact on the environment and especially of their impacts on climate change. They are changing their consumption to lead a more environmentally friendly lifestyle, and want to know that what they buy has been produced in an environmentally sustainable way. To proactively meet the needs of the marketplace, the U.S. dairy industry commissioned a detailed greenhouse gas (GHG) life cycle assessment (LCA), or carbon footprint study, for fluid milk (Thoma et al., 2013b,c) to identify where the industry can innovate to reduce GHG emissions across the supply chain to achieve the greatest gains. This article builds on that detailed study to develop a parsimonious, but still accurate and representative tool for farmers to determine and potentially reduce their cradle to farm gate carbon footprint.

In recent years, various tools have been developed to assess the GHG emissions in agriculture. Some tools, like Century (Parton, Schimel, Cole, & Ojima, 2006), DayCent (Parton, Ojima, Cole, & Schimel, 2008), US Department of Agriculture's Comet VR (USDA NRCS, 2011), US Cropland GHG Calculator (McSwiney, Bohm, Grace, & Robertson, 2010), or US Energy Information Administration's (EIA's) "N_2O from agricultural soils" (EIA, 2010), specifically aim at assessing crop production emissions or footprint per surface unit. Others, like EIA's "Livestock waste" and "Enteric Fermentation" (EIA, 2010), assess part of the emissions in the milk production chain, at the farm level, but do not cover the whole milk production process at the farm gate.

Tools like the Integrated Farm System Model (IFSM; Rotz et al., 2011), Denitrification–Decomposition (DNDC; Giltrap, Li, & Saggar, 2010), the "Cool Farm Tool" (Unilever, 2011), aim at assessing a given farm carbon footprint. They cover the different steps of milk production, assessing the overall farm emissions; similarly, The Dairy Greenhouse Gas Abatement Strategies (DGAS) tool (Eckard et al., 2009) enables Australian farmers to compute their footprint, which also enables them to test strategies of mitigation. But the farm may also carry out activities other than milk production, e.g., cash crop production; the assessment of the overall farm print does not enable fair comparisons per quantity of milk produced. The "Shades of Green" (SOG) dairy farm management calculator (Benbrook et al., 2010), encompasses the dairy production boundaries but only assesses the methane emissions, missing other compounds.

Other simplified tools such as the "Carbon Calculator" (CFG, 2009), compute simplified footprints per head or per farm that

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http://dx.doi.org/10.1016/j.idairyj.2012.09.004

do not account for the broad diversity of farm practices and hence for the subsequent range of emissions.

There are companies that assess the GHG per kg of milk. The E-CO_2 project (E-CO_2 Project, 2012) in the UK is one of them.

Some decision-making tools for farmers already exist. One of the most notable ones is the Dairy GHG (Rotz & Chianese, 2009). It is a simplified version of IFSM that encompasses the boundaries of dairy production, and excludes other farm activities; it enables the farmer to enter the characteristics of the herd, the target milk production, as well as the quantities and types of feed, and computes a carbon footprint per kg of milk. However, it is not possible to enter farm-specific information on fuel consumption and incidences of simplification still need to be systematically and statistically evaluated on a large number of farms.

The determination of the carbon footprint for a given farm by Thoma et al. (2013c) involved an intensive data collection and modeling effort to include the GHG emissions associated with the whole supply chain of agricultural inputs (fertilizers, diesel, etc.), feed production, direct enteric and combustion emissions at the dairy farm, as well as emissions occurring during milk processing, transportation, retail and eventually consumption. Focusing more specifically on the farm operations, the detailed assessment made by Thoma et al. (2013c) constitutes a good basis to start from, but required intensive inputs for the modeling of more than 160 animal-ration combinations (27 feed rations for 6 classes of animals) per farm.

There is therefore a need to analyze how data needs and the number of model parameters can be reduced to produce a "cleverly simple" model for the emissions up to the farm gate, while maintaining accuracy. This model should represent the variations in carbon footprint across farm practices, while being more transparent and parsimonious in terms of data collection needs. To address this, the present article aims to:

a) Identify the key parameters determining the cradle to farm gate carbon footprint on a functional basis, i.e., per kg fat–protein corrected milk. Life cycle boundaries usually extend far upstream beyond farm boundaries;
b) Develop a parsimonious model that predicts the variation in footprint among farm management practices and characteristics;
c) Evaluate and verify that the simplified model results fall within the range of the detailed results;
d) Provide farmers with an easy-to-use GHG tool, enabling them to calculate and potentially reduce the GHG impacts associated with the specific characteristics of fluid milk production at their farm;
e) Carry out a scenario analysis to explore how potential reduction scenarios could help reach the reduction goals of 25% reduction in GHG by the year 2020.

2. Methods

2.1. Survey data, and carbon footprint detailed assessment

Thoma et al. (2013b) carried out a detailed carbon footprint study in a life cycle perspective encompassing activities performed in support of milk production and including: raw material and energy extraction, production and distribution, fertilizer and agricultural input production, feed production, enteric emissions and manure management system at a dairy farm. The study also included the production of packaging material, the impacts of distribution and refrigeration, as well as product loss through the supply chain. The functional unit for this study was one kg of milk consumed by USA consumers.

Farm-level data were collected through a detailed survey, with responses from 531 farms grouped into 5 regions as shown in Fig. 1 (Popp, Thoma, Mulhern, Jaeger LeFranc, & Kemper, 2013).

Feed rations, including on-farm produced feed, purchased feed, and feed intake during pasture (also accounting for feed losses) were specifically requested for the following 6 animal classes: Open Heifer – Birth to Breeding; Bred Heifer – Breeding to Springer; Springer – approximately 3 weeks prior to first calving; First-Calf Heifer – post-calving animal, but before second calf; Lactating Cow; and Dry Cow – multiparous animal approximately 60 days prior to calving. Less than 25% of farms had mature cows who received the majority of forage intake from pasture (this excludes harvested hay) in any month. Approximately 160 distinct feeds were identified and then aggregated into 27 feed types for which cradle to mouth burdens were determined on a farm-by-farm basis. Regional average rations were also calculated from reported data for each animal class. Each of the feeds has a feed characterization factor (CF), which includes the impacts of both synthetic fertilizer and manure application, and an average impact of the transportation of feed to the dairy farm. Feed CFs do not differentiate between feeds grown on-farm and purchased feeds: both are assumed to be represented by the CF for the farm's region. Enteric methane emissions were calculated per animal per day based on the farm specific dry matter intakes (DMIs) for the different animal classes. Standardized methodologies were used to determine emissions of the manure print as described in the Intergovernmental Panel on Climate Change (IPCC, 2006) guidelines. Since the emissions of field manure application are accounted for in the feed print, they are not considered in the manure print to avoid double counting. To estimate the annual CH_4 emission factor from livestock manure, the predicted volatile solids (VS) excretion rates per animal type were used in conjunction with herd demographics to estimate the total VS produced per farm per year, but without considering the ration-specific conversion between DMIs and VS.

On-farm fossil fuel and electricity use were collected in the survey. For each print category, these farm-specific data were then combined with relevant standard data coming from life cycle databases for upstream processes (mainly from ecoinvent (Frischknecht et al., 2005) for, e.g., energy extraction, electricity production, fertilizer production, etc.) to calculate the GHG footprint. The IPCC Global Warming Potentials (GWPs) with a time horizon of 100 years (GWP100) were used to compare and aggregate the impacts of CO_2 ($GWP_{CO_2} = 1$), CH_4 ($GWP_{CH_4} = 25$), N_2O ($GWP_{N_2O} = 298$) and other GHGs.

The main results obtained by Thoma et al. (2013b) show the following:

(i) The overall footprint of fluid milk consumed in the USA is 2.05 kg CO_2e kg^{-1} milk consumed, with a 90% confidence band ranging from 1.77 to 2.4 kg CO_2e kg^{-1} milk consumed. This cradle to grave footprint includes on-farm production, processing and packaging, transport, distribution and consumption.
(ii) The overall on-farm footprint is created from the combination of feed, enteric, manure management and fuel contributions. From the analysis of all farm respondents, the dairy cradle to farm gate carbon footprint shows a strong variability across farms of more than a factor of 4. Much of the observed differences between regions are more properly attributed to the on-farm practice (e.g., manure management system used in the region) rather than the geographic location.
(iii) The majority of the GHG emissions from the full cradle to grave life cycle (72% of the total) occur before the milk leaves the farm. The implications of this with regards to lowering the industry footprint are clear: on-farm practices provide the

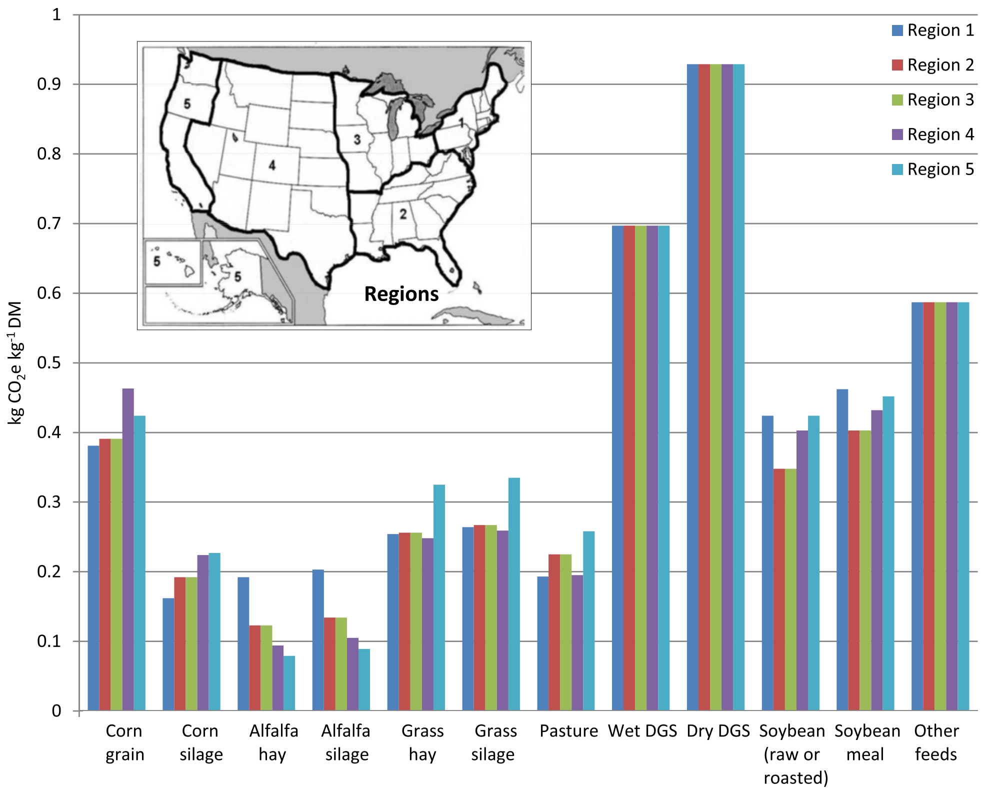

Fig. 1. Map of the five regions of Popp et al. (2013).

most significant opportunities. These opportunities are not limited to any particular region(s) or herd size(s).

Though this detailed and relatively complex analysis involved a large number of animal-ration combinations, several findings from Thoma et al. (2013b) can trace the path toward a more parsimonious model while maintaining accuracy:

(i) The top four feeds, accounting for approximately 55% of all feed DMIs, are corn silage, alfalfa hay, alfalfa silage and corn grain.
(ii) Important variations are observed in the carbon footprint of various manure management systems (MMSs), with solid storage, dry lot, and deep bedding being the three most frequently used manure management practices nationwide. Deep bedding (stored longer than one month) and anaerobic lagoons are two of the largest sources of methane from manure management, and opportunities for important reduction of GHG emissions are associated with modifications to these practices.
(iii) Feed conversion efficiency, also called the DMI ratio and expressed in kg dry matter (DM) feed per kg fat and protein-corrected milk (FPCM), is the most important individual factor in explaining differences in the footprint. Not surprisingly, more efficient feed conversion results in a lower footprint. This variable alone explains over 70% of the observed variability in the farm gate footprint: feed is a major farm input and directly affects both enteric emissions and the quantity of manure excreted.

These results point toward several simplification and improvement opportunities to limit the amount of data farmers are asked to provide, and to raise the following points:

(i) How to focus on the main feeds while still representing the main variability in feed print across farms?
(ii) How could replacement animals and dry cows be modeled in a generic way, limiting data requests to rations for lactating cows?
(iii) How to model the MMSs, while accounting for the ration-specific variability in VSs?

2.2. Development of the parsimonious simplified model: general approach

As this article builds on the detailed study of Thoma et al. (2013c), its main characteristics and its limitations as described in Section 3.3 of the study, which also apply to this study. The system boundaries encompass the same processes as described by Thoma et al. (2013c) for milk production from cradle to farm gate.

Focusing on the cradle to farm gate climate change impacts, the above questions were addressed by systematically and successively analyzing each of the main cradle to farm gate print categories (feed print, enteric print and fuel print) using the following steps:

a) Identify the key parameters of influence: based on the detailed survey results from Thoma et al. (2013b,c) and their analysis, identify the main parameters of influence for each print that need to be taken into account. Determine default values at a regional or national level for parameters of secondary influence, whose impact may be fitted to a simple multi-linear regression.
b) Identify the form of the function to fit: from an analytical analysis of the model, determine the shape of the function and corresponding equation that will then be fitted to determine each footprint based on the key parameters described above.

c) Perform a statistical regression to determine the main regression coefficients and to evaluate the quality of the parsimonious versus the detailed model (R^2 and standard deviation). Combining the additional uncertainty of the parsimonious model with the uncertainty analysis of Thoma et al. (2010) will allow placement of uncertainty ranges on the results of the GHG tool.
d) Analyze the efficiency of potential reduction scenarios.

For the manure management print, an alternative method was selected to account for the IPCC volatile solid approach for specific animals and feed. The method was then simplified accounting for a limited number of feed-animal rations and then compared with the Thoma et al. (2013c) methodology.

The following sections detail the algorithms used in the base model. The results section then compares results from the simplified model with those derived from the full survey of Thoma et al. (2013b,c). Table 1 lists the input variables collected from the user for the GHG tool; those variables are the ones used in the equations below.

2.3. Background calculations

All calculations are made on a FPCM basis in kg y^{-1}, as given by the International Dairy Federation (IDF, 2010) as follows:

$$\mathrm{FPCM_{annual}} = Y_{\mathrm{milk}} \times [0.1226 \times \mathrm{Fat\%} + 0.0776 \times \mathrm{protein\%} + 0.2534] \quad (1)$$

Where:

Y_{milk} = total farm milk production (kg y^{-1}),
Fat% = user defined average milk fat content, and
Protein% = user defined average milk protein content.

The total population of replacement animals (P^{replace}) contributing to the milk life cycle is given by

$$P^{\mathrm{replace}} = P^{\mathrm{calf,on-farm}} + P^{\mathrm{heifer,on-farm}} + P^{\mathrm{calf,off-farm}} + P^{\mathrm{heifer,off-farm}} \quad (2)$$

This accounting is necessary to accommodate both farms raising their own replacement animals and those that contract heifer rearing off-farm. It is important that only replacement animals that are to become part of the milking herd are included in this accounting. The population of dry cows (P^{dry}) and lactating cows (P^{lactate}) are derived from the population of mature cows (P^{mature}) as follows:

$$P^{\mathrm{dry}} = \%\mathrm{dry} \times P^{\mathrm{mature}} \quad (3)$$

$$P^{\mathrm{lactate}} = P^{\mathrm{mature}} - P^{\mathrm{dry}} \quad (4)$$

2.4. Feed print

The following 11 main feed types were identified, covering 82% of the feed footprint: corn grain, corn silage, wet distillers grains (DGS), dry DGS, raw or roasted soybeans, soybean meal, alfalfa hay, alfalfa silage, grass hay, grass silage and pasture. The other feeds were grouped in a twelfth feed category. The carbon footprint associated with feed production for a given dairy farm in a specific region is estimated by summing the total DMI of each animal group (lactating, dry, and replacement) for each of the 12 feed types, and multiplying by a regional characterization factor ($\mathrm{CF_{feed}}$), as shown in Fig. 1. The 12 feed types are then summed to give the overall feed print:

$$\mathrm{GHG_{feed}} = \frac{\sum_{i=1}^{12} \mathrm{CF}_{\mathrm{feed}\ i}^{\mathrm{region}\ j} \times \mathrm{DMI}_{\mathrm{feed}\ i}^{\mathrm{TOTAL}}}{\mathrm{FPCM_{annual}}} \quad (5)$$

Table 1
Input variables of the greenhouse gas tool (parsimonious model, i.e., the variables supplied by the end user), giving the symbols used in this paper and the expected units of the user input data.

Variable	Symbol	Units	Variable	Symbol	Units
Total annual milk production (pounds)	Y_{milk}	lb y^{-1}	LCR: alfalfa hay fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{alfalfa\ hay}}$	%
Average milk production per head (hd)		lb hd^{-1} d^{-1}	LCR: grass hay fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{grass\ hay}}$	%
Average milk fat content	Fat%	%	LCR: grass silage fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{grass\ silage}}$	%
Average milk protein content	Protein%	%	LCR: pasture fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{pasture}}$	%
Production herd: number of mature animals[a]	P^{mature}	hd	LCR: all other feed fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{other\ feed}}$	%
Fraction of total herd dry at a given time	%Dry	%	Total annual on-farm electricity purchased	E^{elec}	kWh
Number of on-farm replacement calves[b]	$P^{\mathrm{calf\ on\text{-}farm}}$	hd	Fraction of electricity used directly for dairy activities	λ^{elec}	%
Number of on-farm replacement heifers[b]	$P^{\mathrm{heifer\ on\text{-}farm}}$	hd	Total gallons of diesel purchased	E^{diesel}	gallon[d]
Number of off-farm replacement calves[b]	$P^{\mathrm{calf\ off\text{-}farm}}$	hd	Fraction of diesel used directly for dairy activities	$\lambda^{\mathrm{diesel}}$	%
Number of off-farm replacement heifers[b]	$P^{\mathrm{heifer\ off\text{-}farm}}$	hd	Total gallons of gasoline purchased	E^{gasoline}	gallon
PP: lactating cows: weeks per year[c]	%Time on past$^{\mathrm{cows}}$	wk y^{-1}	Fraction of gasoline used directly for dairy activities	$\lambda^{\mathrm{gasoline}}$	%
PP: dry cows: weeks per year	%Time on past$^{\mathrm{dry}}$	wk y^{-1}	Total gallons of propane purchased	E^{propane}	gallon
PP: young stock: weeks per year	%Time on past$^{\mathrm{rplct}}$	wk y^{-1}	Fraction of propane used directly for dairy activities	$\lambda^{\mathrm{propane}}$	%
Mature animals culled for beef	$P^{\mathrm{adult\ beef}}$	hd	Total amount of natural gas purchased	$E^{\mathrm{nat.\ gas}}$	Therm
Average weight of mature culls	$\mathrm{wt}^{\mathrm{adult\ beef}}$	lb	Fraction of fuel oil used directly for dairy activities	$\lambda^{\mathrm{nat.\ gas}}$	%
Calves sold for beef	$P^{\mathrm{calf\ beef}}$	hd	Total gallons of fuel oil purchased	$E^{\mathrm{fuel\ oil}}$	gallon
Average weight of cull calves	$\mathrm{wt}^{\mathrm{calf\ beef}}$	lb	Fraction of fuel oil used directly for dairy activities	$\lambda^{\mathrm{fuel\ oil}}$	%
Average DMI for lactating animals	$\mathrm{DMI}^{\mathrm{lactate}}$	lb hd^{-1} d^{-1}	Total gallons of biodiesel purchased	$E^{\mathrm{biodiesel}}$	gallon
LCR: corn grain fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{corn\ grain}}$	%	Fraction of biodiesel used directly for dairy activities	$\lambda^{\mathrm{biodiesel}}$	%
LCR: corn silage fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{corn\ silage}}$	%	MMS in use on farm	$\mathrm{MMS_1}$	Select[e]
LCR: wet DGS fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{wet\ DGS}}$	%	Fraction of excreted manure going to this system	$\%\mathrm{MMS_1}$	%
LCR: dry DGS fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{dry\ DGS}}$	%	MMS in use on farm	$\mathrm{MMS_2}$	Select
LCR: soybean (raw or roasted) fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{soy,\ raw}}$	%	Fraction of excreted manure going to this system	$\%\mathrm{MMS_2}$	%
LCR: soybean meal fraction	$\varphi^{\mathrm{lactate}}_{\mathrm{soy\ meal}}$	%	MMS in use on farm	$\mathrm{MMS_3}$	Select

[a] Lactating and dry.
[b] Number of replacement calves (less than 2 months) and of replacement heifers (2 months to first calf) raised on-farm and off-farm.
[c] Abbreviations are: PP, pasturing period; DMI, dry matter intake; LCR, lactating cow ration; MMS, manure management system.
[d] 1 gallon = 0.003785411 m^3; 1 Therm = 105,505,585 J.
[e] Select from 18 MMS options from pull-down menu.

$$\mathrm{DMI}^{\mathrm{TOTAL}}_{\mathrm{feed}\,i} = \left(\mathrm{DMI}^{\mathrm{lactate}} \times 365 \times \varphi^{\mathrm{lactate}}_{\mathrm{feed}\,i} \times P^{\mathrm{lactate}}\right) + \left(\mathrm{DMI}^{\mathrm{dry}}_{\mathrm{region}\,j} \times \varphi^{\mathrm{dry}}_{\mathrm{feed}\,i,\mathrm{region}\,j} \times P^{\mathrm{dry}}\right) + \left(\mathrm{DMI}^{\mathrm{replace}}_{\mathrm{region}\,j} \times \varphi^{\mathrm{replace}}_{\mathrm{feed}\,i,\mathrm{region}\,j} \times P^{\mathrm{replace}}\right) \quad (6)$$

GHG_{feed} = unallocated feed print for a specific region j (kg CO_2e kg^{-1} FPCM), where:
$CF_{feed\ i,\ region\ j}$ = characterization factor (kg CO_2e kg^{-1} DM) for feed i in region j, given in Fig. 1,
$DMI^{lactate}$ = user-defined average daily DMI for lactating cows (kg d^{-1}),
$\phi^{lactate}_{feed\ i}$ = user-defined fraction of feed i in the lactating cow ration,
$DMI^{dry}_{region\ j}$ = archetypical DMI for dry cows in region j (kg y^{-1}), given in Table 2,
$\phi^{dry}_{feed\ i,region\ j}$ = fraction of feed i in the archetypical dry cow ration in region j, given in Table 2,
$DMI^{replace}_{region\ j}$ = archetypical DMI for replacement heifers in region j (kg y^{-1}), given in Table 3, and
$\phi^{replace}_{feed\ i,region\ j}$ = fraction of feed i in the archetypical replacement heifer ration in region j, given in Table 3.

Fig. 1 compares the carbon footprint per kg DM feed in the 5 regions according to Thoma et al. (2013c). This GHG characterization factor can vary from 0.08 up to 0.9 depending on the feed type and region. Since the original survey results for region 2 from Thoma et al. (2013c) were based on a limited number of farms and limited feed crop production data from a few states, the CF for region 3 has also been used for region 2. Detailed information is provided in the Supplementary data section S1

The simplified feed print presented here uses archetypical regional feed rations derived from survey results for dry cows and replacement heifers. The rations for replacement heifers are the same whether the animals are raised on-farm or off-farm.

2.5. Enteric print

GHG emissions associated with enteric fermentation were found to be closely correlated to the total DMI of all animals as follows:

$$GHG_{enteric} = \gamma_{enteric} \frac{DMI^{TOTAL}}{FPCM_{annual}} \quad (7)$$

Table 2
Archetypical rations for dry cows, by region.

Dry cows	Region 1	Region 2	Region 3	Region 4	Region 5
DMI[a]	4510	4389	4491	4675	4550
Fractional makeup of each feed					
Corn grain	0.016	0.018	0.020	0.027	0.065
Corn silage	0.406	0.099	0.339	0.205	0.171
Wet DGS	0.000	0.000	0.018	0.003	0.000
Dry DGS	0.015	0.070	0.039	0.029	0.015
Soybean (raw or roasted)	0.005	0.000	0.000	0.000	0.000
Soybean meal	0.037	0.047	0.056	0.017	0.021
Alfalfa hay	0.057	0.000	0.028	0.112	0.189
Alfalfa silage	0.159	0.000	0.123	0.071	0.078
Grass hay	0.144	0.307	0.239	0.254	0.165
Grass silage	0.035	0.048	0.008	0.103	0.136
Pasture	0.043	0.275	0.033	0.023	0.019
Other feeds	0.083	0.136	0.096	0.155	0.141

[a] DMI : dry matter intake (kg DM hd^{-1} y^{-1}).

Table 3
Archetypical rations for replacement heifers, by region.

Replacement heifers	Region 1	Region 2	Region 3	Region 4	Region 5
DMI[a]	2414	2398	2663	3051	2412
Fractional makeup of each feed					
Corn grain	0.029	0.075	0.038	0.028	0.053
Corn silage	0.308	0.068	0.304	0.172	0.147
Wet DGS	0.001	0.000	0.006	0.026	0.006
Dry DGS	0.017	0.068	0.042	0.041	0.037
Soybean (raw or roasted)	0.003	0.001	0.000	0.000	0.000
Soybean meal	0.031	0.062	0.053	0.017	0.046
Alfalfa hay	0.067	0.034	0.086	0.225	0.175
Alfalfa silage	0.296	0.004	0.177	0.088	0.018
Grass hay	0.045	0.159	0.150	0.129	0.132
Grass silage	0.058	0.063	0.032	0.092	0.174
Pasture	0.073	0.271	0.033	0.040	0.016
Other feeds	0.072	0.195	0.078	0.142	0.196

[a] DMI: dry matter intake (kg DM hd^{-1} y^{-1}).

$$DMI^{TOTAL} = \sum_{i=1}^{12} DMI^{TOTAL}_{feed\ i}, \quad (8)$$

where

$GHG_{enteric}$ is the unallocated enteric print (kg CO_2e kg^{-1} FPCM), and
$\gamma_{enteric}$ is the enteric print regression factor = 0.46, derived by a regression of the enteric print from the detailed survey performed by Thoma et al. (2013c) against the total DMI per kg FPCM for the 12 feed types of the simplified model.

2.6. Fuel print

With the exception of electricity, where regional differences in emission factors have been simplified by deriving a fitting factor, the various fuel prints are calculated by multiplying fuel use by the emission factor reported in Thoma et al. (2010). The user of the GHG Tool is able to indicate a percentage of the total fuel purchased that is used directly for dairy operations. This is important, especially in the case where a farm produces feed on-farm. Fuel use associated with feed production should not be included in the reported “directly for dairy operations” category. The total fuel print is the sum of the each individual fuel print calculated as follows:

$$GHG_{elec} = \gamma_{elec} \times \frac{E_{elec}}{FPCM_{annual}} \times \lambda_{elec} \quad (9)$$

$$GHG_{diesel} = \gamma_{diesel} \times \frac{E_{diesel}}{FPCM_{annual}} \times \lambda_{diesel} \quad (10)$$

$$GHG_{gasoline} = \gamma_{gasoline} \times \frac{E_{gasoline}}{FPCM_{annual}} \times \lambda_{gasoline} \quad (11)$$

$$GHG_{propane} = \gamma_{propane} \times \frac{E_{propane}}{FPCM_{annual}} \times \lambda_{propane} \quad (12)$$

$$GHG_{nat.\ gas} = \gamma_{nat.\ gas} \times \frac{E_{nat.\ gas}}{FPCM_{annual}} \times \lambda_{nat.\ gas} \quad (13)$$

$$GHG_{fuel\ oil} = \gamma_{fuel\ oil} \times \frac{E_{fuel\ oil}}{FPCM_{annual}} \times \lambda_{fuel\ oil} \quad (14)$$

$$GHG_{biodiesel} = \gamma_{biodiesel} \times \frac{E_{biodiesel}}{FPCM_{annual}} \times \lambda_{biodiesel} \quad (15)$$

$$GHG_{fuel} = GHG_{elec} + GHG_{diesel} + GHG_{gasoline} + GHG_{propane} + GHG_{nat.\ gas} + GHG_{fuel\ oil} + GHG_{biodiesel} \quad (16)$$

where

γ_x = emission factor for each fuel type x (given in Table 4),
E_x = user-defined annual energy use for each fuel type, and
λ_x = user-defined fraction of annual energy use used directly for dairy operations.

2.7. Manure print

The detailed model from Thoma et al. (2010) used standard VS emissions per animal. Here, we suggest to refine the approach and to account for the feed-specific VSs per kg DM as proposed by IPCC (2006) while keeping the assessment parsimonious. For consistency, we also used the IPCC model for N excretions, and updated the detailed model.

VSs and N excretions are broken down between MMSs and manure spread on pasture according to the average yearly time spent on pasture by each animal group.

Estimates of GHG emissions associated with manure (CH_4 and N_2O) are calculated based on the Tier 2 methods presented by IPCC (2006), both for MMSs and for manure spread on pasture. Specific calculations, including the method for estimating diet-based VS excretions, are detailed in the Supplementary data sections S2–S4.

Methane and nitrous oxide emissions from MMS are combined with respective GWP to give a total unallocated MMS Print (kg CO_2e kg^{-1} FPCM):

$$GHG_{MMS} = \left(GWP_{CH_4} \times \frac{CH_{4_{MMS}}}{FPCM_{annual}}\right) + \left(GWP_{N_2O} \times \frac{N_2O^{TOTAL}_{MMS}}{FPCM_{annual}}\right) \quad (17)$$

where

$CH_{4_{MMS}}$ = total methane emissions from all MMS in kg CH_4 y^{-1} given in Supplementary data section S3 as a function of total VS
GWP_{CH_4} = GWP for methane = 25 kg CO_2e kg^{-1} CH_4
$N_2O^{TOTAL}_{MMS}$ = total N_2O emissions from all MMS in kg N_2O y^{-1} given in Supplementary data section S2 as a function of total volatile solids
GWP_{N_2O} = GWP for N_2O = 298 kg CO_2e kg N_2O^{-1}
$FPCM_{annual}$ = annual FPCM production kg FPCM y^{-1}.

Table 4
Fuel emission factors used in GHG[a] tool.

Fuel	Emission factor (γ)	Units[b]
Electricity	0.842	kg CO_2e kWh^{-1}
Diesel	11.89	kg CO_2e $gallon^{-1}$
Gasoline	10.21	kg CO_2e $gallon^{-1}$
Propane	7.66	kg CO_2e $gallon^{-1}$
Natural gas	7.54	kg CO_2e $Therm^{-1}$
Fuel oil	12.37	kg CO_2e $gallon^{-1}$
Biodiesel	7.96	kg CO_2e $gallon^{-1}$

[a] GHG: greenhouse gas.
[b] kWh: kilowatt hour. 1 kWh = 3,600,000 J; 1 gallon = 0.003785411 m^3; 1 Therm = 105,505,585 J.

Methane and nitrous oxide emissions from manure excreted on pasture are similarly combined with respective GWPs to give a total manure print similar to the MMS print.

$$GHG_{pasture} = \left(GWP_{CH_4} \times \frac{CH_{4_{pasture}}}{FPCM_{annual}}\right) + \left(GWP_{N_2O} \times \frac{N_2O^{TOTAL}_{pasture}}{FPCM_{annual}}\right) \quad (18)$$

where

$CH_{4_{pasture}}$ = total methane emissions from all MMS in kg CH_4 y^{-1} given in Supplementary data section S3 as a function of total VS and
$N_2O^{TOTAL}_{MMS}$ = total N_2O emissions from all MMS in kg N_2O y^{-1} given in Supplementary data section S3 as a function of total VS.

2.8. Digester

Anaerobic digesters present a particularly interesting opportunity for dairy farms to reduce their GHG emissions. As such, it is desirable that the GHG Tool be equipped to evaluate the inclusion (either in operation or as a hypothetical scenario) of a digester in the farm operation. Anaerobic digesters function as a controlled environment where the production of methane from manure is encouraged, captured, and often, utilized. This can potentially reduce the carbon footprint of the farm in a number of ways: by reducing the methane emitted to the atmosphere; by generating electricity with the biogas, and thus displacing the need to purchase electricity; and by utilizing the waste heat from the genset to heat water, thus displacing the need to purchase other fuels for water heating or milk cooling.

Refined modeling and feasibility studies using, for example, the AgSTAR FarmWare tool (EPA, 2010) are recommended before the implementation of a digester. However, the simplified approach presented in Supplementary data section S5 provides a baseline assessment of the impacts of a digester. Impacts are determined as a function of the VSs available in the manure. However, unlike earlier evaluations where the location of the animals was irrelevant, only manure from animals located on the farm is available for the digester. Thus, it is necessary to differentiate between on-farm- and off-farm-raised replacement heifers.

2.9. Allocation

A total unallocated farm footprint is simply the sum of the individual prints:

$$GHG^{TOTAL}_{unallocated} = GHG_{feed} + GHG_{enteric} + GHG_{fuel} + GHG_{MMS} + GHG_{pasture} \quad (19)$$

Using the allocation rules details from Thoma, Jolliet, and Wang (2013a) the portion of the total carbon footprint that can be allocated to milk production (AF) is calculated as a function of the beef-milk production ratio (BMR) in kg beef kg^{-1} FPCM as follows:

$$AF = 1 - (4.67 \times BMR) \quad (20)$$

$$BMR = \left(P^{adult\ beef} \times wt^{adult\ beef} + P^{calf\ beef} \times wt^{calf\ beef}\right) / FCPM_{annual} \quad (21)$$

$$GHG^{TOTAL}_{allocated,milk} = AF{*}GHG^{TOTAL}_{unallocated} \quad (22)$$

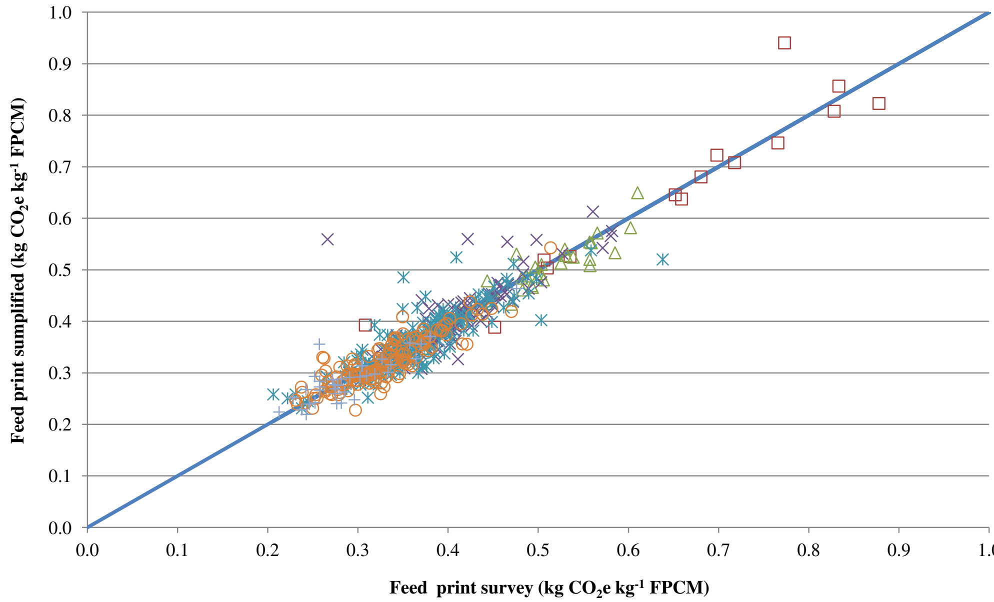

Fig. 2. Unallocated simplified feed print based on 12 main feed types and generic replacement animals as a function of the unallocated feed print from the detailed survey (531 observations, $R^2 = 0.91$, standard error = 0.035 kg CO_2e kg^{-1} FPCM), grouped by milk productivity in kg FPCM head^{-1} y^{-1} (□, 1700–4999; △, 5000–6999; ×, 7000–8999; ∗, 9000–10,999; ○, 11,000–12,999; +, >13,000).

where $P^{\text{adult beef}}$ = head of mature animals sold for meat,
$wt^{\text{adult beef}}$ = average live weight of mature animals sold for meat (kg),
$P^{\text{calf beef}}$ = head of calves sold for meat (or to be raised off-farm for beef), and
$wt^{\text{calf beef}}$ = average live weight of calves sold for meat (kg).

3. Results and discussion

3.1. Comparison of results between the simplified model and the full survey for each print category

This section first performs the regression analysis for each print category to determine the regression coefficients. It then compares

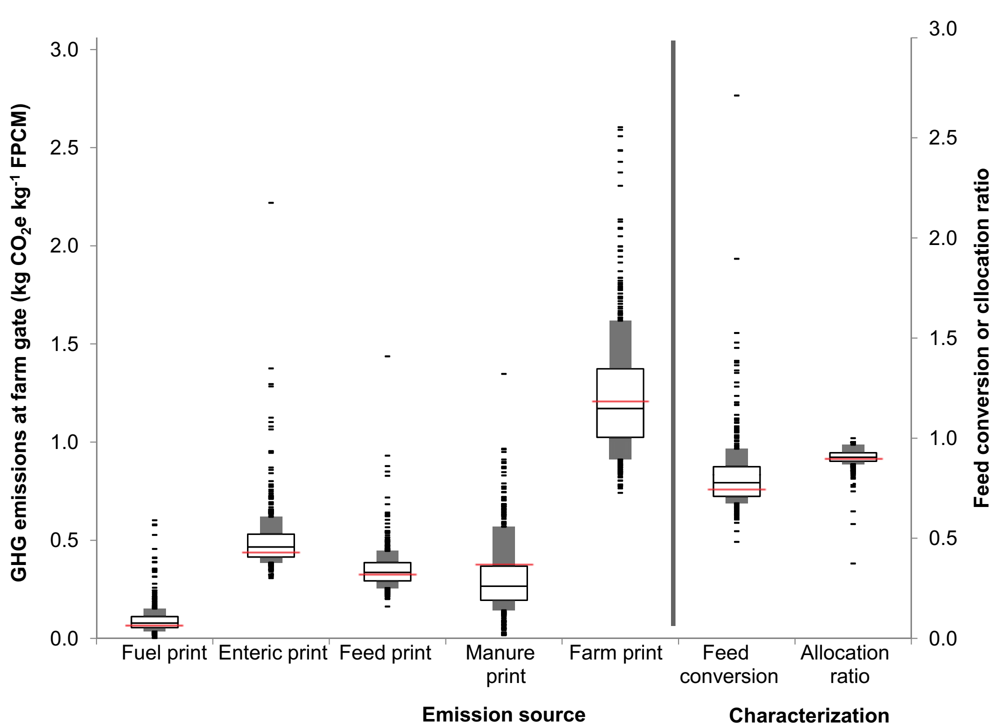

Fig. 3. Box–whisker plot showing the range of allocated carbon footprints from the 500 farms. Boxes bound the 25th and 75th percentiles of the data, while the median is marked by the black horizontal line. The narrow solid gray boxes show the 10th and 90th percentiles, and individual markers are given for the outliers. The red line is plotted at the production-weighted mean value of the specific greenhouse gas (GHG) emission total. The "manure" plot is the sum of manure management system and manure on pasture prints. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the results of the simplified GHG with those of the detailed survey of Thoma et al. (2013c).

3.1.1. Feed print

Fig. 2 shows that the simplified model presents an R^2 of 91%; this means that the model is able to explain 91% of the initial variability in carbon feed print across the 531 survey farms, while strongly reducing the farm-specific data requirement to 12 feed rations for lactating cows against the 162 animal-rations of the detailed survey. Since the generic rations for the replacement animals are equal to the regional averages, the simplified model provides on average results equal to the detailed survey model of Thoma et al. (2013b,c) and the feed regression factor is equal to 1 (0.981 ± 0.004). The different marker types and colors (in the web version) in Fig. 2 show that the farms with the highest feed prints (expressed in kg CO_2e kg^{-1} FPCM) are those with low milk productivity (<5000 kg FPCM head^{-1}). On the contrary, higher milk productivity usually corresponds with a lower footprint, with a variation that depends on the feed ratio composition. Fig. 3 shows that the median allocated feed print amounts to 0.33 kg CO_2e kg^{-1} FPCM, typically varying between 0.19 (1st percentile of farms) and 0.68 kg CO_2e kg^{-1} FPCM (99th percentile of farms). In comparison, the 95% confidence interval on the individual farm print due to model simplification amounts to ±0.07 kg CO_2e kg^{-1} FPCM.

3.1.2. Enteric print

A value of 0.46 kg CO_2e kg^{-1} DM is obtained for the enteric print factor, and the simplified model explains 97% of the initial variability in the specific farm enteric print (Fig. 4). Fig. 3 shows that the median allocated enteric print amounts to 0.45 kg CO_2e kg^{-1} FPCM typically varying between 0.31 (1st percentile of farms) and 1.07 kg CO_2e kg^{-1} FPCM (99th percentile of farms). As for the feed print, the farms with the highest feed prints (expressed in kg CO_2e kg^{-1} FPCM) are those with low milk productivity (<5000 kg FPCM head^{-1}). In comparison, the 95% confidence interval on the individual farm print due to model simplification amounts to ±0.06 kg CO_2e kg^{-1} FPCM.

3.1.3. Fuel print

For fuel print, there is no difference between the simplified and the detailed models as the data requirement is already limited in the detailed survey from Thoma et al. (2013c). Fig. 3 shows that for most farms, the median allocated fuel print is limited compared with the other prints and amounts to 0.08 kg CO_2e kg^{-1} FPCM, typically varying between 0.008 (1st percentile of farms – no pasture) and 0.40 kg CO_2e kg^{-1} FPCM (99th percentile of farms).

3.1.4. Manure print

3.1.4.1. Manure management system. Fig. 5 compares the typical manure GHG print for the considered MMSs. It demonstrates large variation in manure print depending on the MMS type ranging from 300 to 7200 kg CO_2 per head per year, with high impacts for uncovered anaerobic lagoon, composting – intensive windrow and deep bedding with more than a month storage.

Fig. 6 shows that the simplified model is able to explain 99% of the variability in carbon feed print across the 531 survey farms. Since the generic rations for the replacement animals are equal to the regional averages, the simplified model provides, on average, results equal to the detailed survey and the manure regression factor is equal to 1. The median allocated MMS print amounts to 0.20 kg CO_2e kg^{-1} FPCM, typically varying between 0 (1st percentile of farms) and 0.77 kg CO_2e kg^{-1} FPCM (99th percentile of farms). In comparison the 95% confidence interval on the prediction of the manure print due to model simplification amounts to ±0.03 kg CO_2e kg^{-1} FPCM for an individual farm.

3.1.4.2. Manure deposited on pasture. Fig. 7 shows that the simplified model is able to explain 99% of the variability in carbon feed print across the 531 survey farms. The median print amounts to 0.008 kg CO_2e kg^{-1} FPCM, typically varying between 0 (1st percentile of farms – no pasture) and 0.49 kg CO_2e kg^{-1} FPCM (99th percentile of farms). In comparison, the 95% confidence interval on the individual farm print due to model simplification amounts to ±0.02 kg CO_2e kg^{-1} FPCM.

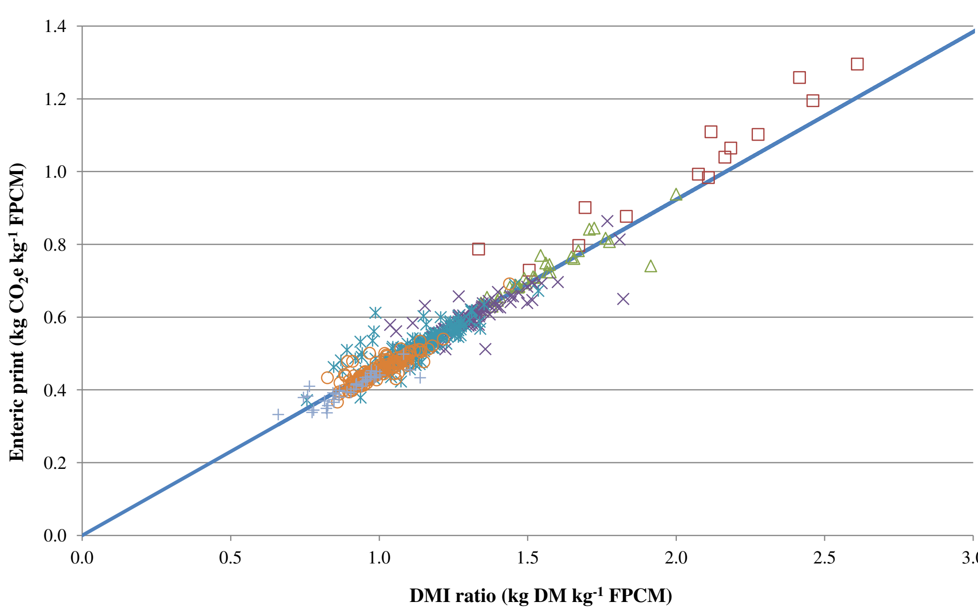

Fig. 4. Unallocated enteric print from the detailed survey as a function of the dry matter intake (DMI) per kg FPCM for the 12 main feed types and for generic replacement animals [regression line: $GHG^{enteric}_{detailed} = \gamma^{enteric} DMI^{TOTAL}/FPCM$, 531 observations, $R^2 = 0.97$, standard error = 0.031 kg CO_2e kg^{-1} FPCM, slope = 0.461 kg CO_2e kg^{-1} DM (95% CI 0.459–0.464)], grouped by milk productivity in kg FPCM head^{-1} y^{-1} (□, 1700–4999; △, 5000–6999; ×, 7000–8999; ∗, 9000–10,999; ○, 11,000–12,999; +, >13,000).

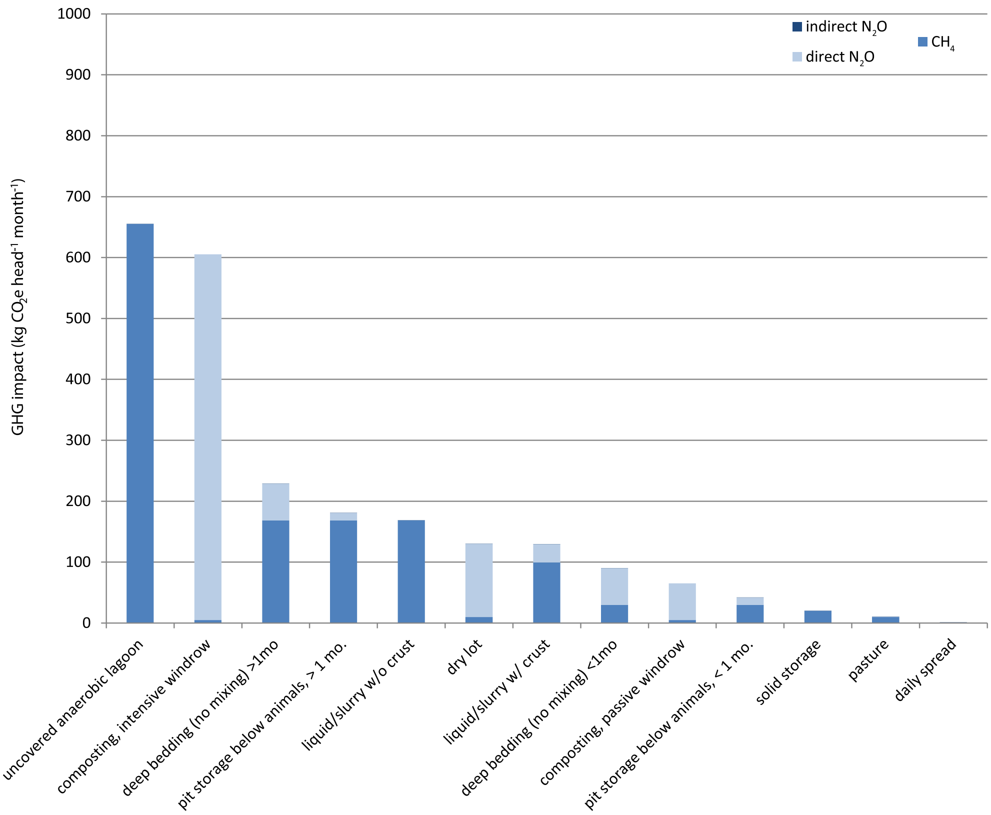

Fig. 5. Typical variation in manure carbon print among the Intergovernmental Panel on Climate Change manure management systems considered, for an average diet for lactating cows.

3.1.5. Total simplified print

Summing across all print categories, the total footprint model gives highly comparable results to the detailed survey, and the simplified model explains 98% of the variability across farms (see Fig. 8). The resulting 95% confidence interval on the prediction of an individual allocated farm footprint amounts to 0.12 kg CO_2e kg^{-1} FPCM.

The median overall allocated footprint across all farms amounts to 1.14 kg CO_2e kg^{-1} FPCM, typically varying between 0.74 (1st percentile of farms) and 2.46 kg CO_2e kg^{-1} FPCM (99th percentile of farms). These figures are very close to the figures obtained by the detailed model: the median overall allocated footprint across all farms amounts to 1.14 kg CO_2e kg^{-1} FPCM (note that minor modifications for consistency purposes have been made to Thoma

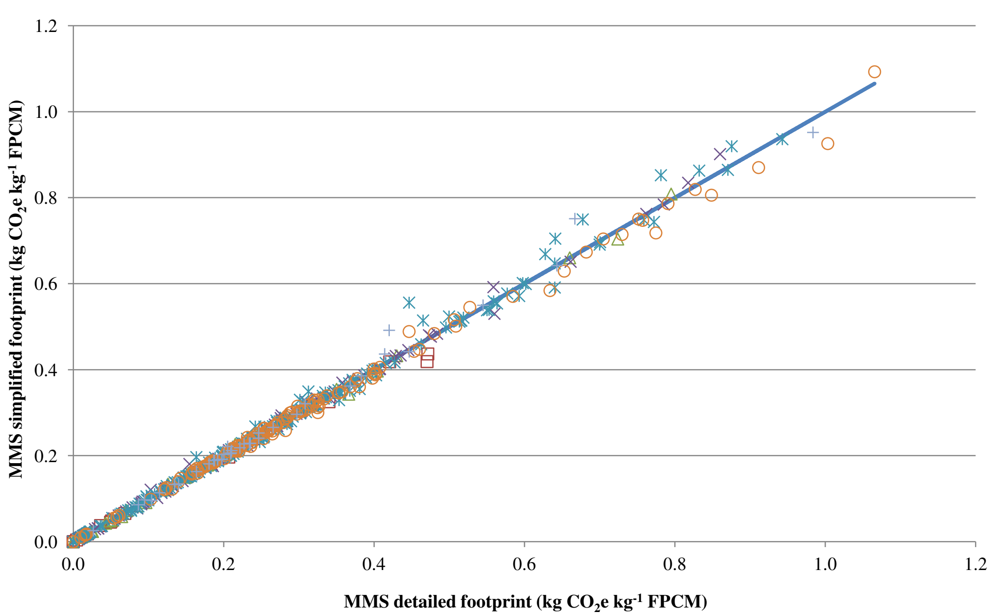

Fig. 6. Unallocated simplified manure management system (MMS) print based on 12 main feed types and generic replacement animals as a function of the unallocated MMS print using the detailed set of animal rations (531 observations, R^2 = 0.99, standard error = 0.014 kg CO_2e kg^{-1} FPCM), grouped by milk productivity in kg FPCM head^{-1} y^{-1} (□, 1700–4999; △, 5000–6999; ×, 7000–8999; ∗, 9000–10,999; ○, 11,000–12,999; +, >13,000).

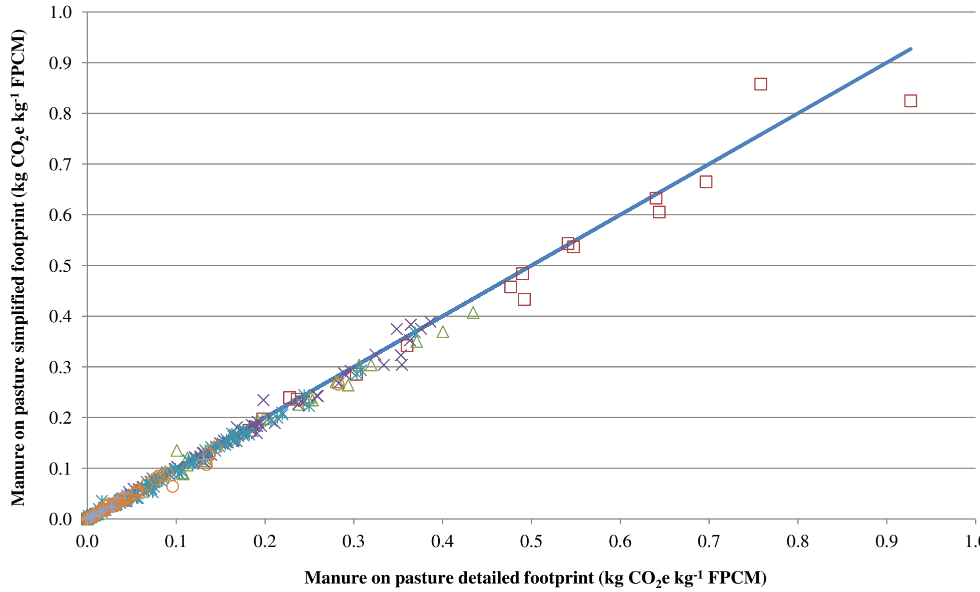

Fig. 7. Unallocated simplified manure pasture print based on 12 main feed types and generic replacement animals as a function of the unallocated manure pasture print using the detailed set of animal rations (531 observations, $R^2 = 0.99$, standard error = 0.010 kg CO_2e kg^{-1} FPCM), grouped by milk productivity in kg FPCM head^{-1} y^{-1} (□, 1700–4999; △, 5000–6999; ×, 7000–8999; ∗, 9000–10,999; ○, 11,000–12,999; +, >13,000).

et al. (2013c), that reduces the average from 1.26 to 1.14 kg CO_2e kg^{-1} FPCM), typically varying between 0.73 (1st percentile of farms) and 2.48 kg CO_2e kg^{-1} FPCM (99th percentile of farms).

The farms with the highest footprint are those with the highest ratios of DMI per kg FPCM (DMI ratio). The DMI per kg FPCM based on the 12 selected feeds is therefore able to explain a large share of the variability on its own (76%: Fig. 9). The 95% confidence interval on prediction based solely on the DMI ratio instead of the 12 individual feed types increases to 0.42 kg CO_2e kg^{-1} FPCM for an individual farm: a factor 3.5 times higher than for the simplified model. Indeed, the prediction based on the DMI ratio is less refined, as it does not account for the fact that different feeds have different CFs, which is accounted for in the model based on the 12 feed types.

3.2. Scenario analysis and uncertainty

The variability across farms from the different prints can be represented by a histogram of the total carbon footprint sorted by increasing farm gate footprint (per kg FPCM; Fig. 10).

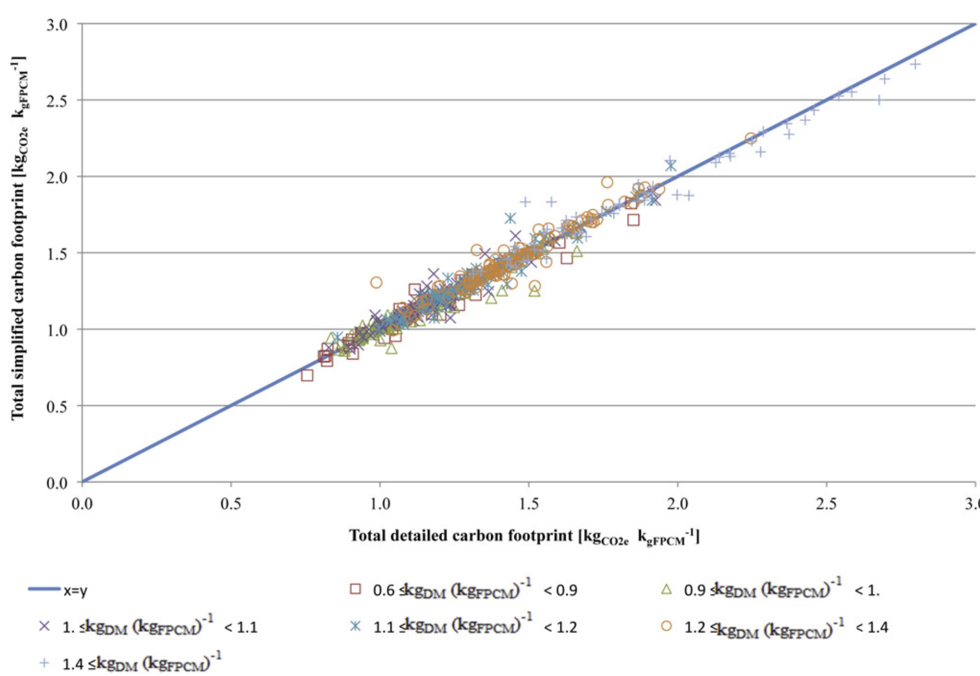

Fig. 8. Total simplified print as a function of the total print from the detailed survey (531 observations, $R^2 = 0.98$, standard error = 0.062 kg CO_2e kg^{-1} FPCM), grouped by dry matter intake (DMI) ratios in kg DM kg^{-1} FPCM (□, 0.60–0.89; △, 0.90–0.99; ×, 1.00–1.09; ∗, 1.10–1.19; ○, 1.20–1.39; +, >1.40).

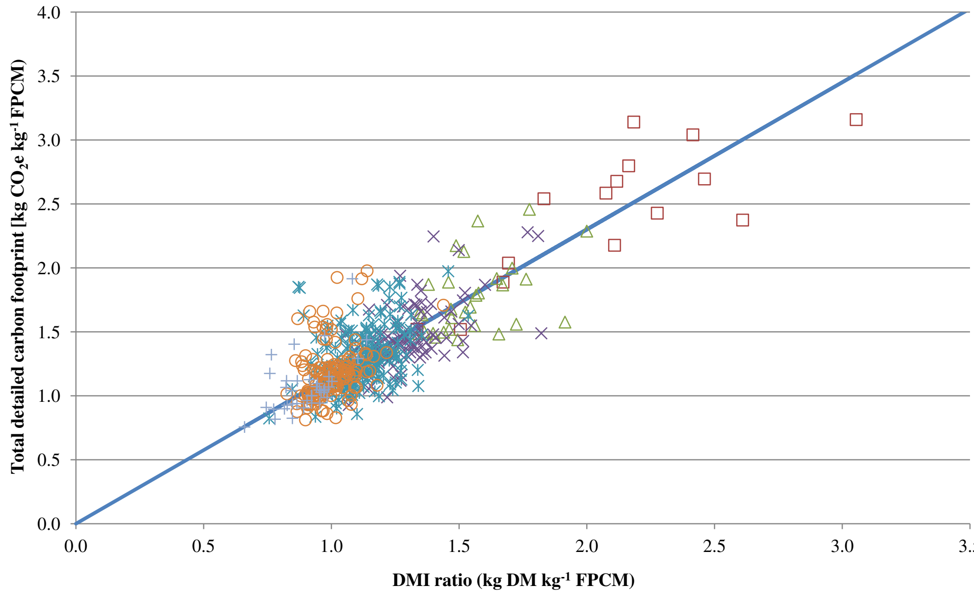

Fig. 9. Total unallocated print from the detailed survey as a function of the dry matter intake (DMI) ratio per kg FPCM [regression line: $GHG^{total}_{detailed} = \gamma^{total\ DMI} \cdot DMI^{TOTAL}$; 531 observations, $R^2 = 0.76$, standard error = 0.21 kg CO_2e kg^{-1} FPCM, slope = 1.15 (95% CI 1.14–1.17)], grouped by milk productivity in kg FPCM head^{-1} y^{-1} (□, 1700–4999; △, 5000–6999; ×, 7000–8999; ∗, 9000–10,999; ○, 11,000–12,999; +, >13,000).

As discussed by Thoma et al. (2013c), there appears to be a generally increasing contribution from manure management with increasing overall footprint. However, no other clear correlations between carbon footprint per kg milk and farm operations or size are obvious. The exception to this is that farms with a very high footprint on the right of Fig. 10 are in the low to middle size range in terms of milk production. One implication of these observations is that opportunities for GHG reductions need to be identified on an individual farm basis, thus validating the need for a simplified tool that enables each farmer to identify opportunities for improvement.

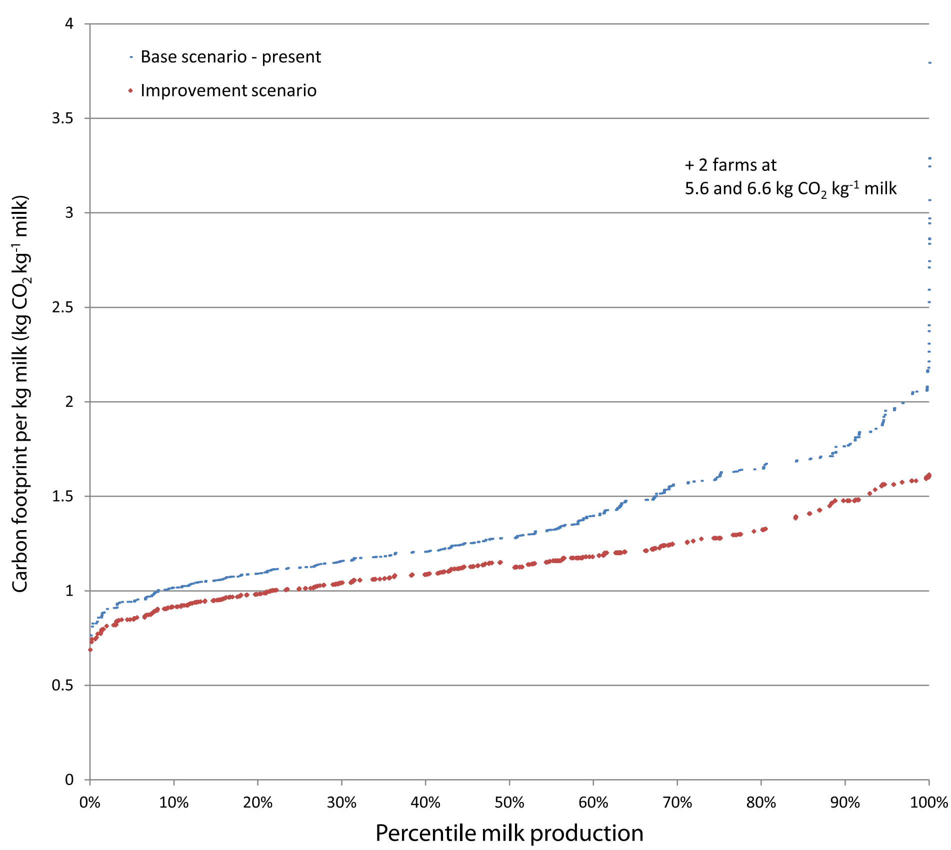

Fig. 10. Distribution of the unallocated greenhouse gas impact among farms as a function of the percentile milk production of all surveyed farms.

Based on Fig. 10, we suggest that national-level improvement strategies should address both the farms with a high carbon footprint as well as the best farms that are driving best management practices. Based on this representation, we tested the following improvement scenario:

a) For the footprint per kg below the 50th percentile, the footprint is reduced by 10%;
b) For the footprint above the 50th percentile, the carbon footprint per kg milk is reduced to the value of farms for a percentile 25% lower (Fig. 10 – improvement scenario).

Overall, this strategy would enable a 15% reduction of the average carbon footprint. The highest and targeted reduction for farms with high footprints therefore enables an important 5% additional reduction on the national average compared to a 10% baseline reduction for all farms.

Regarding the overall uncertainty assessment, the average footprint calculated by Thoma et al. (2013b) yields an average carbon footprint of 2.05 kg CO_2e kg^{-1} FPCM consumed, with a 95% confidence band ranging from 1.7 to 2.6 kg CO_2e kg^{-1} FPCM consumed. Assuming as a first proxy that the uncertainty due to input model parameters as analyzed by Thoma et al. (2013b) is lognormally distributed around the mean with a square of the geometric standard deviation (GSD) of $GSD^2_{GHG\ input\ parameters} \cong 1.23$ (5% percentile = mean/1.23, 95% percentile = mean × 1.23) and that the additional uncertainty due to model simplification is also lognormal with a $GSD^2_{GHG\ additional\ simplified} \cong 1.09$, the overall uncertainty on the final simplified model for individual farms can be characterized by the following GSD^2_{GHG} (Rosenbaum, Pennington, & Jolliet, 2004):

$$GSD^2_{GHG\,overall} = e^{\sqrt{\left(\ln GSD^2_{GHG\,input\,parameters}\right)^2 + \left(\ln GSD^2_{GHG\,additional\,simplified}\right)^2}} = e^{\sqrt{(\ln 1.23)^2 + (\ln 1.09)^2}} \cong 1.25 \quad (23)$$

4. Conclusion

The present analysis has shown the crucial importance of the feed efficiency and the manure management practice on the carbon footprint per kg milk. The simplified model is able to explain 98% of the variability in the total carbon feed print across 531 farms, while strongly reducing the farm-specific data requirement to 12 feed rations for lactating cows against the 162 animal-rations of the detailed survey of Thoma et al. (2013c). The additional 95% confidence interval on the carbon footprint of an individual farm amounts to less than 10%.

The simplified version of the tool represents the variations across farms well with an overall square of the geometric standard deviation of 1.4. This means that the 95% confidence interval is between the best estimate for the considered farm divided by 1.4 and the best estimate multiplied by 1.4. In practice, this means that the simplified tool enables the farmer to have a fair estimate of his footprint while strongly reducing the data requirements compared to the detailed survey of Thoma et al. (2013c).

The uncertainty assessment represents only a first estimate of uncertainty regarding the lack of accurate data on individual parameter distribution and standard deviations. Improvements are especially needed in estimating the fertilizer and different auxiliary inputs per kg crop. In addition, data should be collected in such a manner as to ensure that rations and different regional parameters are determined from a statistically representative sample of the farm demographics.

Mitigation scenarios demonstrate the need to address the less efficient farms, though their impact on the overall USA average carbon footprint remains limited. Effects of different management practices, such as digesters, energy reduction scenarios or cull rates, could be tested using this simplified tool. In addition, future research should target enteric methane emissions, with a focus on microbiological research on diets and biological flora to promote lower emissions.

The developed calculator represents a powerful tool for producers to evaluate their own key parameters of influence, and to test the most efficient best management practices corresponding to their specific behavior. Finally, it is crucial the GHG is not analyzed unilaterally (i.e., without consideration of potential tradeoffs with other impact categories).

Acknowledgments

This work was funded by the Innovation Center for US Dairy. The Innovation Center played an instrumental role in collection of the on-farm data. Without the strong industry commitment to collect high quality data, this study would not have been possible. Finally, the Innovation Center has worked with the publisher in the establishment of this special issue.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.idairyj.2012.09.004.

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