Variation in carbon footprint of milk due to management differences between Swedish dairy farms

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Abstract

To identify mitigation options to reduce greenhouse gas (GHG) emissions from milk production (i.e. the carbon footprint (CF) of milk), this study examined the variation in GHG emissions among dairy farms using data from previous CF studies on Swedish milk. Variation between farms in these production data, which were found to have a strong influence on milk CF were obtained from existing databases of e.g. 1051 dairy farms in Sweden in 2005. Monte Carlo analysis was used to analyse the impact of variations in seven important parameters on milk CF concerning milk yield (energy corrected milk (ECM) produced and delivered), feed dry matter intake (DMI), enteric methane emissions, N content in feed DMI, N-fertiliser rate and diesel used on farm. The largest between farm variation among the analysed production data were N-fertiliser rate (kg/ha) and diesel used (l/ha) on farm (coefficient of variation (CV) 31-38%). For the parameters concerning milk yield and feed DMI the CV was approx. 11 and 8%, respectively. The smallest variation in production data was found for N content in feed DMI. According to the Monte Carlo analysis, these variations in production data led to a variation in milk CF of between 0.94 and 1.33 kg CO_2 equivalents (CO_2e) per kg ECM, with an average value of 1.13 kg/CO_2e kg ECM. We consider that this variation of ±17% that was found based on the used farm data would be even greater if all Swedish dairy farms were included, as the sample of farms in this study was not totally unbiased. The variation identified in milk CF indicates that a potential exists to reduce GHG emissions from milk production on both national and farm level through changes in management. As milk yield and feed DMI are two of the most influential parameters for milk CF, feed conversion efficiency (i.e. units ECM produced per unit DMI) can be used as a rough key performance indicator for predicting CF reductions. However, it must be borne in mind that feeds have different CF due to where and how they are produced.

Keywords: Monte Carlo analysis, life cycle assessment, greenhouse gases, feed efficiency, production parameters

Introduction

World dairy production is today estimated to contribute 3% (±26%) of total anthropogenic greenhouse gas (**GHG**) emissions, or 4% when dairy-related meat production (i.e. culled and fattening animals from dairy production) is included (Gerber *et al.*, 2010). To devise and develop strategies to reduce GHG emissions from the milk production chain, all sources of emissions connected to the system need to be included in analyses. Life Cycle Assessment (**LCA**), an ISO standardised method, has been used in several studies of the environmental impact of milk production (de Vries and de Boer, 2009). During recent years this method has also been used in calculations of GHG emissions from a product's lifecycle (BSI, 2008), i.e. the product carbon footprint (**CF**). The CF of livestock products is commonly presented as a single average value on national level or for a specific production system, e.g. intensive, extensive, conventional or organic farming (de Vries and de Boer, 2009).

The CF of agricultural products (e.g. milk) always includes a certain level of uncertainty, since emission estimates of the GHG nitrous oxide (N_2O) and methane (CH_4) are associated with large uncertainties due to the nature of the biological processes causing these emissions in soil, the rumen and manure (Rypdal and Winiwarter, 2001). This is especially the case for N_2O emissions from soil, where the recommended emissions factor (**EF**), according to the Intergovernmental Panel on Climate Change (**IPCC**) guidelines, is 0.01 kg N_2O-N/kg applied nitrogen (N), with the uncertainty ranging between 0.003 and 0.3 kg N_2O-N/kg applied N (IPCC, 2006a). Only deeper knowledge of how to model the biological processes producing biogenic CH_4 and N_2O can reduce this type of uncertainty in CF estimates of agricultural products. There are also uncertainties in the CF of milk associated with the production data used in the calculations (e.g. average milk yield, fertiliser rate, feed intake, etc) which are often collected as mean values from statistics or from farm inventories. These uncertainties in the production data are due to *i)* inadequate official statistics and *ii)* differences in management practices among farms resulting in variations in the production data across farms. Precise values of important production parameters can be difficult to obtain at farm level, especially when estimating yields and consumption of silage and grazing. A deeper knowledge of uncertainties and variations in production data is important when analysing feasible strategies to decrease the CF of milk.

Uncertainty in estimates of milk CF caused by variations in production data have so far been analysed in combination with uncertainty due to the EF used for N_2O and CH_4 emissions. Basset-Mens *et al.* (2009) found that the standard deviation in the CF of milk in New Zealand was 38% of the mean value due to variations in feed intake and N-fertiliser rate, as well as uncertainties in the EF used in the estimates of N_2O from soil, enteric CH_4, leached NO_3 and NH_3 from manure and fertiliser. Other studies describe the influence of management practices on GHG emissions from dairy farms. For example, Gibbons *et al.* (2006) reported a wide range of total emissions at farm level in the UK (approx. 4 200-16 400 kg CO_2e per hectare) and attributed such variation to different farm management methods. Estimates of milk CF in pastoral-based dairy systems in Ireland indicate that simple changes in management (e.g. pasture quality, nitrogen application rates and silage quality) can affect the total GHG emission estimates by 5-6% at both farm and national levels (Lovett *et al.*, 2008).

According to Flysjö *et al.* (2010), the production parameters with the largest impact on the average CF of milk in Sweden are milk yield (as it is the reference unit to all GHG emissions), feed dry matter intake (**DMI**), N in excreta, N-fertiliser rate and diesel fuel used. These parameters are affected by management, and thus by the dairy farmers' decisions, and are therefore an important area of study in seeking mitigation strategies to reduce milk CF in similar production systems. In this context, uncertainties in the EF used to estimate N_2O and CH_4 emissions are same irrespective of the farmers' decisions, and cannot be controlled or changed by the individual farmer at present. Our starting hypothesis was that variation in production data (e.g. management methods) among farms leads to significant differences in milk CF between farms. The novel aspects of this study are that we *i)* analysed how different management practices affect the uncertainty in the national average CF of milk from a high yielding production system with intensive use of concentrate feed and housed animals by *ii)* using large existing datasets of production data for dairy farms instead of using data from farm inventories (Cederberg and Flysjö, 2004; Thomassen *et al.*, 2008) or surveys (Winsten *et al.*, 2010). Farm inventories are commonly used in CF estimates and have the advantage of uniformly collected data but the disadvantage of relatively small samples. The advantage with surveys is that they can provide large datasets, but the disadvantage is the higher risk of inconsistency in the data.

The main objectives of this study were to analyse the variation in important production data among Swedish dairy farms and to investigate the impact of these variations on the national average CF of milk, using Monte Carlo (**MC**) analysis. The latter calculates the probable variation in milk CF instead of a one-point estimate of the average CF of Swedish milk. The overall aim was to gain further knowledge of how improvements in management practices can reduce GHG emissions from dairy farms. We examined the following questions:
1) What variations exist in the most important production parameters used in CF estimates between Swedish dairy farms?
2) How much do milk CF estimates vary between Swedish dairy farms as a result of variations in the most important production parameters?

The study also examined the most crucial production factors in terms of potential of reducing milk CF at farm level, based on current practices on Swedish dairy farms.

Materials and Methods

Data acquisition

Swedish average production data

Production data used in this study to represent average Swedish milk were taken from national GHG estimates in 2005 presented by Cederberg *et al.* (2009). The data which were derived from national accounts and statistics with complementary data from advisory services, research reports and agricultural businesses, were used when calculating the average milk CF that constituted the basis in our variation analysis of CF. During the study year (2005), approximately 393 000 cows in Sweden produced 3 250 000 ton energy corrected milk (**ECM**), of which 5% was organically produced. Cows in Sweden are mainly kept indoors, in tied stalls or loose housing systems, and are milked all year around, with a mean lactation period of 305 days. The replacement rate is about 38%, and heifers start milking at an average age of 28 months. The average cow weight is 600 kg. The diet consists of approximately equal shares of roughage and concentrate, with the latter consisting of half grain and half protein feed (mostly rapeseed meal, soy cake meal and by-products from the cereal and sugar industries). The roughage mainly consists of grass or grass/clover silage produced on the farm. Maize silage and by-products from the sugar beet industry may also be used in southern Sweden. The cows feed intake from grazing is relatively low, an estimated <10% of total DMI on average. The grain in the feed is mainly cultivated on the dairy farm, while the protein feed is supplied by the feed industry. Of the manure management systems, approx. 70% are based on slurry and 30% on solid manure and for heifers also some deep litter. The manure is mainly used on the farm or on neighbouring farms if extra field spreading acreage is needed.

Variations in production data

The farm production parameters considered in this study were 'milk yield' (ECM produced and delivered), 'feed DMI', 'enteric CH_4 emissions', 'N content in DMI', 'N-fertiliser rate' and 'diesel on farm' (defined further in *Calculating variations in production data)*, since these are reported to have the greatest impact on the estimated CF of Swedish milk (Flysjö *et al.*, 2010). To determine how these production parameters vary between dairy farms, the required data were collected from three different sources (Table 1).

Animal production data were obtained from the Swedish Dairy Association (**SDA**) and originated from the feed advisory service 'IndividRam' (www.svenskmjolk.se). This advisory service includes individual feeding regimes, which are followed up monthly during visits by feed advisors to individual farms. The system involves continuous recording of production data such as milk yield (derived from the national recording program), feed DMI and feed quality in a management software program. These production parameters and costs are compiled in a national database from which SDA derives statistics when investigating e.g. dairy farm profitability. The dataset used in our study comprised 1051 dairy farms for the year 2005. Milk production on these farms, which represented around 12% of all dairy farms in Sweden, corresponded to 12% of total national milk production. The production data obtained included dairy cows but not replacement animals.

Data on N-fertiliser rates used on dairy farms were obtained from a large national database of farm-gate nutrient balances created by the national advisory project 'Focus on Nutrients' carried out by the Swedish Board of Agriculture since 2000 (Jordbruksverket, 2008). The nutrient balances are drawn up by advisors during individual farm visits. The dataset used in this study comprised 920 conventional dairy farms during the period 2004-2006.

Official statistics on diesel use at dairy farms were not available: so, data were taken instead from two earlier LCA studies (Cederberg and Flysjö, 2004; Cederberg *et al.*, 2007). Those studies were based on farm inventories from a total of 46 dairy farms in western and northern Sweden.

Table 1: Sources of data used to determine variations in chosen production parameters on dairy farms

Parameters of production data	Number of farms	Year	Origin of data	Reference
ECM[a] produced Delivered share (of produced ECM) Feed DMI[b] N content in DMI Enteric CH_4	1051	2005	National database with production data collected in the advisory service of individual feeding plans ('IndividRam')	Swedish Dairy Association (www.svenskmjolk.se)
N-fertiliser rate (on farm)	920	2004-2006	National database with farm balances of nutrients performed by advisory service 'Focus on Nutrients'	Swedish Board of Agriculture (www.greppa.nu)
Diesel used (on farm)	46	2003 2005	23 farm inventories in western Sweden 23 farm inventories in northern Sweden	Cederberg and Flysjö (2004) Cederberg *et al.* (2007)

[a] Energy corrected milk, [b] Dry matter intake

Methodology

Estimating average carbon footprint

The average CF of Swedish milk was estimated according to Flysjö *et al.* (2010) using a standardised method of LCA (ISO, 2006a and 2006b) for calculating the environmental impact of a product in a life cycle perspective. All calculations were carried out using the LCA software tool SimaPro 7 (PRé Consultants bv., 2010). The GHG emissions were expressed as global warming potential (GWP) in a 100-year time horizon according to IPCC (2007), defined as carbon dioxide equivalents (CO_2e); 1 kg CO_2 = 1 kg CO_2e, 1 kg CH_4 = 25 kg CO_2e and 1 kg N_2O = 298 kg CO_2e.

The functional unit (**FU**) used as the reference unit for all flows within the system studied was 1 kg ECM at farm gate, including all by-products, surplus calves and meat from culled cows. Since the aim of the present study was to analyse variations and uncertainties in CF as a consequence of farm management methods, there was no need to allocate emissions between milk and meat.

The system boundary was 'cradle-to-farm gate'. A schematic overview of the production system is shown in Figure 1. All major emissions of CH_4, N_2O and CO_2 associated with production of input products and processes used in dairy farm production were accounted for, from the extraction and refinement of raw materials until the milk is delivered from the farm. Some minor emissions (contributining less than 1% of the total emissions) were omitted, e.g. emissions from the production of pesticides, detergents and medicines. Farm land is related to feed DMI as an average yield per hectare for each feed crop used (i.e. the estimated average crop yields for total feed cultivation in Sweden 2005 (Cederberg *et al.*, 2009)). Emissions associated with the construction of agricultural buildings and machinery were not included. Capital goods for transport and energy (e.g. car manufacture, power plant construction) were considered, since these are included in existing databases. GHG emissions associated with changes in land use were not considered.

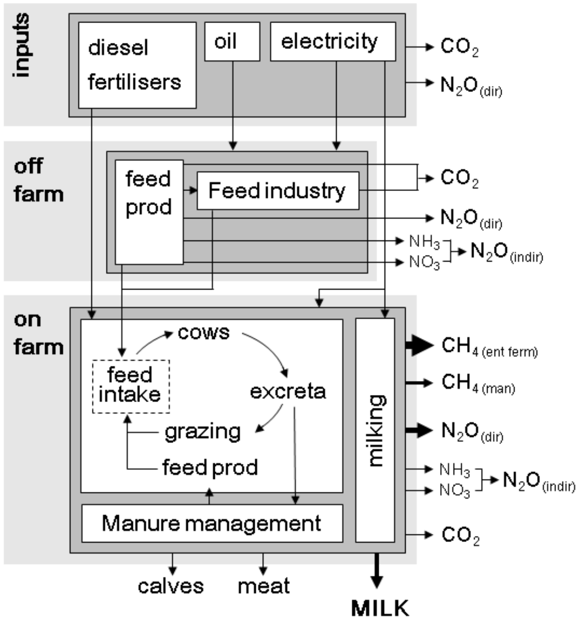

Figure 1: Schematic overview of the milk production system from 'cradle-to-farm gate' in Sweden.

Emissions of enteric methane were calculated using the national model (Lindgren, 1980; Bertilsson, 2001), which is also used in the national inventory report for Sweden. Input data in this model are: animal live body weight (to estimate the energy required for maintenance), milk yield (to estimate the energy required for production), lactation period, energy content in feed intake, and proportions of roughage feed and crude protein in total DMI. For the average Swedish dairy cow producing 8 843 kg ECM/year in 2005, the annual emissions were estimated to be 127 kg CH_4. For heifers, an estimated average value for CH_4 emissions of 53 kg CH_4/head per year was used (Cederberg *et al.*, 2009).

Methane emissions from stored manure and excreta deposited on the field during grazing were calculated according to IPCC guidelines (IPCC, 2006a and 2006b).The emission factors and methane conversion factors (**MCF**) used were those proposed by IPCC, except the MCF for slurry, where we used the value of 4% suggested in Swedish national studies (Rodhe *et al.*, 2008). Production of manure was calculated based on DMI with 70% digestibility.

Direct emissions of nitrous oxide from soil and stored manure were estimated following IPCC guidelines and EF values (IPCC, 2006a). Nitrogen applied to soil as manure was calculated as N in excreta (in average 134 kg N/cow per year and 40 kg N/heifer per year) plus N in straw (for cows 2.5 and for heifers 1.0 kg N/head per year) and feed waste (5.7 kg N/cow per year, including both cows and heifers), minus N losses of ammonia (NH_3) and N_2O in the house and storage. N in excreta was calculated as the total amount of N in feed DMI minus the amount of N in milk and animals (calves and growth).

Indirect emissions of N_2O, i.e. emissions caused by volatilisation of NH_3 and leaching of nitrate (NO_3), were estimated using EF values according IPCC (2006a). Volatilised NH_3 in the house, manure storage and at manure spreading was calculated using the national software program 'Stank in Mind' (version 1.17) developed by the Swedish Board of Agriculture (www.sjv.se) and used e.g. for calculating nutrient flows and losses on farms by farm advisory services (Linder, 2001). The program uses national EF values for volatilisation of NH_3 from manure (Karlsson and Rodhe, 2002) and leaching of NO_3 (Aronsson and Torstensson, 2004). The average ammonia losses from manure handling in the dairy system were calculated to be 0.059 kg NH_3-N/kg $N_{excreted}$ in the house, 0.0068 kg NH_3-N/kg $N_{excreted}$ during storage and 0.219 kg NH_3-N/kg $N_{excreted}$ when applied to fields (Cederberg *et al.*, 2009). Volatilied NH_3 from excreta deposited on pasture and NH_3 from ammonium nitrate fertilisers were calculated with the EF values 0.08 kg NH_3-N/kg $N_{excreted}$ and 0.02 kg NH_3-N/kg N respectively. Leached NO_3 from feed production as an average for a loamy soil in western Sweden was esstimated to be 28-30 kg NO_3-N/ha per year for grass/clover leys and 37 kg NO_3-N/ha per year for grain (Cederberg *et al.*, 2009). Autumn spreading of manure was assumed to give an additional 0.017 kg NO_3-N/kg $N_{excreted}$ (Cederberg *et al.*, 2009).

Calculating variations in production data

All animal production parameter data obtained from 'IndividRam' were given as total monthly values for each farm. Data for the parameters 'ECM produced' and 'ECM delivered' (see definition below), 'protein in milk, 'feed DMI', 'metabolisable energy' and 'protein in DMI' were recalculated to an annual mean value per cow for each dairy farm. All mean values that included data for 8-12 months resulted in a dataset of 1051 farms (226 farms with fewer than 8 months of data were excluded). Another eight parameters were calculated for each farm separately. 'N content in DMI' was calculated from the parameters 'protein content in DMI' and 'feed DMI', using a factor of 6.25 to convert protein to N. DMI is in the advisory service recorded either manually, or directly by automatic feeding systems on farms. Protein content and other feed qualities in the feeding strategies are based on default values, lists of ingredients for purchased feed and farmers' own feed analyses. The parameters 'feed DMI' and 'ECM produced' were used to calculate feed conversion efficiency, '**FCE**' (kg ECM produced/kg DMI) (Beever and Doyle, 2007). Also another parameter on feed intake were calculated; 'feed DMI_{ECM}' (i.e. kg DMI/kg ECM produced) to relate feed DMI to milk yield. The parameter 'roughage share' (used in emission estimates of enteric fermentation) was calculated as the difference between total 'feed DMI' and intake of concentrate, divided by total 'feed DMI'. It is not specified in the dataset whether grazing is included in total DMI, and according to feed advisors it may or may not be, but it is probably included for farms where grazing is a large part of the feed intake during summer. 'Excreted N' was calculated as the total amount of N in feed DMI minus the amount of N in milk and N in calves and growth (using an average value of 3.7 kg N/cow per year for calf and growth). 'Enteric CH_4 emissions' was calculated for each farm according the national model described above, using farm-specific parameters of milk yield, energy and protein content in feed DMI and share of roughage in feed DMI. The parameter 'EF CH_4' is a farm-specific emissionfactor for CH_4 calculated by dividing 'enteric CH_4 emissions' by 'feed DMI' and used to combine parameters. Finally, the parameter 'delivered share' of ECM produced was calculated. In Sweden, milk yield is recorded and presented in two ways: *i)* ECM *produced* (quantities and qualities are recorded monthly by the official milk recording programme) and *ii)* ECM *delivered* (recorded by the dairy for each milk delivery). 'ECM produced' includes fresh milk fed to calves, as well as milk wasted due to infections and pharmaceuticals. This parameter is used when calculating enteric fermentation, N in excreta and feed efficiency. 'ECM delivered' is milk delivered to the dairy industry and this is the functional unit (reference basis) by which the GHG emissions are divided. Basic statistics were calculated on all these parameters to establish the variation between dairy farms: mean, standard deviation (s.d.), coefficient of variance (CV), minimum, maximum, and lower (Q_1) and upper (Q_2) quartiles (Table 2).

The parameter 'N-fertiliser rate' was given as a total for each farm, divided by farm area to obtain kg N/ha, i.e. an average value for all crops. There were no crop yields given in the database to correlate to the N-fertiliser rates, mening that the variation in N-fertiliser rates can be due also to differences in crop yields. In the MC analysis a fixed yield/ha for each crop is presumed (i.e. the average for feed cultivation in Sweden 2005). Regression analysis was carried out on the correlations between N-fertiliser rate and livestock density. The parameter 'diesel on farm' was given in litres per hectare for each farm. Basic statistics were calculated as described for animal parameters.

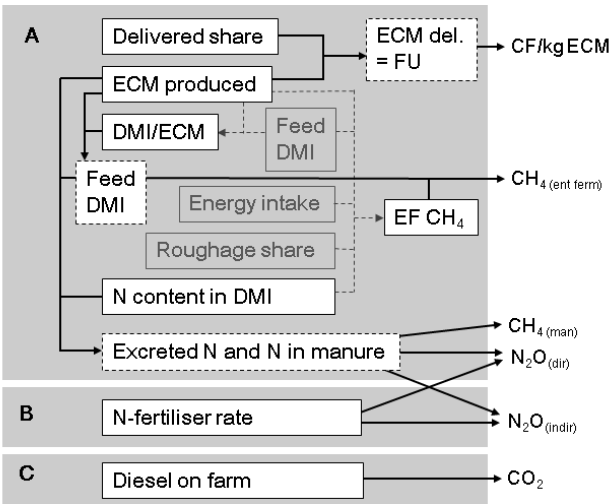

Figure 2: Parameters used in Monte Carlo (MC) analysis of variation in carbon footprint CF for Swedish milk (white boxes with solid borders show parameters varied in MC analysis, those with dashed borders show calculated parameters in MC analysis and grey boxes show production data used in calculation of enteric methane emissions on individual farms). Arrows show connections between parameters and the greenhouse gas calculation in which they are used; dashed lines indicate calculations of the parameters used in MC analysis. Sources of statistics are A: Swedish Dairy Association, B: Swedish Board of Agriculture and C: farm inventories by Cederberg and Flysjö (2004) and Cederberg et al. (2007).

Connecting correlated parameters

Since relatively strong correlations were found in the data set between parameters (e.g. R^2>0.5 for 'ECM produced' and 'feed DMI' as well as 'ECM delivered' and 'N content in

DMI'), these were connected to each other to avoid unrealistic combinations of data in the MC analysis (see Figure 2). To do this, we used 'ECM produced' as the key parameter (Figure 2) and multiplied it by 'delivered share' (of ECM produced) to give the functional unit (i.e. 'ECM delivered') to obtain the final CF. The parameter 'feed DMI' was obtained by multiplying the parameter 'ECM produced' by the parameter 'feed DMI_{ECM}' (kg DMI/kg ECM produced). This calculated value of 'feed DMI' was multiplied by the parameter 'EF CH_4' to calculate the emissions of enteric methane. The calculated parameter 'feed DMI' was also used, together with the parameters 'N content in DMI' and 'ECM produced', to calculate 'excreted N', which is one of the parameters used in calculations of N_2O emissions from soil.

Statistics

Monte Carlo analysis

The influence of variations in production data on the CF was analysed by MC analysis. This method randomly chooses, for each iteration, one value for each of the defined parameters within the range of that parameter defined by standard deviations. Based on 5000 iterations the probability distribution of CF values for milk from Swedish dairy farms was estimated. Parameters varied in the analysis were 'ECM produced', 'delivered share', 'feed DMI_{ECM}', 'N content in DMI', 'EF CH_4', 'N-fertiliser rate' and 'diesel on farm' (Table 2). The MC analysis was performed with the same software tool, Sima Pro 7, as was used for calculating the CF.

Standard deviations

In MC analysis in Sima Pro 7, the distribution of the parameters varied had to be classified as normally or log-normally distributed. In our analysis a normal distribution was assumed for all parameters used. The distribution of each parameter did not exactly follow the normal distribution (tested by Anderson-Darling test), but even if the P-values were low we chose the normal distribution as it fitted better than a log-normal distribution and graphically the discrepancy from normal distribution was not to large.

Since CF of the national average milk production was the baseline in our analysis of the impact of variations in production data, we needed standard deviations corresponding to the national mean values. The standard deviations used were therefore calculated using mean values from the national average and CV of the farm data from the 1051 dairy farms in 'Individ Ram' of each parameter as well as the parameter 'N-fertiliser rate' from the 920 farms, following the definition of CV as s.d. divided by the mean ($s.d._{\text{used in MC analysis}} = CV_{\text{farm data}} \times mean_{\text{national average}}$). For the parameter 'diesel on farm', the s.d. from the datasets was used.

All calculations for basic statistics and regression analysis were performed with the software Minitab® (www.minitab.com).

Results

Variation in production data

Animal parameters

The largest between farm variations in the dataset for the 1051 dairy farms analysed were found in milk yield, roughage share in feed DMI and calculated N in excreta, with CV around 10% (Table 2), i.e. the average standard deviation was 10% of the mean value. The variation in feed DMI, intake of metabolisable energy, feed efficiency and enteric CH_4 emissions was slightly lower, with CV of 6.5-8.0%. Protein content in DMI varied with a CV of 4.6%. Methane emissions from enteric fermentation, calculated with the national model for each individual herd, varied between 91-151 kg CH_4/cow per year (not including replacement animals).

As expected due to their participation in advisory work, the dairy farms analysed produced 540 kg ECM/cow per year more than the average estimated for Swedish milk by Flysjö *et al.* (2010) (see ‘average SE milk’ in Table 2). Also feed efficiency, expressed as kg ECM/kg DMI and kg ECM/unit energy intake, were approximately 7% higher than the Swedish average.

Nitrogen fertiliser rate and diesel use

The variation in N-fertiliser rate in the dataset of 920 dairy farms was large (Table 2). The mean amount of N applied as synthetic fertiliser to the farm´s entire arable land was 85 kg N/ha (range = 0-252 kg N/ha), also including non-feed crops if cultivated. Corresponding figures to the ‘average SE milk’ (Table 2) are the average N-fertiliser rates used in all grain and grasslands that is cultivated for feed in Sweden. The variation found between the farms can to some extent depend on the variation in the type of crops grown. However, only a minor share of the farms had significant areas with non-feed crops, e.g 14% of the farms used more than one-fourth of the arable land to grow crops like bread wheat, sugar beet, rapeseed, pota-toes and vegetables. There was a tendency that farms growing bread wheat (around one-third of the farms) had higher average N-fertiliser rates which can be the effect of relatively higher fertiliser rates used in this type of crop. No correlations were found between N-fertiliser rate and livestock density on the farms. The variation in amount of diesel used per hectare was also large (Table 2), with a mean value of 113 l diesel/ha. There was no corresponding figure with which to compare this value, as it was given separately for roughage feed (49 l/ha), grain (22 l/ton) and protein crops (11 l/ton) in calculation of the ‘Swedish average’ (Flysjö *et al.*, 2010).

Table 2: Basic statistics on parameters for milk production (n=1051), N-fertiliser rate (n=920) and diesel use (n=46) collected from Swedish dairy farms (average values for Swedish milk production the year 2005 are shown in italics)

Parameter	Units	Average *SE milk*	Farm data Mean	s.d.	CV[a] %	Q_1	Q_2	min	max
ECM produced	kg ECM/cow per year	*8 843*	9 386	983	**10.5**	8 794	10 000	5 838	12 026
ECM delivered[b]	kg ECM/cow per year	*8 274*	8 886	980	11.0	8 293	9 505	4 724	11 785
Delivered share	%	*93.6*	94.6	2.6	**2.8**	93.5	96.4	80.3	100.0
Protein in milk	%	*3.38*	3.35	0.21	6.2	3.30	3.38	1.24	4.07
Feed DMI[d]	kg DMI/cow per year	*6 559*	6 534	448	6.9	6 276	6 822	4 539	8 002
Feed DMI_{ECM}	kg DMI/kg ECM prod.	*0.74*	0.70	0.054	**7.66**	0.67	0.73	0.55	1.04
Metabolisable energy	10^3 MJ/cow per year	*77.3*	77.8	6.08	7.8	74.2	81.8	54.4	99.8
Protein in DMI	% crude protein	*16.8*	17.2	0.8	4.6	16.8	17.7	13.8	20.7
N content in DMI	g N/kg DMI	*27.0*	27.5	12.8	**4.6**	26.9	28.3	22.1	33.1
Roughage share	%	*52.8*	52.5	5.5	10.4	49.1	55.0	37.0	78.0
Enteric CH_4 [c]	kg CH_4/cow per year	*127.6*	125.4	8.1	6.5	120.7	130.8	91.1	150.9
EF[f] CH_4	g CH_4/kg DMI	*19.4*	19.3	1.5	**7.7**	18.4	20.1	14.1	30.5
FCE[g]	kg ECM/kg DMI	*1.35*	1.44	0.10	7.0	1.37	1.50	0.96	1.82
Nitrogen efficiency	kg N_{ECM}/kg N_{DMI}	*25.6*	26.7	1.96	7.3	25.6	27.9	18.3	35.1
Excreted N[d]	kg N/cow per year	*126.7*	128.8	13.0	10.1	120.9	136.5	74.9	177.8
N-fertiliser rate	kg N/ha	*48.8*[e] *78.5*[f]	85	33	**38.5**	64	107	0.0	252
Diesel on farm	l/ha	*n a*[g]	113	35	**31.2**	88	134	62	191

Q_1=lower quartile; Q_2=upper quartile; ECM = energy corrected milk, DMI = dry matter intake; EF = emission factor; FCE =feed conversion efficiency; NA = not available.
Reference figures of mean values in the column 'average SE milk' is from a study of CF of average Swedish milk (Flysjö et al., 2010) are shown in italics. Parameters and figures marked in bold were varied in the MC analysis.
[a] Coefficient of variation is the average variance of the mean value.
[b] ECM delivered is ECM produced excluding fresh milk fed to calves and milk destroyed by infections and pharmaceuticals
[c] Calculated with the method of Lindgren (1980)
[d] N in DMI minus N in milk produced, calf and gain in weight
[e] In cultivation of grass and grass/clover silage
[f] In cultivation of grain to feed
[g] No available data at the farm level per hectare in the study cited

Variation in Carbon Footprint

The Monte Carlo analysis resulted in a Swedish average CF of 1.13 kg CO_2e/kg ECM, with a 95% confidence interval of 0.94-1.33 kg CO_2e/kg ECM (Figure 3). This variation was solely attributable to management differences between the dairy farms. The distribution of GHG emissions was 46% CH_4, 35% N_2O and 18% CO_2, with CO_2 having the smallest confidence interval, while N_2O and CH_4 had almost the same interval (Figure 4). The reason for the moderate variation in N_2O emissions despite a very large variation in N-fertiliser rates is that N in manure represents a larger proportion of N input to soil and it does not vary as much as the fertiliser rate.

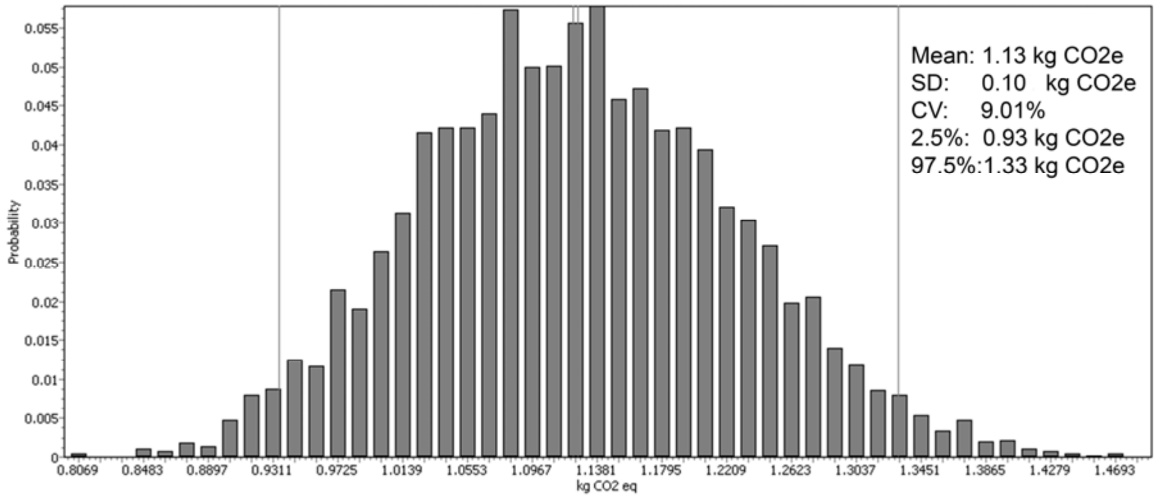

Figure 3: Frequency distribution of GHG emissions of 1 kg ECM as a result of variation in production data on farm level, based on the Monte Carlo analysis in Sima Pro. Right and left vertical lines indicate the predicted 95% confidence interval (from 2.5% to 97.5%).

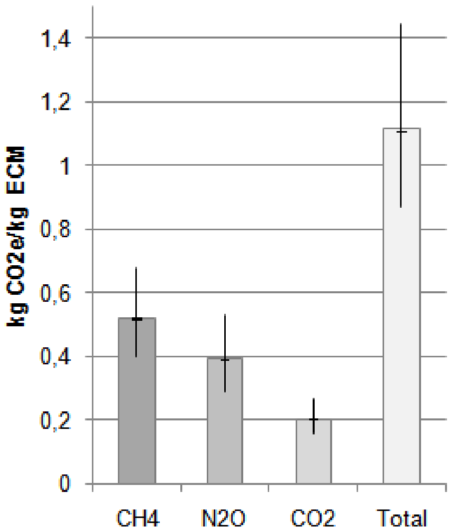

Figure 4: Contribution of each GHG to the total CF and their variations. Error bars represent the 95% confidence interval. GHG =greenhouse gas; CF = carbon footprint

Discussion

Based on the variations found in production data among Swedish dairy farms, our study suggests that the average CF of Swedish milk can be expected to vary by at least ±17%. However, the actual variation is probably higher, since the production data used in our study were obtained from dairy farms connected to the advisory service and with e.g. higher average milk yield and better feed efficiency than the average Swedish milk produced (Table 2). In addition, the set of animal production data did not include production systems using total mixed rations, a feeding system where overconsumption of feed is common (Stallings and

McGilliard, 1984). Neither did we consider other parameters in feed crop cultivation at farm level than the use of N-fertiliser (e.g. fertiliser rates in relation to crop yields and used land area for feed production), du to lack of data. Finally, other production parameters, e.g. animal health, calving age and replacement rate, also affect milk CF at the farm level (Hospido and Sonesson, 2005; Place and Mitloehner, 2010), but were not included in our study due to lack of data.

The variation in milk CF presented here is approximately in the same range that reported in two earlier LCA studies (Cederberg and Flysjö, 2004; Cederberg *et al.*, 2007) which each examined 23 dairy farms in two different regions of Sweden (Figure 5). Differences can be explained by slightly different calculation methods and probably also by the higher number of farms analysed in our study. However, the result of the comparison suggest that the method we used, analysing defined production parameters with MC analysis, is likely to include most of the variation and not overestimate it. It is also interesting to relate the uncertainty in CF caused by varying management factors, as determined in this study, with the uncertainty in CF caused by uncertain emission factors used in estimates of N_2O from soil and enteric CH_4 emissions. This latter uncertainty due to uncertain EF values was approximately ±30% for Swedish milk when analysed by Flysjö *et al.* (2010) using the same average production parameters and EF values (except for enteric CH_4 emissions) as in this study.

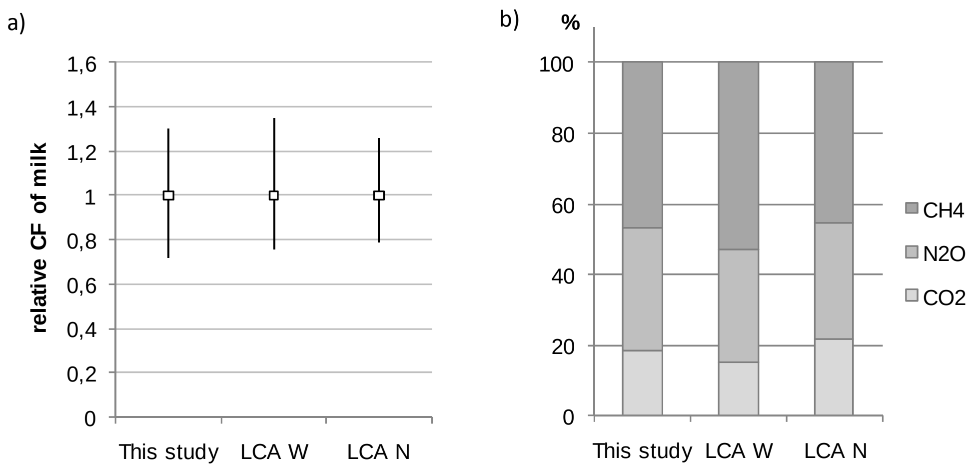

Figure 5: Comparison of normalised results from Monte Carlo analysis (this study) with (a) corresponding variation in the range of CF values and (b) distribution of GHG for two LCA studies made on 23 farms in western Sweden in 2002 (LCA W) (Cederberg and Flysjö, 2004) and 23 farms in northern Sweden in 2005 (LCA N) (Cederberg et al., 2007). GHG =greenhouse gas; CF = carbon footprint; LCA = Life Cycle Assessment

The datasets of animal production parameters (1051 dairy farms) and N-fertiliser rates (920 dairy farms) used in this study provide the most comprehensive production data available for Swedish dairy production. They represent those regions (with different climate conditions and feed production) in the country where milk production is situated. The reason for using these sources of production data despite some bias (i.e. farms connected to the advisory service having better performance than the average dairy farm) was that they gave us the opportunity to calculate variations based on production data from a considerable number of farms without the effort of performing inventories or a survey. The disadvantage of using existing datasets was that other parameters affecting milk CF, such as replacement rate, heifer calving age, composition of feeding strategies as well as factors related to feed production (e.g. crop yields per ha), could not be analysed.

The parameters varied in the MC analysis have different levels of certainty. Delivered milk has a high level of certainty, as it is measured by the dairy industry and provides the basis for the dairy farmers' payment. Produced milk yield also has a high certainty level, as it is checked once a month on each farm. Lower levels of certainty are found in the parameter 'feed DMI', where consumption of concentrates is relatively certain as opposed to intake of roughage, which is seldom weighed on dairy farms and can also be fed in free rations (*ad libitum)*. Grassland yields are often poorly documented by farmers and mostly not weighed. Feed intake from grazing is probably the most uncertain parameter when studying milk and beef production, although this parameter is not so significant in this study of a production system with a low intake of roughage from grazing. In addition, some feed components, e.g. maize silage and super-pressed beet pulp, can be classified as either roughage or concentrate. The roughage share of total feed DMI is important in some models that calculate enteric CH_4, e.g. Lindgren (1980), Ellis *et al.* (2007) and Yan *et al.* (2006). Better knowledge of roughage feed intake (including grazing) will also be important when carbon sequestration in grasslands is included in CF estimates and when strategies to reduce GHG emissions are discussed (Soussana *et al.*, 2009). As feed intake is one of the most important production parameters in dairy production with an obvious risk of data uncertainty, accurate feed data are important in estimates of CF for milk.

A crucial finding of this study was the importance of connecting closely correlated parameters to each other to avoid unrealistic combinations of parameter values when performing the MC analysis. Unrealistic combinations, e.g. combining the highest feed intake with the lowest milk yield, would over- or under-estimate the CF and to eliminate this risk, we used standard deviations of the relationship between two dependent parameters instead of the standard deviation of the single parameters. For example, a randomly selected milk yield was multiplied by the factor 'DMI per kg ECM' in the range of this factor's standard deviation to obtain a value of DMI, instead of risking a random combination of high milk yield with DMI for a low-yielding cow in the MC analysis. By connecting the parameters in this way, we avoided over-estimating the range of variation in the average CF of Swedish milk.

Potential to reduce carbon footprint of milk

Variations in production data between farms are partly a consequence of different conditions for farming due to climate, soil type, genetic breeds and production systems (e.g. high versus low use of grazing). Another important factor is differences in farm management, which influence feed efficiency, animal health, N-fertiliser use, etc. Since these factors depend on decisions by the farmer, the potential should exist to improve milk CF at farm level (Garnsworthy, 2004; Gill *et al.*, 2010). The relatively high variation found in milk CF in this study implies that there is potential to reduce GHG emissions, i.e. if dairy farms with high CF can apply methods and techniques used on farms with lower CF. The MC analysis in this study indicates the existing variation in the average CF of Swedish milk and cannot provide any information about the characteristics of the dairy farms with high or low CF values.

The two parameters with the individual largest impact on the milk CF were 'ECM produced' and 'feed DMI', according to Flysjö *et al.* (2010). The importance of milk yield (ECM) is that it forms the functional unit by which all emissions are divided to obtain the final CF. Feed intake (DMI) is important since around 43% of the life cycle GHG emissions of milk are due to feed cultivation (including production and use of N fertilisers and diesel) (Flysjö *et al.*, 2010). These two parameters together also affect calculations of enteric CH_4, which accounts for approx 46% of the milk CF (Flysjö *et al.*, 2010). In addition, they affect N content in excreta and thereby the estimates of ammonia emissions and indirect emissions of N_2O. Thus, the merging of these two important parameters in the parameter FCE (units ECM produced per unit DMI) can be used as a type of key performance indicator to predict the potential to reduce GHG emissions at farm level. The variation in FCE found among the 1051 dairy farms in this study, i.e. 0.96-1.82 kg ECM/kg DMI (Table 2 and Figure 6), can to some extent depend on variations in the content of fat and energy in different diets. Due to lack of reference data, it is difficult to estimate how much the FCE can be improved to reduce milk CF, since FCE is not an indicator used by the Swedish feed advisory service. If also heifers feed intake could have been included the variation in FCE would probably have been greater, as it would also be effected by the replacement rate at farm level. A herd's feed efficiency is influenced by a number of different factors, with e.g. feed digestibility being important (Britt *et al.*, 2003; Beever and Doyle, 2007). It is therefore an important task for farmers and/or advisors to find the underlying reasons for low feed efficiency.

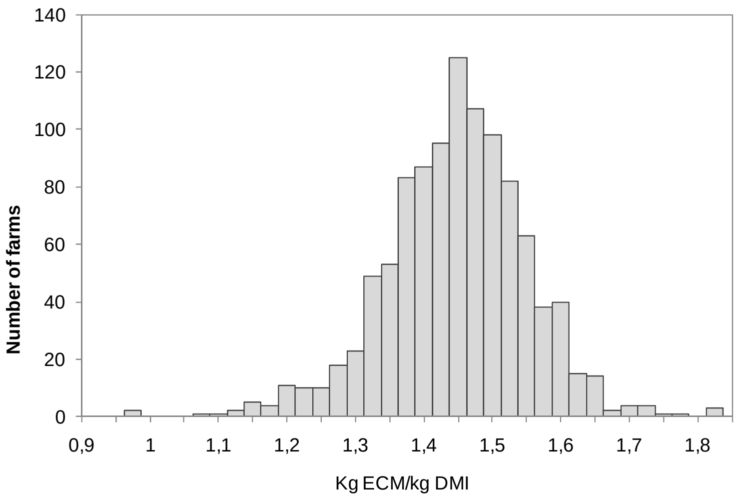

Figure 6: Distribution of feed efficiency (ECM produced per unit DMI) among 1051 Swedish dairy farms.

In contrast to production systems where feed intake is homogeneous, e.g. pasture-based milk production in New Zealand, for a production system with a large variety of feed products, FCE can not be the single ultimate indicator to suggest potential improvement in milk CF at farm or national level. It must also be emphasised that the CF of feed products differs on the basis of how they are cultivated, transported and processed in the feed industry. Even the same feed product, e.g. barley, can have different CF due to e.g. different fertiliser rates and yields. Thus, feed efficiency can be combined with feed products having both high and low possible CF values. Today, emissions from land use and changes in land use are often not included in CF calculations due to lack of consensus on methodology. In the future, when these emissions are also included in the CF for milk, it is likely that the impact of some feed crops will contribute to higher as well as lower GHG emissions, thus increasing the importance of reliable data on feed intake. For example, the use of soy cake from newly deforested land will increase the CO_2 emissions in milk CF (Gerber *et al.*, 2010), whereas the sequestration of carbon in long established grassland may decrease them (Soussana *et al.*, 2009). Another important issue regarding N_2O emissions from cultivated soils is that factors other than amount of N applied also play a part (e.g. soil type, drainage, degree of soil compaction and climate). These factors are not often considered when calculating N_2O emissions from soil, which are important for feed CF. Further studies on the impact of individual feed components on milk CF (including diet composition, influence on enteric CH_4 production and cultivation strategy) are needed to help farmers in their choice of feeding strategy.

In addition to improving feed efficiency, the potential also exists to reduce N-fertiliser rates on dairy farms, as indicated by the large variation (0-250 kg N/ha) found among the 920 dairy farms in this study, even if some of this variation also can depend on the type of crops grown and differences in crop yields due to soil and climate conditions. Supporting this conclusion is the fact that we found no correlation between purchased N in synthetic fertiliser and livestock density (and thereby access to manure) on the farms studied. This expected correlation was also found to be weak in earlier studies by Domburg *et al.* (2000) and Swensson (2002). The efficiency of N used in feed production can be improved, and thereby also the CF of feed, if the use of N in manure is optimised and adjusted to the N-fertiliser rate.

Conclusions

The national average CF of milk, which is often presented as a one-point value, includes a large variation due to differences in production parameters between dairy farms, i.e. management practice and biological outputs (e.g. milk, manure). The variation in CF found in this study (±17%) can be regarded as the least expected among Swedish dairy farms and indicates a potential to decrease the CF for Swedish milk, both at national level and on individual farms with high CF values. Milk yield and feed intake are two of the most influential parameters in CF estimates, indicating that ‘feed conversion efficiency’ (units ECM produced per unit DMI) can be used as a rough key performance indicator of measures to reduce milk CF on farm level. As there is a risk of large uncertainties in feed intake data, especially in intake of roughage from grazing and silage, accurate feed data are important for CF calculations on milk.

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