

Contribution of milk production to global greenhouse gas emissions

An estimation based on typical farms

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Abstract

Background, aim and scope Studies on the contribution of milk production to global greenhouse gas (GHG) emissions are rare (FAO 2010) and often based on crude data which do not appropriately reflect the heterogeneity of farming systems. This article estimates GHG emissions from milk production in different dairy regions of the world based on a harmonised farm data and assesses the contribution of milk production to global GHG emissions.

Materials, methods and results The methodology comprises three elements: (1) the International Farm Comparison Network (IFCN) concept of typical farms and the related globally standardised dairy model farms representing 45 dairy regions in 38 countries; (2) a partial life cycle assessment model for estimating GHG emissions of the typical dairy farms; and (3) standard regression analysis to estimate GHG emissions from milk production in countries for which no typical farms are available in the IFCN database. Across the 117 typical farms in the 38 countries analysed, the average emission rate is 1.50 kg CO₂ equivalents (CO₂-eq.)/kg milk. The contribution of milk production to the global anthropogenic emissions is estimated at 1.3 Gt CO₂-eq./year, accounting for 2.65% of total global anthropogenic emissions (49 Gt; IPCC, Synthesis Report for Policy Maker, Valencia, Spain, 2007).

Discussion and conclusion We emphasise that our estimates of the contribution of milk production to global GHG emissions are subject to uncertainty. Part of the uncertainty stems from the choice of the appropriate methods for estimating emissions at the level of the individual animal.

Keywords Greenhouse gas emissions · ‘Cradle-to-farm-gate’ life cycle assessment · Milk production · Typical dairy farms

1 Introduction

Total anthropogenic greenhouse gas (GHG) emissions increased from 28.7 Gt (gigatonnes) CO₂ equivalents (CO₂-eq.) per year in 1970 to 49 Gt in 2004. Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), the main GHGs from agriculture, account for more than 98% of global GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) estimates that 13.5% of global GHG emissions can be attributed to the agricultural sector (IPCC 2007). The global contribution of agriculture, considering all direct and indirect emissions, is estimated to be between 8.5 and 16.5 Gt CO₂-eq. per year, accounting for 17% to 32% of total anthropogenic GHG emissions (Bellabary et al. 2008). The contribution of agricultural emissions in absolute terms is highest in the USA, Brazil, India and China. Each of these countries releases between 151 and 605 million tonnes CO₂-eq. per year (UNSTAT 2010).

The FAO calculates that the dairy sector emitted 1.969 million tonnes of CO₂-eq. in 2007 of which 1.328 million tonnes were attributed to milk, 0.151 to meat from culled animals and 0.49 to meat from fattened calves. Milk and meat production from dairy herds including the processing of dairy products, production of packaging materials and transport activities are estimated to contribute 4.0% to

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global anthropogenic GHG emissions of around 49 Gt in 2004 (IPCC 2007). Milk production, processing and transport alone are estimated to account for 2.7% of global anthropogenic GHG emissions. However, studies on the contribution of milk production to global GHG emissions are rare (FAO 2010) and often based on crude data which do not appropriately reflect the heterogeneity of farming systems.

Against this background, this article sets out to improve current estimates of dairy-related GHG emissions. We estimate GHG emissions from milk production in different dairy regions of the world and investigate the contribution of milk production to global GHG emissions. Our analysis explicitly caters for the heterogeneity of dairy farming systems around the globe by drawing on the database of typical farms of the International Farm Comparison Network (IFCN). The analysis is thus based on data from 117 typical farms in 45 dairy regions representing approximately 70% (by volume) of milk production worldwide (Hemme 2007). Emissions are estimated from ‘cradle to farm gate’. This includes both on-farm emissions and emissions caused by the production of inputs used in dairy production. Emissions which occur beyond the farm gate (e.g., transport, processing, packaging) are therefore not included in the analysis.

2 Material and methods

2.1 International farm comparison network and the typical farm approach

The analysis draws on the typical farms of the IFCN. The IFCN is a worldwide association of dairy scientists, advisors and farmers. Within this network, farms and dairy production systems are defined that are typical of their region. The typical farm models allow the analyst to assess the farms’ present economic situation and to simulate the impact of technological, market or policy changes on their economic performance. The IFCN’s database is unique in that it contains a consistent set of typical farms which are all modelled with a common, internationally standardised methodology. This approach enables international comparison of farms and farming systems (Hemme 2000). The IFCN database was established with the intention to characterise milk production in different parts of the world in terms of their technological, economic and environmental performance. For this purpose, typical farms were devised for each location and analysed using internationally harmonised methods and the TIPI-CAL software (Technology Impact Policy Impact Calculations; Hemme 2000).

The concept of typical farms dates back to the 1970s when the USDA’s Economic Research Service began to

construct a set of typical farms in the USA (Hatch et al. 1982). The Agricultural and Food Policy Center (AFPC) at Texas A&M University is currently applying this approach to quantify the impact of alternative policies on representative farms in the USA (AFPC 2010).

Given the availability of accounting databases in most regions, one might ask why the IFCN has created a new database. This was done because existing data sets show significant country-to-country differences in the methodology used and in the type and quality of data available. These differences include, for example, depreciation methods, the recording and valuation of labour input and the separate recording and valuation of volumes and prices of inputs to production. Moreover, important data is often missing so that only partial production cost estimates can be carried out. Ex-post correction or amendment of the datasets, besides being a potential source of error, is often impossible or requires prohibitively high effort.

Figure 1 shows countries for which typical farms have been elaborated and emissions can be assessed based on data from those farms. For the remaining countries, emissions were estimated with the use of a regression model, which will be explained later. Two typical farms (one average-sized and one larger farm) were included for each country. The selection of farms was based on the size of the country, the heterogeneity of farm structures and the availability of research partners (data availability). In most of the developed countries, farm survey data were used in modelling the typical farms. Since such information was not available in developing countries, we modelled existing farms for which sufficient data were available. Each typical farm modelled was discussed with a panel of local dairy experts to ensure that the farm represented the typical farm type, i.e., the one that produces most of the milk in the respective country or region. Modelled in this way, the typical IFCN farms are not representative of their country or region in the statistical sense; they rather represent the farm types that account for the bulk of milk production in the respective country or region.

2.2 The TIPI-CAL software and the LCA module for estimating GHG emissions

The software used for modelling typical farms and comparing their performance internationally is the TIPI-CAL model. This model was originally developed in the late 1990s (Hemme 2000). The Farm Level Income and Policy Simulation Model (FLIPSIM) developed by the Agricultural and Food Policy Center at Texas A&M University served as the prototype for TIPI-CAL. TIPI-CAL consists of a farm-level model representing technical parameters of the production process as well as economic performance

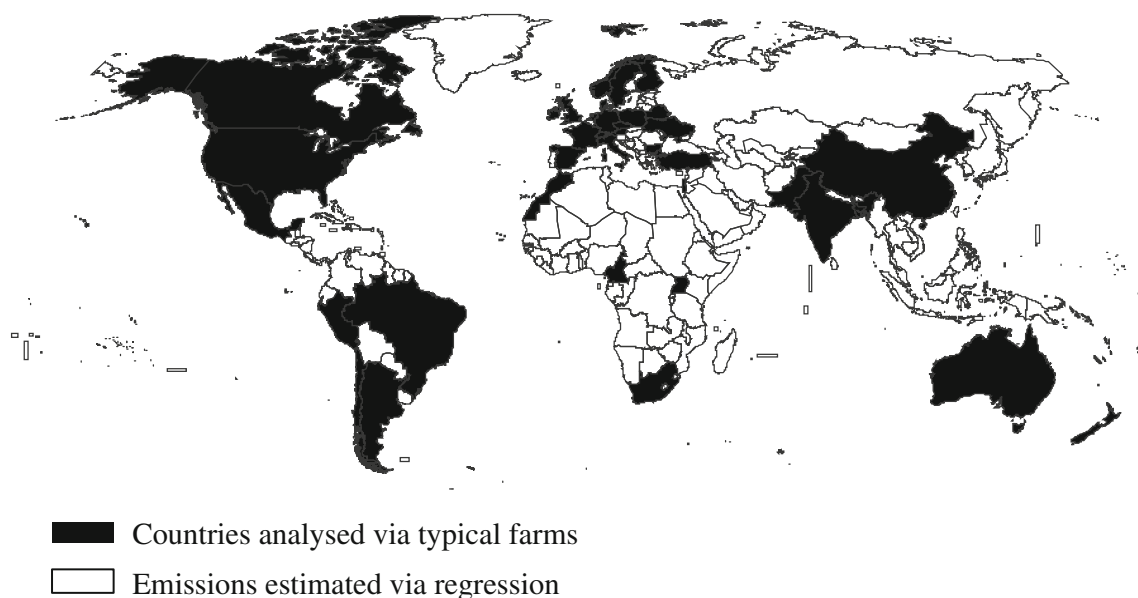


Fig. 1 Countries included in the analysis (source: Hemme 2007)

parameters. The key strength of the model is the possibility to assess the impact of changes in policies, technology or markets. Moreover, the design of TIPI-CAL is modular, thus providing the opportunity of adding further modules to address specific research questions, in this case estimation of GHG emissions. The current version is TIPI-CAL-5.1, which was thus extended by a partial Life Cycle Assessment (LCA) module to estimate GHG from milk production at the farm level. The underlying method used in this analysis applies the principles of LCA according to ISO (2006).

The scope of this LCA module is the entire production process of raw milk, from the production of inputs to products leaving the farm gate. Thus, the direct and indirect emissions of the entire milk production process up to the farm gate are considered. The direct emissions include all emissions which originate at the farm level. Indirect emissions include emissions from the production and transportation of intermediate products such as fertilisers or concentrates as well as emissions from the production of farm assets (e.g., buildings and machineries). Emissions from deforestation and other land use changes are not included in the LCA framework used in this study (see Fig. 2).

2.3 Estimating greenhouse gas emissions at the farm level

In order to compare emissions across a wide variety of farming systems, a functional unit is needed. The functional unit describes the primary function fulfilled by a production system and enables different systems to be treated as functionally equivalent (Guinée et al. 2002). As the primary

function of dairy farming systems is the production of milk, 1 kg of energy-corrected milk (ECM)¹ serves as the functional unit in this analysis. GHG emissions are thus quantified in kilograms CO₂-eq. per kg of ECM produced.

2.3.1 Methane emissions

The level of CH₄ emission caused by the digestion in the rumen depends on the breed, age and weight of the animal, the quality and quantity of the feed used and the energy expenditure of the animal (IPCC 1996). More than 30 different mathematical models for estimating enteric methane emissions exist in the literature. These include estimation equations and estimates based on emission factors. The equation-based approaches can be categorized into two classes depending on the required input parameters: (1) models using feed input data and (2) models based on physiological parameters, i.e., milk yield and metabolic body weight. An overview on applications of the different approaches is presented by Kebreab et al. (2006) and Ellis et al. (2007).

For the purpose of this study, we estimated enteric methane emissions with the use of a formula based on physiological parameters which was initially developed by Kirchgessner et al. (1991):

$$\text{CH}_4(\text{g/day}) = 55 + 4.5 \text{ kg milk yield/cow/day} + 1.2 \text{ metabolic weight} \quad (1)$$

where metabolic weight = (live weight in kilograms)^{0.75}.

¹ ECM = energy-corrected milk with 4% fat and 3.3% protein; ECM = (milk production × (0.383 × % fat + 0.242 × % protein + 0.7832)/3.1138) >< (GFE 2001)

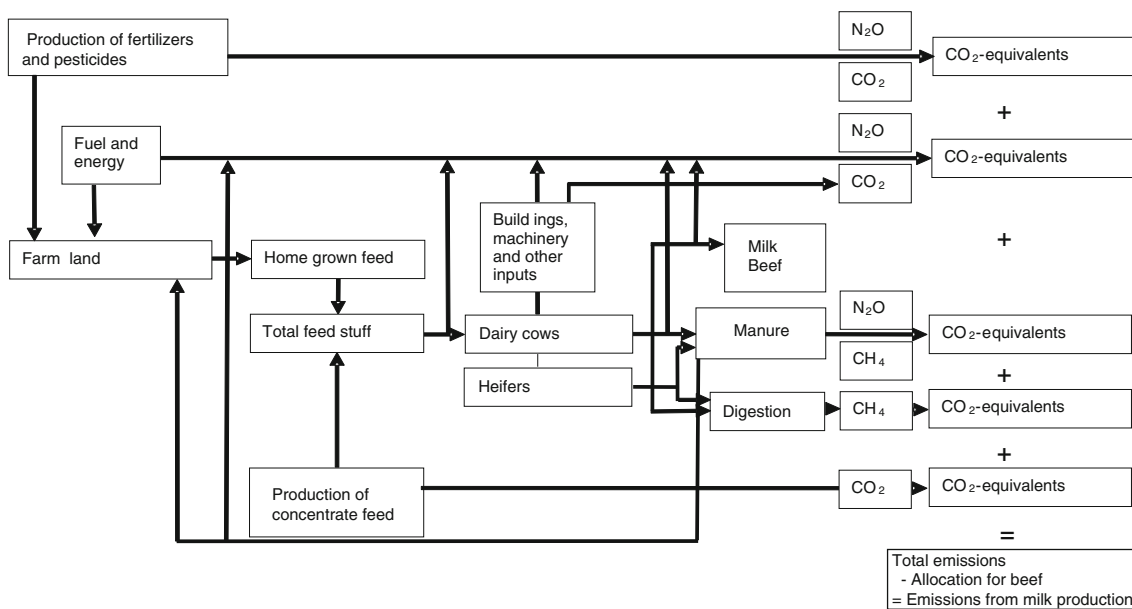


Fig. 2 System boundaries ‘cradle to farm gate’ LCA

This approach (Eq. 1) was selected because the required input data for this estimator, i.e., milk yield and live weight, is available for all typical farms included in the analysis. Given the diversity of feeding regimes across the typical farms, the use of feed input-based models would clearly have been preferable. However, these models require data on dry matter intake, NDF (neutral detergent fibre) or ADF (acid detergent fibre) intake, which is not available for all of our typical farms. In order to analyse the sensitivity of the emission estimates to the estimation method chosen, we applied six different estimation formulas to six of our typical farms for which detailed feed data is available. The results, reported in Appendix 2, show that the formula by Kirchgessner et al. (1991) tends to underestimate enteric emissions relative to the equations based on feed intake data. We may thus hypothesize that our estimation results err on the side of caution.

For the estimation of CH₄ emissions from calves and heifers, Eq. 2 was applied (Kirchgessner et al. 1991):

$$CH_4(g/day) = 55 + 1.2 \text{ metabolic weight} \quad (2)$$

The live weights of heifers were set according to the number of animals in the age clusters (0–12, 12–24 and >24 months).

Manure handling and storage represents another main source of methane emissions at the farm level. Information on the farming systems and corresponding manure management of the typical farms analysed is given in Appendix 2. In calculating these emissions, cows and heifers were standardised at 650 kg live weight and 350 kg, respectively. If, for example, the average live weight of a small cow breed is 325 kg, two of these cows are counted as one standardised cow of 650 kg live weight. The number of standardised

animals was multiplied by 21 kg of methane emission per cow and year and 10.5 kg of methane per heifer and year, respectively (Van Eerdt and Fong 1998).

In order to obtain the corresponding CO₂ equivalent, methane emissions from digestion and manure were multiplied by 25 (IPCC 2007).

2.3.2 Nitrous oxide emissions

The emissions of nitrous oxide in milk production are caused by manure handling and storage as well as fertiliser denitrification and fuel combustion. Nitrous oxide emissions from manure are calculated by multiplying the quantity of nitrogen excrements of cows, calves and heifers by an N₂O emission factor of 0.0125 kg N₂O per kg N excrement (Cederberg and Flysjö 2004). The N excrements of calves and heifers were computed based on age clusters. Animals between the ages of 2 and 12 months were assumed to excrete 22 kg N per year, and those between 12 and 24 months, 47 kg N per year (Kirchgessner et al. 1991).

The quantity of nitrogen excrements of cows is a function of milk yield as per F3 (Cederberg and Flysjö 2004):

$$\text{kg N/cow year} = 100 + \text{milk yield}(\text{kg ECM/year}) \times 0.008 \quad (3)$$

Regarding the nitrous oxide emissions from nitrogen fertilisers, we distinguish between the direct on-farm emissions and indirect emissions caused in the process of fertiliser production. The direct N₂O emissions were

calculated by multiplying the usage of nitrate nutrients in fertilisers by the N₂O emission factor of 0.013 kg N₂O/kg N nutrient (Cederberg and Flysjö 2004). The indirect N₂O emissions were computed by multiplying the usage of N nutrients by the N₂O emission factor 0.012 kg N₂O/kg N nutrient (Simon 1998).

N₂O emissions from fuel combustion were computed by multiplying the diesel fuel usage in litres by the N₂O emission factor of 0.007 g N₂O/l (Audsley et al. 2003).

Total N₂O emissions were multiplied by 298 in order to obtain the corresponding CO₂ equivalents (IPCC 2007).

2.3.3 Carbon dioxide emissions

The sources of CO₂ emissions in dairy farms are fuel combustion, fertilisers, concentrates, pesticides, machinery, buildings and other assets and inputs such as bedding material or dairy chemicals. Table 1 shows the emission factors used in the calculations.

The CO₂ emissions from concentrate feeds were calculated based on average emission rates of three typical feed classes being: protein sources (e.g., soybean meal, soybean cake, rapeseed cake), carbohydrates (e.g., wheat, barley, rye, corn) and minerals. It was assumed that the concentrate feed used on a farm contained 600 g/kg carbohydrate sources, 300 g/kg protein sources and 100 g/kg minerals and vitamins. Farm assets were clustered into vehicles, implements, buildings and fences. In order to compute the emissions from vehicles and implements, factors converting their weight into emissions (see Table 1) were applied. For buildings the

size was estimated in square metres based on the number of animals on the farm and a minimum space allowance per animal (UK Agriculture 2010). The fences were assumed to be made from wire and the indirect emissions were calculated from its length which was estimated based on the grazing area per farm. The indirect emissions of assets were divided by the expected working life which was assumed to be 10 years for vehicles and implements and 25 years for buildings. Finally, the usage of bedding material (measured in kilograms per year) was multiplied by 0.05 g CO₂/kg bedding material and dairy chemicals by 0.1 g CO₂/kg input (see Table 1).

2.3.4 Carbon credit

Carbon credit is an allocation of emissions to the side products of milk production. These include meat, manure, animal draught power and capital functions. This study only considers beef credits because there exist internationally accepted methods for quantifying such credits (Cederberg and Stadig 2003; Sevenster and de Jong 2008). However, draught power and capital functions are motives for some farmers for keeping cows, especially in developing countries. Due to these motives, high milk yield (which reduces GHG emissions per kg milk) may not be a major objective of such farmers.

The method applied in this study is the so-called cause–effect physical ('biological') allocation (Cederberg and Stadig 2003), whereby emission credits for the beef

Table 1 CO₂ emission factors used for resource inputs to dairy production

Input	Emission factor	Source
Diesel (g CO ₂ /l)	2,961	Audsley et al. (2003), Weitowitz (2007)
Electricity (g CO ₂ /kW h)	648	
Nitrogen (g CO ₂ /kg nutrient)	610	Wood and Cowie (2004), Cederberg and Flysjö (2004), Taylor (2000)
Phosphor (g CO ₂ /kg nutrient)	1,051	
Potash (g CO ₂ /kg nutrient)	800	
Lime (g CO ₂ /kg nutrient)	300	
Concentrate ingredients		
Corn (g CO ₂ /kg)	445	Kelm et al. (2004), Nagy (1999)
Minerals (g CO ₂ /kg)	111	
Soy (g CO ₂ /kg)	224	
Bedding material (g CO ₂ /kg)	0.05	Öko-Institute, downloaded from www.probas.umweltbundesamt.de
Dairy chemicals (g CO ₂ /kg)	0.1	
Pesticides (g CO ₂ /kg)	1.7	
Vehicles (kg CO ₂ /kg)	5.9	
Implements (kg CO ₂ /kg)	5.1	
Buildings (kg CO ₂ /m ²)	132.4	
Fence (wire) (kg CO ₂ /kg)	2.51	

Sources: as stated

of culled cows are allocated based on the proportion of the dairy cow’s feed intake that is needed for maintenance and body growth. It is assumed in accordance with GFE (2001) that this proportion is 40% of metabolizable energy (ME) intake, leaving 60% of ME intake for milk production. It is further assumed that male calves are sold at the age of 2 weeks.

For computation of the beef credit, all animals of a farm are first converted via their live weight into livestock units (LU)² and the total number of animals sold (cows, heifers and bull calves) is determined in terms of LU. In a second step, a farm’s total emissions are divided by the total LU per farm in order to obtain an estimate of total farm emissions per LU. The emission credits for culled cows are then computed by multiplying the number of culled cows (in terms of LU) by the total emission per LU weighted by 40% (allocation factor). Beef credits for culled heifers and bull calves are computed by multiplying the animals sold, in terms of LU, by total farm emissions per LU.

2.4 Greenhouse gas emissions from milk production by country

The dairy-related emissions from each country included in the analysis were estimated by multiplying the average emission rates of the typical farms (in kg CO₂-eq. per kg of energy-corrected milk) by the country’s milk production. Milk production data was taken from the IFCN database and contain milk from cows and buffalos. We further computed each country’s share of the aggregate milk production of all countries analysed. We also calculated for each country the corresponding share of aggregate dairy-related GHG emissions.

2.5 Contribution of milk production to GHG emissions worldwide

The 38 countries for which IFCN typical farms are available produce approximately 528 million tonnes of milk, accounting for 70% of global milk production. For 158 countries, information on milk production, i.e., data on the total milk production volume and the average milk yield, was available in the IFCN’s sector data base. Based on IFCN’s statistics these countries produce about 227 million tonnes of milk, accounting for 30% of global milk production. In order to estimate the GHG emissions from these 30% of world milk production an estimation model

was derived from the observed data (see Fig. 3). The model draws on the data of the 117 typical farms analysed to regress emission rates, i.e., the estimated emissions per kg ECM, on the corresponding milk yield. In a second step, the emission rate was multiplied with the total milk production volume of that region. Figure 3 shows the functional form of that relationship.

CO₂ emissions per kg ECM in the remaining countries are thus represented by the following function³:

$$Y = 5.12 - 1.61 \times 10^{-3} * x + 2.24 \times 10^{-7} * x^2 - 1.05 \times 10^{-11} * x^3 \quad (4)$$

where *Y* represents the emission rate (kg CO₂-eq. emissions per kg ECM) and *x* is the milk yield in kg ECM per cow and year. The *t*-statistics in Appendix 3 indicate that all coefficients are significantly (*p*<0.001) different from zero.

3 Results

3.1 GHG emissions from milk production in different countries

Tables 2 and 3 report for each of the analysed countries the average GHG emissions per kg ECM, the milk production volume and the country’s share of global milk production. The tables further display the estimated emission volumes from milk production per country and each country’s contribution to global dairy-related GHG emissions. Table 2 lists the results for European countries, Table 3 displays the results for the remaining countries included in the analysis.

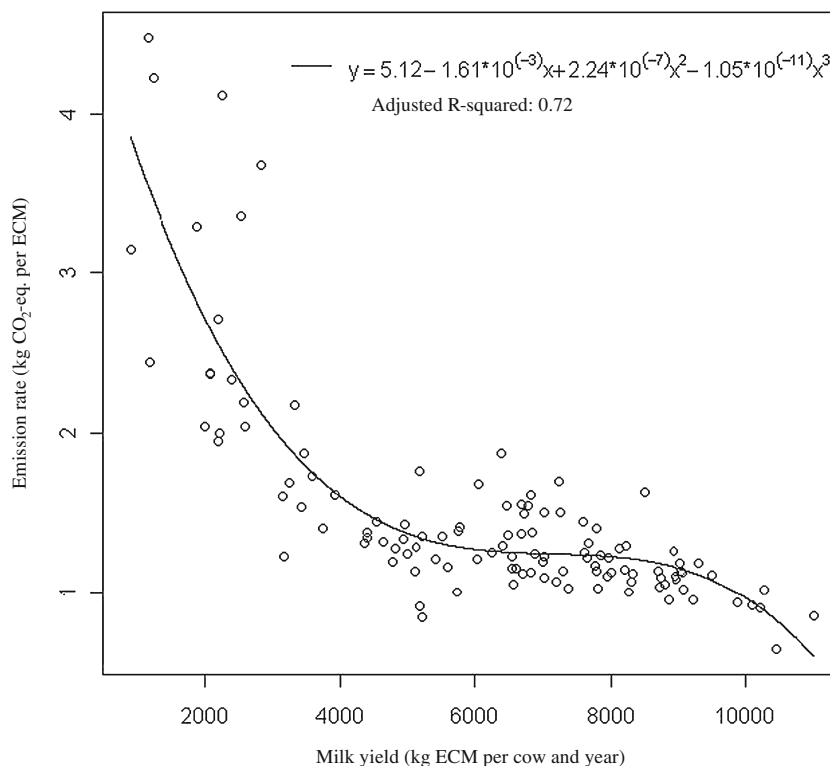
In Europe, emissions from milk production range from 0.98 kg CO₂-eq. per kg ECM in Spain to 1.71 kg in Norway. Germany, the EU country with the highest proportion of global milk production (5.54%), emits on average 1.44 kg CO₂-eq. per kg ECM and accounts for 5.32% of global dairy-related GHG emissions.

Table 3 reveals that emissions per kg ECM in the developing countries vary widely. The difference between the minimum and maximum emission rate is 260% in Africa and 160% in Asia. The highest emission rates were found in Cameroon (4.08 kg CO₂-eq. per kg ECM), followed by Bangladesh with 3.69 kg CO₂-eq. per kg ECM. Israel emerged as the country with the lowest estimated emission rate (0.88 kg CO₂-eq. per kg ECM). Weighting national emission rates by the respective milk production volumes yields an estimate of the worldwide average GHG emission rate. This was estimated to be 1.50 kg CO₂-eq. per kg ECM.

² 1 livestock unit (LU) = 650 kg live weight (Kirchgeßner et al. 1991).

³ The regression output for this cubical model is shown in Appendix 3.

Fig. 3 Relationship between milk yield and GHG emissions derived from typical farms



In Table 4, countries have been regrouped by their emission rates (bottom 10 and top 10 countries) and by their milk production volumes (top 10 milk producing countries).

Dairy farming systems with the lowest emissions per kg ECM are located in Israel, USA, and European countries. South Africa is the only African country among the 10 countries with the lowest emission rates. This is the case because South African dairy farming systems are more similar to high-intensity European counterparts than with low-intensity systems typical of other African countries. The average emission rate of the bottom 10 countries is 1.03 kg CO₂-eq. per kg ECM compared to 2.43 kg CO₂-eq. per kg ECM in the top 10 countries. The standard deviation is about ten times lower in the bottom 10 countries than in the top 10 countries.

The right-hand panel of Table 4 reveals considerable differences in the emission rates of the world's largest milk producing countries. India, as the largest milk producing country (14.1% of world milk production) has an emission rate of 1.98 kg CO₂-eq. per kg ECM. This is roughly 0.5 kg CO₂-eq. per kg ECM above the worldwide average of 1.50 kg CO₂-eq. per kg ECM. By contrast, the USA as the world's second largest milk producer was found to have the lowest average GHG emissions per kg ECM among the top 10 milk producing countries and the second lowest of all countries analysed. The emission rate of

China, the third largest producer of milk, was estimated to be 65% above the US emission rate, but 73% below that of India. As the fourth largest milk producing country, Pakistan's dairy industry is characterised by the fourth highest emission rate. Based on these estimations, we conclude that the top 10 milk producing countries account for approximately 50% of global dairy-related GHG emissions.

3.2 Greenhouse gas emissions from world milk production

Table 5 shows the results of the estimation of global dairy-related GHG emissions. As explained above, the data set of typical farms maintained by the IFCN covers approximately 70% of the global milk production volume. The emissions from the remaining 30% were estimated as per equation F4 above. The average emission rate (kg CO₂-eq. per kg ECM) per country was estimated using data on the average milk yield per cow per year. In a second step the emission rate was multiplied by milk production volume of the country—data available in the IFCN's data base.

According to these estimations, milk production in the observed countries (accounting for roughly 70% of world milk production) is responsible for 61% of global dairy-related GHG emissions. The remaining 30% of world milk production account for 39% of global dairy-related

Table 2 Milk production and GHG emission data for European countries

	Typical farms per country	Emission rate (kg CO ₂ /kg ECM)	Milk production from cows and buffalos (t ECM)	Proportion of world milk production (%)	Emissions from milk production (t CO ₂ eq.)	Percent contribution to global dairy-related CO ₂ emissions (%)
Western Europe						
Switzerland	2	1.25	4,076,940	1.09	5,096,175	0.85
Austria	6	1.28	3,292,234	0.88	4,214,060	0.70
Germany	11	1.44	29,248,736	7.82	42,118,180	6.99
Netherlands	2	1.03	11,510,751	3.08	11,856,074	1.97
Luxembourg	2	1.32	282,952	0.08	373,497	0.06
France	2	1.18	24,331,069	6.51	28,710,662	4.77
Spain	3	0.98	5,903,807	1.58	5,785,730	0.96
Italy	2	1.06	10,952,314	2.93	11,609,453	1.93
United Kingdom	2	1.08	13,897,220	3.72	15,008,997	2.49
Ireland	2	1.23	4,997,949	1.34	6,147,477	1.02
Denmark	2	1.13	4,842,075	1.29	5,471,545	0.91
Sweden	2	1.06	3,326,383	0.89	3,525,966	0.59
Finland	3	1.19	2,441,788	0.65	2,905,727	0.48
Norway	2	1.71	1,760,459	0.47	3,010,386	0.50
Central, Eastern Europe						
Poland	5	1.30	11,976,073	3.20	15,568,895	2.58
Czech Republic	3	1.45	2,730,315	0.73	3,958,956	0.66
Bulgaria	2	1.37	1,128,474	0.30	1,546,010	0.26
Ukraine	4	1.04	12,166,702	3.25	12,653,370	2.10
Belarus	3	1.67	5,503,098	1.47	9,190,174	1.53
Sum production/emissions			154,369,339		188,751,333	
Mean (weighted)		1.22				

Source for milk production data: Hemme (2007)

emissions. Based on the allocation method explained above, 0.113 Gt CO₂-eq. (accounting for about 8% of total emissions) were allocated to beef from dairy cattle. The share of GHG emissions from world milk production in global anthropogenic emissions was computed based on two estimates of the latter (FAO 2006; IPCC 2007). These two estimates (33 and 49 Gt) represent a minimum and a maximum figure of total anthropogenic GHG emissions. Depending on which of these estimates is chosen, world milk production contributes between 2.65% and 3.94% to global anthropogenic GHG emissions and thus to climate change.

4 Discussion and conclusion

This study has estimated GHG emissions for 117 typical dairy farms from 38 countries, representing 70% of global milk production. The methodology of partial life cycle analysis was applied to extensive farm data to estimate the GHG emission per kg ECM for each of the typical farms.

The results were used to derive an estimate of the contribution of world milk production to global anthropogenic GHG emissions.

Israel, USA, South Africa and most of European countries were found to have the lowest emissions per unit of milk and, at the same time, the highest milk yields. Among the European countries, Norway emerged as the country with the highest emission per unit of milk produced. This may be attributed to the fact that the typical farms of Norway keep dual-purpose breeds. These are characterised by lower milk yields and an emphasis on beef, resulting in higher emissions per kg milk.

The average emission rate across all farms analysed was 1.50 kg CO₂-eq. per kg milk. This estimate remains below FAO’s estimate of 2.4 kg CO₂-eq per kg milk (FAO 2010). However, the FAO figure includes emissions from the transportation and processing of milk which are estimated at 0.15 kg CO₂-eq. per kg milk for European countries. In the same study, the FAO observed a range of 1.3 to 7.5 kg CO₂-eq. per kg milk between the

Table 3 Milk production and GHG emission data for non-European countries included in the analysis

	Typical farms per country	Emission rate (kg CO ₂ /kg ECM)	Milk production from cows and buffalos (t ECM)	Proportion of world milk production (%)	Emissions from milk production (t CO ₂ eq.)	Percent contribution to global dairy-related CO ₂ emissions (%)
Middle East						
Turkey	2	1.61	10,645,297	2.85	17,138,929	2.84
Israel	2	0.88	1,148,986	0.31	1,011,108	0.17
Africa						
Morocco	2	2.35	1,558,790	0.42	3,663,157	0.61
Cameroon	2	4.08	129,857	0.03	529,818	0.09
Uganda	2	2.87	1,615,566	0.43	4,636,675	0.77
South Africa	2	1.13	2,589,532	0.69	2,926,171	0.49
North America						
Canada	2	1.20	8,199,905	2.19	9,839,886	1.63
USA	2	0.92	80,254,467	21.46	73,834,110	12.25
Middle and South America						
Mexico	2	1.49	10,290,000	2.75	15,332,100	2.54
Argentina	2	1.24	9,036,056	2.42	11,204,709	1.86
Brazil	4	1.29	25,930,805	6.93	33,450,738	5.55
Chile	3	1.19	2,345,636	0.63	2,791,307	0.46
Peru	2	1.63	1,436,228	0.38	2,341,051	0.39
Asia						
India	9	1.98	115,161,282	30.79	228,019,338	37.84
Pakistan	3	2.69	37,167,500	9.94	99,980,574	16.59
Bangladesh	2	3.69	2,576,631	0.69	9,507,770	1.58
China	5	1.44	37,037,922	9.90	53,334,607	8.85
Oceania						
Australia	4	1.13	9,640,930	2.58	10,894,251	1.81
New Zealand	3	1.28	17,257,319	4.61	22,089,368	3.67
Sum production/emissions			374,022,709		602,525,667	
Sum production/emissions (Table 2 countries)			154,369,339		188,751,333	
Total production/emissions			528,392,048		791,277,000	
Mean all countries ^a		1.50				

Source for milk production data: Hemme (2007)

^a Weighted by production volume per country

minimum and maximum cradle-to-farm-gate emission rates. The corresponding range found in the present analysis was 0.88 to 4.08 kg CO₂-eq. per kg ECM. The differences found between the two studies can be mainly attributed to differences in the approach chosen. While the FAO study used aggregated data from different sources, the present study relies on farm data from typical farms. The use of typical farms has the advantage of capturing the heterogeneity of farming systems. We thus claim that our analysis provides more accurate estimates than the FAO study.

It has to be considered, however, that the present analysis does not account for emission from land use change and forestry (LUCF). According to FAO (2010), the

use of concentrates, i.e., soybean cake in the dairy sector indirectly releases 17 million tonnes CO₂-eq. as a result of land use change in USA, Brazil and Argentina. These countries are the major exporters of soybean and soybean cake. The study estimates that Europe accounts for 94% of these emissions because of the great importance of soybean in the diet of European dairy cattle. Based on this estimate, the LUCF emissions would account for 0.09 kg CO₂-eq. per kg milk for Europe as well as for most OECD countries in Asia and Oceania. Meanwhile, the LUCF emissions are negligible in the rest of the world (FAO 2010).

Based on the results of the present study, world milk production contributes 2.65% to total global anthropogenic

Table 4 Countries grouped by average emission rate and proportion of global milk production

Rank	Bottom 10 countries by emission rate		Top 10 countries by emission rate		Top 10 milk producing countries	
	Country	Emission rate (kg CO ₂ -eq.)	Country	Emission rate (kg CO ₂ -eq.)	Country	Emission rate (kg CO ₂ -eq.)
1	Israel	0.88	Cameroon	4.08	India	1.98
2	USA	0.92	Bangladesh	3.69	USA	0.92
3	Spain	0.98	Uganda	2.87	China	1.44
4	Netherlands	1.03	Pakistan	2.69	Pakistan	2.69
5	Ukraine	1.04	Morocco	2.35	Germany	1.44
6	Italy	1.06	India	1.98	Brazil	1.29
7	Sweden	1.06	Norway	1.71	France	1.18
8	United Kingdom	1.08	Belarus	1.67	New Zealand	1.28
9	Denmark	1.13	Peru	1.63	United Kingdom	1.08
10	South Africa	1.13	Turkey	1.61	Ukraine	1.04
	Mean (SD.)	1.03 (0.08)		2.43 (0.89)		1.43 (0.53)

GHG emissions. This figure does not include emissions from beef of dairy cattle as well as transportation and processing of milk. Meanwhile, the FAO estimated a contribution of 2.7% inclusive of emissions from transportation and processing (FAO 2010). Both proportions were calculated based on global GHG emissions of 49 Gt according to IPCC (2007). However, the total global milk production volume was assumed to be 553 million tonnes in the FAO study and 755 million tonnes (cows and buffalos) in this study. The latter figure is based upon IFCN sector data which are continually updated. Consequently, the difference in milk production volume of about 200 million tonnes accounted for the same amount of emissions than those of transportation and processing of milk calculated by the FAO.

Finally, we emphasize that our estimates of the contribution of milk production to global GHG emissions are

subject to uncertainty. Part of the uncertainty stems from the choice of the appropriate methods for estimating emissions at the level of the individual animal. Given the great diversity of dairy farming systems across the globe, a one-size-fits-all formula can only yield rough estimates. This must be born in mind when interpreting the results. The sensitivity analysis carried out on a small subset of our typical farms revealed that the Kirchgeßner formula tends to result in lower estimates than alternative formulas based on feed intake data. We are thus confident that our estimates err on the side of caution. All estimation methods available in the literature were derived in developed countries and thus represent intensive farming systems. Hence, both model types, those using feed input data and those based on physiological data, are fraught with uncertainty, when applied to farms in the developing world. Future research will have to fill this gap.

Table 5 Contribution of milk production to global GHG emissions

	Milk production (t ECM)	Proportion (%)	t CO ₂ -equivalents	Proportion (%)
Observed countries	528,392,048	70	791,277,000	61
Remaining countries	227,236,951	30	509,247,425	39
Global volumes	755,628,999	100	1,300,524,425 ^a	100
Emissions allocated to beef from dairy cattle			113,089,080	
Global emissions from milk production incl. beef			1,413,613,505	
Contribution of milk production (excl. beef) to global anthropogenic emissions	Based on IPCC estimate of 49 Gt		2.65%	
	Based on FAO estimate of 33 Gt		3.94%	

Source: own calculations; FAO (2006), IPCC (2007)

1 Gt=1,000,000,000 kg

^a Global emissions from milk production excluding emissions from beef of dairy cattle

Appendix

Table 6 Enteric and total emissions by different methods (kg CO₂-eq./100 kg ECM)

Formula and exogenous variables	DE-80N	US-1710CA	NZ-294	BR-25RS	CM-1	BD-2
F1—Milk yield, live weight	33	29	44	53	54	140
F2—Dry matter intake	37	38	61	189	61	277
F3—Dry matter intake	46	44	76	236	74	347
F4—Neutral detergent fibre intake	47	43	92	181	80	324
F5—Acid detergent fibre intake	36	33	74	151	70	257
F6—Acid, neutral detergent fibre, dry matter intake	48	46	84	205	75	339
Maximum estimate	48	46	92	236	80	347
Minimum estimate	33	29	44	53	54	140
Total emissions using F1	111	82	118	136	213	307
Total emissions using F6	126	99	158	288	234	505

Estimation formulas: F1 — — CH₄(g/day) = 55 + 4.5 × kgmilkyield/cow/day + 1.2 × liveweight^{0.75} (Kirchgessner et al. 1991);
 F2 — — — CH₄(MJ/day) = 3.23(SE1.12) + 0.809(SE 0.0862) × DM intake (kg/day)(RMSPE 25.6%);
 F3 — — — CH₄(MJ/day) = 56.27 − (56.27 + 0) × e^[−0.028 × DMI(kg/day)](RMSPE 28.9%);
 F4 — — — CH₄(MJ/day) = 3.14(SE1.88) + 2.11(SE0.407) × NDF(kg/day)(RMSPE 35.0%);
 F5 — — — CH₄(MJ/day) = 5.87(SE1.77) + 2.43(SE0.556) × ADF(kg/day)(RMSPE 35.4%);
 F6 : CH₄(MJ/day) = 2.16(SE1.62) + 0.493(SE 0.192) × DM intake(kg/day) − 1.36(SE0.631) × ADF(kg/day) + 1.97(SE 0.561) × NDF(kg/day)(RMSPE 28.2%). (Source: Ellis et al. 2007)

Table 7 Description of the analysed typical farms

Country/ farm code	Region	No. of cows	Type of farming/ manure system	Total agricultural land area (ha)	Land used for dairy enterprises (%)	Stocking rate on total ha	Total labour input (labour unit) ^a	Family labour input (% for dairy total)	Milk yield (kg ECM/ cow) ^b	Milk production (t ECM/ year) ^b	Replacement rate (%)	Age of first calving (month)
CH-20	Hilly area	20	S2	22	98	0.91	2.0	81%	6,485	130	32	30
AT-12	Murau	12	S2	25	100	0.48	1.2	100%	5,767	69	27	32
DE-80N	Northern Germany	80	F1	80	87	1.00	2.3	96%	8,126	650	38	30
DE-30BW	Southern Germany	30	S2	50	93	0.60	1.5	100%	6,813	204	35	30
NL-57	Eastern part of Netherlands	57	F1	36	100	1.57	1.7	98%	8,794	501	34	25
LU-36	Luxembourg	36	F1	74	62	0.49	1.6	92%	7,793	281	40	30
FR-38	Montains of Massif Central	38	F1	56	88	0.67	1.7	100%	6,541	249	32	33
ES-45GA	Galicia, Lugo, Barreiros	45	F1	17	100	2.58	2.8	100%	9,231	415	20	24
IT-133	Lombardia	133	F1	54	100	2.46	4.3	56%	8,259	1,098	29	27
UK-96	Southw est England	96	F1	153	84	0.63	4.3	56%	7,796	748	26	27
IE-51	South	51	F1	35	80	1.46	1.7	91%	6,039	308	20	25
DK-100	Jutland	100	F1	92	75	1.09	1.7	71%	8,694	869	45	28
SE-50	Skåne, Hörby	50	F1	80	70	0.63	1.9	90%	9,507	475	39	27
FI-24	Päijät-Häme	24	S2	30	100	0.80	2.3	96%	8,931	214	38	26
NO-19	Nord-Østerdalen	19	S2	26	79	0.73	1.6	90%	6,681	127	43	24
PL-15	Central-Eastern of Poland	15	S2	32	99	0.47	2.5	100%	6,714	101	21	27
CZ-428	North-East Bohemia	428	F1	1,537	32	0.28	70.4	0%	7,583	3,245	40	28
BG-2	Central North, Veliko Tarnovo	2	G	16	69	0.13	1.5	46%	4,532	9	8	27
UA-2	Vinnitsa	2	G	1	40	2.00	0.7	100%	3,170	6	20	24

Table 7 (continued)

Country/ farm code	Region	No. of cows	Type of farming/ manure system	Total agricultural land area (ha)	Land used for dairy enterprises (%)	Stocking rate on total ha	Total labour input (labour unit) ^a	Family labour input (% for dairy total)	Milk yield (kg ECM/ cow) ^b	Milk production (t ECM/ year) ^b	Replacement rate (%)	Age of first calving (month)
UA-443	Vinnitsa	443	F1	2,954	0	0.15	31.4	0%	4,771	2,114	35	24
BY-650	All over the country	650	F1	2,650	59	0.25	202.9	0%	3,332	2,166	33	27
TR-4	Thrace	4	S2	4	41	1.00	1.7	100%	3,458	14	27	27
IL-63	All over the country	63	F1	0	0	landless	2.1	56%	10,103	636	39	25
MA-4	Doukkala, Benihlel	4	G	2	27	2.00	1.4	100%	2,214	9	26	30
CM-1	Western Highlands	1	G	5	11	0.21	1.8	77%	2,825	3	14	34
UG-1	Mukono District	1	G	1	50	1.24	1.7	100%	2,530	3	8	27
ZA-89	Free-State	89	F1	480	54	0.19	4.9	20%	7,797	694	17	26
CA-57	Ontario	57	F1	121	100	0.47	3.0	85%	7,963	454	22	24
US-80WI	Wisconsin	80	F1	93	100	0.86	2.6	54%	8,703	696	40	27
US-1710CA	1710	F1	445	100%	Feedlot	24.2	6%	99%	16,877	35%	25	
MX-22	Chihuahua, Julimes	22	F1	16	25	1.38	3.2	79%	5,187	114	27	28
AR-170	Córdoba, Santa Fé	170	G	227	80	0.75	4.8	20%	4,919	836	26	29
BR-25RS	Rio Grande do Sul	25	G	30	100	0.82	1.8	50%	3,921	98	17	28
BR-90MG	Minas Gerais	90	F1	75	100	1.21	3.5	0%	5,230	471	20	30
CL-355	Xa región, Llanquihue	355	F1	270	100	1.31	22.7	4%	8,952	3,178	27	24
PE-6	Cajamarca, Polloc	6	S2	8	83	0.79	1.9	100%	2,196	13	22	32
IN-2PU	Punjab, Ropar	2	G	3	19	0.63	2.7	48%	3,140	6	25	46
IN-7GU	Gujarat, Patan	7	G	6	21	1.09	6.5	73%	2,080	15	23	42
IN-2KA	Karnataka, Kolar	2	G	0	0	landless	1.3	100%	3,573	7	21	23
PK-1	South Punjab, Layyah	1	G	0	0	landless	1.0	100%	1,177	1	32	42
BD-2	Sirajganj	2	G	0	39	5.00	2.1	100%	894	2	20	36
CN-3	North China, Hebei	3	G	0	0	landless	0.9	100%	2,583	8	34	27
CN-300-12	North China, Hebei	300	F1	0	0	landless	82.6	4%	4,397	1,319	9	26
AU-225VI	Victoria	225	G	122	100	1.85	2.5	99%	5,100	1,147	15	24
NZ-294	Waikato	294	G	98	100	3.00	2.5	50%	4,361	1,282	20	24

Type of farming/manure system: *S* stacion barn, *F* free stall barn, *G* grazing; manure management system: *1* slurry-based, *2* solid manure; no manure mangement in grazing farms

^a Hired and family labour input for the w hole farm (1 unit = 2,100 h)

^b ECM = energy-corrected milk (4% fat, 3.3% protein)

Table 8 Coefficients and statistics of the regression model

	Estimate	Std. error	<i>t</i> Value	Pr(> - <i>t</i>)
(Intercept)	5.12E+00	3.08E-01	16.628	<2.00E-16 ^a
MilkYield	-1.61E-03	1.98E-04	-8.144	5.65E-13 ^a
I(MilkYield^2)	2.24E-07	3.67E-08	6.108	1.47E-08 ^a
I(MilkYield^3)	-1.05E-11	2.05E-12	-5.097	1.40E-06 ^a

^a Significantly different from zero at the 0.01 level

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