A simplified tool for estimating carbon footprint of dairy cattle milk

Giacomo Pirlo, Sara Carè
Centro di Ricerca per le Produzioni Foraggere e Lattiero-casearie, Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Cremona, Italy

Abstract

The article presents a simplified method for estimating milk carbon footprint. LatteGHG is an electronic worksheet dedicated to the typical Italian dairy production systems. The literature concerning the estimation of milk carbon footprint has been examined, with particular attention to background information and methodologies that are adopted for estimating greenhouse gas emissions. The aim is to identify the solutions that best fit an intensive production system, such as the milk production system in Italy. The article includes an in-depth description of the procedures used in the estimation in order to ensure the greatest transparency. The proposed tool is also flexible because it allows the users to upload the most up-dated and suitable emission factors. LatteGHG has been tested by simulating four dairy farm models and has been shown to be able to at least point out differences due to milk productivity, the stocking rate and the manure management system.

Introduction

Nowadays there is a growing demand for information about the impacts of livestock farming on the environment and human health. However, estimating the environmental impact of a human activity is complex, because there are a variety of mass fluxes between the production installations and the surrounding environment and the chemical and biological processes that they regulate (Roy et al., 2009). Special difficulties are met when the environmental impact of agricultural systems are being estimated, because farming is both a large source and at the same time a sink for pollutants or substances which potentially have some detrimental effects on the environment. In addition, there is a wide variety of agricultural systems and the techniques for measuring nutrients or gas emissions are usually too sophisticated to be used on commercial farms. Although there is clear evidence that agriculture plays a minor role compared with the energy sector of developed countries (EEA, 2009), there is great concern about emissions of greenhouse gases (GHG) from livestock farming (Steinfeld et al., 2006).

The Intergovernmental Panel on Climate Change (IPCC) methodology is followed to estimate GHG emissions from a particular economic sector and to compile national and international inventories. The IPCC framework identifies six aggregated source categories: energy, industrial processes, solvents and other products, agriculture, land use change and forestry, and waste. Agriculture is divided into five specific sectors: i) enteric fermentation; ii) manure management; iii) rice cultivation; iv) agricultural soil; v) savannah burning and burning of agricultural waste. According to the IPCC framework, only CH4 and N2O are attributed to the agricultural category. Another approach is that of life cycle assessment (LCA). This evaluates the environmental effects of a particular activity, service or product. Its key concept is to take into account all the environmental impacts during the entire life of a product, and for this reason it is also called from-cradle-to-grave analysis. Carbon footprint (CF) is the total amount of GHG caused by a particular organisation, activity, product or person, and it is calculated according to LCA methodology. Life Cycle Assessment has been standardized by the International Organization for Standardization (ISO, 2006a, 2006b) in four steps.

Definition of goal and scope: concerns the reason why the study has been carried out, the functional unit (FU), the system boundaries, and the allocation criteria.

Life cycle inventory: concerns data collection.

Life cycle impact assessment: the evaluation of the magnitude and significance of the potential environmental impacts of a production system. In CF studies, this is a very simple step because only characterisation is required.

Interpretation of the study: here the results of the analysis are discussed in order to draw conclusions about representativeness, practical application, and sensitivity.

This approach has been approved by the International Dairy Federation (FIL-IDF, 2010) to estimate the contribution of milk production to global warming (GW). In most reports of studies concerning milk CF, there is a lack of information about the emission factors used for quantifying the GHG emissions, which makes interpreting and comparing the results difficult. Table 1 shows a list of some papers concerning milk CF chosen because they present a complete framework of nearly all the main GHG emissions and because they give detailed information on the method used to estimate emissions. The majority of them adopt the IPCC framework for estimating CH4 and N2O emissions. On the contrary, there is no uniformity in the estimation of CO2 emissions associated with fuel combustion of farm engines or for the production of electricity and other inputs. The papers in Table 1 do not report Land Use Change (LUC). As protein feed, most of the intensive animal production systems use soybean meal grown in cultivation established after felling tropical forests or transforming perennial grasslands. For this reason, LUC is considered to be a very important factor in the livestock carbon budget. Nevertheless, LUC is only considered in a few papers in the literature because there is still no shared agreement on the methods to be adopted to evaluate its effect on milk CF and the various methods used have all yielded different results (Flysjø et al., 2012).

There is a huge need for simplified and user-friendly tools for estimating GHG emissions from dairy farms. There have been some attempts to create models requiring less data for estimating milk CF (Asselin-Balençon et al., 2006). However, there is no shared agreement on the methods to be adopted to evaluate its effect on milk CF and the various methods used have all yielded different results (Flysjø et al., 2012).
The aim of this paper is to present LatteGHG, a simplified tool to estimate the CF of cow milk produced under typical conditions in Italy. This tool is completely open and offers the user the chance to modify parameters to better adapt the equation to specific conditions. In order to ensure the greatest transparency, the article gives an insight into the methodologies that can be used for milk CF, and makes some speculation about what improvements could be made to obtain a better fit to accommodate the various production systems.

**Goal of carbon footprint studies**

The goal of a milk CF study could be to compare two or more production systems (i.e., conventional vs organic), explore the possibility of reducing GHG emissions, or support marketing strategies. LatteGHG can be used to compare the environmental performances across farms. Milk CF can also be used as an indicator of the progress made on a farm or on a regional level in making the utilisation of natural resources more efficient.

**Functional unit**

The FU is the unit associated with GHG production. This could be an animal, a farm, a cultivated area, and so on. In the case of milk CF, it is a unit of milk (kilogram or litre). There is no uniformity in the definition of FU among milk CF studies (Pirlo, 2012) or to allow results to be compared. The International Dairy Federation (FIL-IDF, 2010) proposed 1 kg of fat protein corrected milk (FPCM) as FU. In LatteGHG, FPCM is calculated according to the equation of Gerber (2011):

\[
\text{FPCM (kg)} = \frac{M (\text{kg}) \times [0.337 + 0.116 \ \text{FC} (\%)]}{0.06 \ \text{PC} (\%)}
\]

where:
\( M \) is the mass of raw milk;
\( \text{FC} \) is the fat content (%);
\( \text{PC} \) is the protein content (%).

According to this equation milk is converted into FPCM with 4.0% of fat and 3.3% of protein.

**System boundaries**

Most LCA of milk do not consider the whole life cycle and stop at the farm gate, without analysing transport, processing or retail procedures. A list of these analyses are reviewed by Pirlo (2012). Consequently, they are defined as from-cradle-to-farm gate. However, some authors expanded the analysis to the dairy gate, estimating the CF of cheese (Berlin, 2002; González-García et al., 2013), drinking milk (Fantin et al., 2012; Hagaas Eide, 2002; Hospido et al., 2003), and butter (Flysjö, 2011). The system boundaries of LatteGHG are shown in Figure 1.

**Allocation**

In cases of multifunctional processes, the environmental impact could be shared among several products. Dairy farms produce other products as well as milk, such as surplus calves, culled cows, and sometimes replacement heifers and fattened bulls. Thomassen et al. (2008) defined alternative co-product handling criteria as: i) no allocation: when milk takes all the environmental burden; ii) physical allocation: that considers the mass of milk and meat (that is the live body weight of animals leaving the system boundaries); iii) economic allocation: based on the income from the co-products; iv) system expansion: when the effects of alternative production ways are explored.

LatteGHG gives a number of outputs, as described in detail below: i) CF without allocation; ii) CF with physical allocation; iii) CF with economic allocation.

**Life cycle inventory**

To avoid possible confusion between Intergovernmental Panel on Climate Change (IPCC) and CF approaches, the user should bear in mind that, in the case of livestock productions, the main feature of CF is that it considers direct emissions of GHG from animals, manure, soil and fuel use from engines within the farm, and indirect emissions deriving from the processes for producing chemical fertilisers, plastic, seeds, pesticides, etc. On the contrary, according to the IPCC framework, GHG emissions from the production of these items and from the use of fuels in the agricultural operations are put in the energy category, which is made up of transport, fuel extraction, and industrial processing. According to the LCA methodology, two kinds of data are needed to estimate the CF of a product such as milk:

- i) foreground data, collected on the specific farms which are, in the case of a livestock installation, farm size, number of animals, diet, production, forage system, purchased feeds, fertilisers, electricity consumption, agricultural operations; ii) background data, the...
Choice of the emission factors

Emission factors of the IPCC framework have three different levels of precision: Tier 1, Tier 2, and Tier 3 (IPCC, 2006). Tier 1 is a simplified approach based on default and not on country-specific EF Tier 1 is used when there are no data about animal breed, productivity or feeding system available. It is also suitable when the specific source of emission is not relevant, as in the case of CH4 from enteric fermentation in non-ruminants. Tier 2 can be used if the key source category is of relevant importance and there are enough details concerning the factors influencing gas emissions. Tier 2 is highly country-specific because it incorporates the characteristics of the production systems of the country involved. Tier 3 requires more detailed information about production systems. The information is organised in mechanistic models that can quantify the effect of specific technologies on gas emissions. A Tier 3-based system requires a great amount of experimental data about the effects of each type of technology on EF. In an LCA, implementation of Tier 3 EF can be limited by the difficulty in collecting the necessary data to run the model.

Emission factors of a LCA are generally a mix of Tier 1 and 2 (and sometimes of Tier 3, too) (Zehetmeier et al., 2012; Rotz et al., 2010) as a consequence of: i) the relative importance of a specific key source; ii) the availability of more advanced tiers; iii) the availability of reliable data that can be collected directly.

Enteric fermentations in dairy cattle

Methane from enteric fermentation is the main source of GHG associated with milk production, representing approximately 35-70% of CF of a certain amount of milk (Casey and Holden, 2005; Fysjø et al., 2011; Mc Geough et al., 2012; O’Brien et al., 2011; Phetteplace et al., 2001; Schils et al., 2005). Because of its importance, it is also one of the most promising areas of reduction, through genetic selection (Wall et al., 2010) and feeding strategies (Grainger and Beauchemin, 2011).

The Tier 1 EF for dairy cattle are between 58 and 128 kg of CH4 per head per year in the Indian Subcontinent and North America, respectively. The EF corresponding to the dairy cows in Western Europe is 117 kg of CH4 that is associated to a yearly production of 6000 kg of milk (IPCC, 2006). In those countries, such as Italy, which developed a Tier 2 EF for enteric fermentation CH4 of dairy cattle, Tier 1 is rarely used.

Dry matter intake is the main driver of enteric CH4 emission (Ramin and Huhntanen, 2013). The Tier 2 approach is based upon the relationship between dry matter intake and CH4 enteric production (Kirchgeßer et al., 1995). LatteGHG adopts the Tier 2 model used by the Italian National Institute for Environmental Protection and Research (Istituto Superiore per la Protezione e la Ricerca Ambientale, ISPRA) for its national GHG inventory:

\[
GE = \frac{EF \times Ym \times 3355}{55.65}
\]

where:
- EF, emission factor, kg CH4 head\(^{-1}\) year\(^{-1}\)
- GE, gross energy intake, MJ head\(^{-1}\) year\(^{-1}\)
- Ym, methane conversion factor, percentage of gross energy in feed converted to CH4.

The factor 55.65 (MJ/kg CH4) is the energy content of CH4.

Methane conversion factor (Ym) varies according to the animal category and diet digestibility (Benchaar et al., 1998). IPCC (2006) indicates 3.0%±1.0% for feedlot cattle and 6.5%±1.0% for production and growing cattle. ISPRA (2008) uses an Ym of 6% for high-forage rations and 4% for highly digestible rations; the first one is used for mature cows, the second one for young cattle. The LatteGHG default Ym for lactating cows is 6%.

The amount of daily GE intake is estimated on the basis of nutrient requirements of the National Research Council (NRC, 2001) and the average energy digestibility of feeds, according to the following equation (ISPRA, 2008):

\[
GE(c)(MJ/d) = \frac{NEm + NEa + NEI + NEw + NEp + NEg}{100}
\]

where:
- NEm, NEa, NEg, NEI, NEw, NEp are net energy requirements for maintenance, activity, growth, lactation, work and pregnancy, respectively, and are estimated according to the NRC (2001) as follows:

\[
NEm(M/d) = 0.335 \times BW^{0.75}
\]

\[
NEa(M/d) = NEm \times 0.17 \times grazing \text{ animals (})
\]

\[
NEI[M/d] = 4.18 \times \left(0.0635 \times \left(0.091 \times (BW \times 0.96)
\right) + \left(479 \times (BW)^{0.8} \times (MW)^{2/3}ight)^{0.75}
\right) + \left(2 \times (BW)^{0.75} \times (MWT)^{2/3}ight)^{0.75}
\]

where MW and WG are mature weight and daily body gain, respectively.

\[
NEI(M/d) = Milk(kg/d) \times (1.47 + 0.60 \text{ FC}(%))
\]

\[
NEm(M/d) = 8.1 \times NEm \times power (%)\]

\[
NEg(M/d) = 4.18 \times \left([0.00318 \times 214] - 0.0352 \times 0.118 \right)
\]

The last equation is applied to dry cows. NEma and NEag are net energy available for maintenance and for growth, respectively, and can be calculated as:

\[
NEma = 1.123 - (4092 \times 10^{-3} \times DE) + (1.126 \times 10^{-5} \times (DE)^2) - (254/DE); \]

\[
NEga = 1.164 - (5.160 \times 10^{-5} \times DE) + (1.308 \times 10^{-5} \times (DE)^2) - (374/DE); \]

\[
DE = \text{the digestible energy as percentage of gross energy.}
\]

Specific models that can be used for both adult and young animals on a typical intensive dairy farm without grazing are:

- mature lactating cows:

\[
GEm(m)(MJ/d) = \frac{NEm + NEI}{100}
\]

- dry cows:

\[
GEm(d)(MJ/d) = \frac{NEm + NEp}{100}
\]

- lactating heifers:

\[
GEmh(MJ/d) = \frac{NEm + NEg + NEI + NEw}{100}
\]

- Daily gross energy intake of calves under 1
year and 1-2 years of age are assumed to be 89.4 MJ and 156.9 MJ, respectively (ISPRA, 2008). (For a more detailed description of this method see ISPRA, 2008).

This model is an adaptation of ISPRA Tier 2 (2008). However, despite its extreme simplification, it has several advantages in respect of Tier 1 or Tier 2 for the national inventory. Nevertheless, it requires a fairly good knowledge of animal categories, breed productivity, and feed characteristics. It is well known that there are several feeding strategies for reducing CH4 emissions. In an attempt to consider the effect of feeding strategies on the calculation of CH4 emissions, some authors introduced some correction coefficients obtained from feeding experiments where CH4 emissions were measured directly: for example, Nguyen et al. (2012) considered a reduction factor of 4.8% of enteric CH4 production per percentage unit of added lipid applied in the diet of suckling cows. Mc Geough et al. (2012) adopted a Ym of 5.5% and Yan et al. (2013) gave different values as function of nutritive level of lactating cows. To take these considerations into account, LatteGHG gives the user the possibility to change DE and Ym by introducing the values considered most appropriate.

The results of the Tier 2 model are driven by milk production, body weight, lactating and dry cow ratio, and length of pasture season; no information about effect of genotype or environment is used. Because of the large contribution of CH4 emission on milk CF, models are required that consider the actual genetic animal characteristics, environmental conditions, and feeding parameters influencing dry matter intake, methanogenesis and feed efficiency. For Tier 3 EF, starting with the studies by Dijkstra et al. (1992) and Baldwin et al. (1987), there have been some attempts to develop dynamic mechanistic models that can predict CH4 production by using an accurate description of rumen metabolism. These models require detailed information about dry matter intake, chemical feed composition, and intrinsic degradation characteristics. They incorporate fermentation mechanisms, rumen acidity and VFA stoichiometry. Finally, the output consists not only of an EF but also of a CH4 conversion factor that is no longer constant as in the case of the Tier 2 model (Bannink et al., 2011). These models are expected to considerably improve accuracy and consistency in future calculations of CH4 emissions, but they require a detailed description of animal type, environment and feeding system that is never available on commercial farms.

### Methane emissions from manure management

In the IPCC framework (IPCC, 2006), CH4 emissions from manure management are produced during the storage and treatment of manure and from manure deposited while grazing. In the same guidelines, the term manure means both dung and urine, mixed or separated, with or without straw. The terminology often leads to confusion because of the different systems of classification. For a definition of housing, manure handling and manure storage types, see Olesen et al. (2006) or EMEP/EEA (2009) that reports a comparison between EMEP/EEA and IPCC terminology and gives a description of manure management systems.

Methane from manure management commonly accounts for 8-19% of total CO2eq emissions of a dairy farm (Mc Geough et al., 2012; Phetteplace et al., 2001; Roth et al., 2010; Schils et al., 2005). Methane is a product of the decomposition processes of manure organic matter that require anaerobic conditions and, consequently, CH4 production is higher in confined than in pastoral systems. Production of this gas is also higher with liquid handling or storing than with dry systems (Husted, 1994; Külling et al., 2001, 2002) and is favoured by a high diet protein concentration (Lee et al., 2012).

Similarly to CH4 enteric losses, the IPCC framework (2006) includes a 3-level system to estimate manure CH4 emissions. Husted (1994) proposed two different equations for quantifying manure CH4 emissions from solid and liquid manure. These are determined by the temperature of manure mass and by the amount of annual manure. The experimental data of this author form the basis of the EF used in the IPCC methodology.

In the Tier 1 method, there is a default EF depending only on the geographical area and the average temperature and that does not consider the manure management system. Although conceptually based on the studies of Husted (1994), the Tier 2 method for the definition of the EF of management manure CH4 generally uses some simplified procedures that require estimation of the amount of volatile solids and of the manure management systems. Volatile solids can be quantified through a procedure similar to that used for enteric CH4 emissions or through laboratory measurements. In any case, it is difficult to quantify volatile solids in an extensive study involving a large number of farms. A further simplification has been developed by ISPRA (2008) by using regional data on average volatile solid production. For the compilation of the national inventory, ISPRA (2008) adopted a further radical simplification of Tier 2 by calculating average EFs for all cattle categories and buffaloes for liquid and solid manure (Table 2). LatteGHG uses the EFs reported in Table 2.

### Nitrous oxide emissions from manure management

Nitrous oxide emissions from manure management account for between 7% and 10% of total GHG emissions (Pysõš et al., 2011; Mc Geough et al., 2012). The main source of N2O is the N excreted by animals and that found in synthetic fertilisers. The N is transformed to N2O through several different pathways and classification within the IPCC (2006) framework varies.

Nitrous oxide presented in the N2O emissions from manure management section of the IPCC guidelines (2006) is produced during the storage and treatment of manure before it is applied or otherwise used. Consequently, N2O generating from soil or from faeces or urine of grazing animals does not fall under this category but is included under the section Managed soils.

The most important pathways of N2O formation are nitrification and denitrification. Nitrification has two steps: 1) oxidation of ammonium to nitrate under aerobic condi-

| Table 2. Average emission factors of cattle and buffalo manure CH4 (CH4 kg/head/year) from ISPRA (2008). |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | Liquid manure   | Solid manure    | Total           |
| Calves                         | 6.22            | 0.00            | 6.22            |
| Growing males                  | 5.03            | 3.46            | 8.49            |
| Growing heifers                | 2.8             | 4.04            | 6.84            |
| Other cattle                   | 4.01            | 6.65            | 10.66           |
| Dairy cows                     | 5.64            | 9.41            | 15.04           |
| Buffalo cows                   | 4.99            | 10.26           | 15.25           |
| Other buffaloes                | 3.13            | 3.16            | 6.29            |
tions, with N₂O as by-product; and ii) nitrification that consists in the reduction of nitrate to di-nitrogen gas; this pathway requires anaerobic conditions and N₂O is produced if the reaction is incomplete (Kebreab et al., 2006).

Production of N₂O is greatly determined by the storing system that influences the presence of oxygen and the contact between faeces and urine. When the manure management system is based on slurry and bedding is not used there is a predominantly anaerobic state that does not favour nitrification of ammonium. In this condition, N₂O production is much less than that achieved with a bedded system (Chadwick et al., 2011). The contact between faeces and urine is favourable for N₂O production because cattle faeces contain low amounts of rapidly decomposable N, but urease activity is high. As they come into contact with urine, urea is rapidly hydrolysed (Bussink and Oenema, 1998).

Any tier is used there are two key factors: the amount of N excreted by the animals and the manure management system. In Tier 1, the amount of N excretion of a particular animal category is multiplied by an EF for the specific manure management system. Tier 2 is similar to Tier 1 but it requires country-specific parameters. In Tier 3, country-specific methodologies are used. Most LCA studies use Tier 1 or Tier 2 methods.

In LatteGHG, the amount of animal N excretion is estimated by subtracting the N retained by the animal from the N ingested. According to IPCC (2006) methodology, the two equations used for estimating N intake and retained N are:

\[
N_{\text{intake}} = \frac{kg}{d} = \frac{GE}{18.45} \times \frac{CP\% \times 100}{6.25}
\]

where:
- \(N_{\text{intake}}\) are kg ingested daily;
- \(GE\) are MJ of gross energy consumed by the animal for maintenance, production, pregnancy, growth, activity and work (this variable is calculated with the same equation used for enteric CH₄ emission);
- 18.45 is the conversion factor of MJ into kg of DM;
- CP\% is the percentage of crude protein on diet DM;
- 6.25 is the conversion factor of CP to N.

The N retained is estimated as follows:

\[
N_{\text{retention}} = \left( \frac{Milk \times (\text{Milk P\%} \times 100)}{6.38} \right) - \frac{WG \times (1.69 \times 7.03 - \frac{7.03 \times \text{NEG}}{WG})}{1000 \times 6.25}
\]

where:
- \(N_{\text{retention}}\) is daily N retained by the animal;
- Milk is daily production of milk (kg/d);
- 6.38 is the conversion factor of milk protein to N;
- WG is the weight gain;
- 268 and 7.03 are constants from the NRC (2001);
- NGg is the net energy for growth;
- 1000 is the conversion factor for grams to kilograms;
- 6.25 is the conversion factor from CP to N.

For dry cows, LatteGHG applies a coefficient of 0.95 on \(N_{\text{intake}}\) for calculating \(N_{\text{excreted}}\). The equations above are adopted for producing and dry cows, whereas for calves and growing heifers two parameters are used, i.e. 24.8 and 67.8 kg of N per year, respectively.

Following this methodology, it is possible to estimate N excretion for any specific situation if data about animal characteristics, production and diet are available. Otherwise, national average data can be used. ISpra (2008) gives the average yearly N excretion for each animal category. Combinations between N excretion and EF give the amount of N₂O-N from manure management.

The EF for calculating the amount of N₂O from manure depends on manure management and stocking length. The default EFs are shown in IPCC (2006), which are the same as used in ISpra (2008) for the Italian emissions inventory.

On the farm level of resolution, the above model is sensitive enough to identify the effects of protein feeding. It has been well documented that corn silage-based diets have a higher efficiency of diet N (Weiss, 2004) and that the amount of feed protein intake can be reduced by increasing the proportion of undegradable protein in the diet (Agle et al., 2010; Kalscheur et al., 2006) or feeding rumen protected amino acids (Broderick et al., 2008; Robinson, 2010; St-Pierre and Sylvester, 2005).

Users should consider that there is intensive research into manure management and the EFs in the IPCC guidelines or in the national environment agencies and EFs cannot be up-dated as frequently as research results come in. However, LatteGHG provides for changing the EFs.

Nitrous oxide emissions from managed soil

Another key source of GHG emissions in dairy production systems is N₂O from soil management. This gas is also produced through nitrification and denitrification processes regulated primarily by the soil moisture content (Subbarao et al., 2006).

Estimation of the N₂O from soil is particularly complex because there are several sources and pathways of emissions that require specific accounting models and EFs. The N₂O emissions from soil are divided into two main categories: direct and indirect. The first is generated by the N in the soil it was applied to. Nitrogen is present in organic or synthetic fertilisers, in urine or faeces of grazing animals, in crop residues, or it is the N brought in by N-fixing crops. Nitrogen applied to the soil will not all be lost as N₂O. Part of it is obviously trapped by plant roots, but another part is lost as NO₂ in ground or surface water or dispersed in the atmosphere as NH₃.

Indirect emissions are subdivided into two further categories: i) coming from the atmospheric NH₃ and NO₂ after their reposition to soil and water; ii) from the leaching and runoff of the N from cultivated soils or other sources. A complete and detailed description of the methodology to follow to estimate N₂O emissions from managed soils is to be found in the IPCC guidelines (2006).

However, some sources of N₂O are of little interest for an intensive production system such as dairy production in Italy. The main controlling factor of soil N₂O emissions is the N amount in the soil. For this reason, LatteGHG is based on the estimation of the amount of N brought into the soil through farmers’ activities.

Nitrogen from synthetic fertilisers (FSN): this is the N from the synthetic fertilisers excluding losses such as NH₃ or NO₂. This fraction is calculated as follows:

\[
FSN (kg/yr) = N_{\text{FERT}} \times (1 - \text{FRACGASF})
\]

where:
- \(N_{\text{FERT}}\) is the N applied to the soil with synthetic fertilisers;
- FRACGASF is the fraction of \(N_{\text{FERT}}\) lost as NH₃ or NO₂.

ISpra (2008) uses a FRACGASF of 0.092 (APAT, 2008). This is slightly lower than the default value of 0.1 (IPPC, 2006). Nitrogen content of most common synthetic fertilisers can
be found in ISPRA (2008).

Nitrogen from organic fertilizers (FON): this fraction is calculated by subtracting the losses for volatilisation of NH₃ and NOₓ from the amount of N applied to the soil with manure, compost, sewage sludge, rendering waste. This fraction does not include urine and dung N deposited by grazing animals. Nitrogen from organic fertilisers (FON) can be calculated as follows:

$$ F_{ON}(kg/yr) = N_{EX} \times (1 - FRACGRAZ - FRACGASM) $$

where:

- $N_{EX}$ is the amount of N excreted by the cows, heifers and calves.
- $FRACGRAZ$ is the amount of urine and dung N deposited by grazing animals and is proportional to the duration of the grazing season.
- Since this practice is rarely adopted in Italy, this fraction can be ignored. $FRACGASM$ is the amount of N lost for volatilisation and ISPRA (2008) uses a value of 0.29 (APAT, 2008) that is considerably higher than that reported in IPCC (2006).

Nitrogen from crop residues (FCR): this fraction consists of the N contained in the residues left by the crops above the ground and below the ground (roots), and includes that of the N-fixing crops. Unless specific data are available, N deposition can be estimated by utilising IPCC (2006). Total direct N₂O emissions from managed soils are calculated by summing $F_{SN}$, $F_{ON}$ and $FCR$. The sum has to be multiplied by the EF of 0.0125 kg of N-N₂O/kg of N (ISPRA, 2008). This EF is slightly lower than the default EF of IPCC (2006). The total has then to be multiplied by 44/28 (the conversion factor of (N₂O-N(mm) to N₂O(mm)).

Indirect soil N₂O emissions from atmospheric N depositions (N₂OATOM): this fraction is calculated as follows:

$$ F_{GAM}(kg/yr) = (N_{EX} \times FRACGASF + N_{EX} \times FRACGASM) $$

$F_{GAM}$ x 0.01 kg of N – N₂O per kg of N

The result is multiplied by 44/28. The EF of 0.01 kg of N-N₂O per kg of N corresponds to the default EF in IPCC (2006).

Indirect soil N₂O emissions from N leaching and runoff (N₂O(N)): the inputs of N synthetic fertiliser and of N animal excreta into the soil are added together, subtracting the N lost with leaching and runoff (N). ISPRA (2008) considers Nₐ equivalent to 0.3 kg of N-N₂O/kg of N; this coincides with the corresponding value shown in IPCC (2006). The sum is then multiplied with the EF of 0.025 kg of N-N₂O per kg of N; this EF is considerably higher than the default value shown in IPCC (2006).

Nitrous oxide emissions from grazing cattle: this fraction is calculated by multiplying N excreted on pastures by 0.02 kg of N-N₂O; the result is to be multiplied by 44/28 (ISPRA, 2008).

**Direct and indirect CO₂ emissions**

People working in animal sciences pay a great deal of attention to CH₄ and N₂O emissions. This tendency is probably justified by the fact that enteric fermentation are the main sources of GHG from livestock operations and also because animal scientists can potentially conceive and carry out innovations that can reduce the emissions of these gases. For these reasons, the contribution of CO₂ emissions is often not adequately documented. As a consequence, most of the LCA studies on milk CF give very little information about the methods used to estimate CO₂ emissions. However, if a dairy farm is viewed as a system and a systemic approach is adopted to reduce the environmental impact, the contribution of all emission sources should be carefully considered. In many production systems, indeed, the importance of CO₂ emissions from agricultural operations, electricity production, fertiliser production, off-farm feed production and transport, etc., are of great relevance to CF. Table 3 shows some examples of LCA studies and underlines the variable contribution of CO₂ on CF. The percentage of CO₂ on total GHG emissions of 1 kg or 1 L of milk varies between 5% and 50%. The contribution of CO₂ is typically higher in confined than in pastoral systems that are characterised by less use of concentrates, fertilisers and fossil fuels for cropping operations.

Carbon dioxide emission sources from a dairy farm are divided into two main categories: direct and indirect sources. In the first there is the CO₂ generated inside the farm from the combustion of fossil fuels in engines used for production and distribution of feeds. In the second there is the CO₂ emitted for producing fuels, electricity, machinery, fertilisers, medicines, seeds, and pesticides. However, these sources also consist of feeds and animals purchased outside the farm. The evaluation of direct and indirect CO₂ emissions from a dairy farm poses several problems for the quantification of activities (e.g., how much fuel is consumed) and the choice of EF. Quantification of activities requires a careful analysis of the farm. Some data can be relatively easy to gath-

| Production system | CO₂/CF, % |
|-------------------|-----------|
| Basset-Mens et al., 2005 | 7 | G |
| Bellflower et al., 2012 | 4.9 | G |
| Bell et al., 2011 | 6.9 | C |
| Carè et al., 2012 | 30 | C |
| Casey and Holden, 2005 | 40-50 | C |
| Castanheira et al., 2010 | 19 | C |
| Cederberg and Matsson, 2000 | 20-22 | G/G |
| Cederberg and Flisjö, 2004 | 18.7 | G/G |
| de Boer, 2003 | 18 | C |
| Flysjö et al., 2011 | 17.7 | C |
| Haas et al., 2001 | 13.6 | C |
| Kristensen et al., 2011 | 9.5 | G |
| Lovett et al., 2008 | 6.8 | O |
| Mc Geough et al., 2012 | 28 | C |
| O’Brien et al., 2012 | 18.8 | O |
| Pethelplace et al., 2001 | 12.8 | C |

* styling: C, confined; O, organic; G, grazing.
er (e.g., consumption of electricity), while others are more difficult to obtain (e.g., cropping operations). In selecting EFs, in most LCA the authors resort to datasets. Otherwise more specific procedures can be developed, such as that prepared by Wheeler (2012) or Rott and Chianese (2009). We have developed the following procedure that we consider better fits the characteristics of high productivity, high mechanisation, and high intensity of the Italian production system. Fuel used for agricultural operations, and for milking and animal feeding was estimated using the handbook of fuel consumption in agriculture (ENAMA, 2005). EF for the combustion of 1 kg of diesel is 3.13 kg CO₂/kg (APAT, 2003). Diesel density is 850 kg/m³. For extraction, refining and transport of diesel an EF of 1.0062 kg CO₂eq per litre was considered (O’Brien et al., 2010). This EF comprises CO₂, CH₄ and N₂O emissions caused by engine function and losses. Emission factor associated with the production of 1 kWh of electricity, used for milking, milk cooling, barn lighting and ventilation, and other farm activities, is 0.47 kg CO₂ (ISPRRA, 2011). Emission factors corresponding to manufacturing, packaging, transport and storage of mineral and organic fertilisers were found in Ceschia et al. (2010). Greenhouse emissions from the production of pesticides, seeds, plastic and machinery were estimated following the indications of Rott and Chianese (2009). The EF for plastic is 2 kg CO₂eq/kg. Average weight of plastic films normally used for sealing silage trenches is 0.11 kg/m². Weight of net used for round balls is approximately 33 kg/200 m of length. Emissions of GHG from the production of pesticides were estimated using the average EF of 22 kg of CO₂ per kg of pesticide. Seed use factors were derived from typical seeding rates and yields of each crop. An average EF of 0.3 kg of CO₂eq per kg of seed was used. Greenhouse emissions produced during machine manufacture were calculated on the basis of total mass of farm machines, using an EF of 3.54 kg of CO₂eq per kg of machine mass. Due to the difficulties in estimating the mass of machines of a farm, LatteGHG considers three levels of mechanisation that the user can choose: low, medium, or high. The emission of CO₂eq associated with the production, processing and transport of concentrate feed and straw was calculated adapting the EF proposed by Bell et al. (2011). The values take into account the mass allocation of products and by-products. The emission factor associated with purchased replacement animals is 11 kg CO₂eq/kg BW (Rott et al., 2010).

**Life cycle impact assessment**

In CF, only characterisation, i.e. the relative contribution of each gas to global warming, is required. The GHG emissions were expressed as global warming potential (GWP) in a 100-year time horizon, defined as CO₂eq:

\[ 1 \text{ kg CO}_2 = 1 \text{ kg CO}_2\text{eq}, \text{ 1 kg CH}_4 = 25 \text{ kg CO}_2\text{eq} \text{ and 1 kg N}_2\text{O} = 298 \text{ kg CO}_2\text{eq} \] (Forster et al., 2007).

**LatteGHG outputs of four simulated Italian dairy farm models**

LatteGHG was used to estimate CF of four different dairy farm models (Table 4). The simulation considered an intensive dairy farm characterised by a high milk production per head, large inputs (off-feeds and synthetic fertiliser), slurry manure management and no surplus of replacement heifers. Simulation also considered a low producing dairy breed in the second model; no other characteristic has been changed with the exception of body size, milk prize and income per unit of body weight. The simulation considered that 10 pregnant heifers were sold, thanks to the hypothesised better reproduction performances of this typology than the intensive one. A third model is characterised by a low stocking rate because the forage production is based totally on alfalfa, without any corn silage. The fourth model is similar to the second one, but the manure is managed with a solid bedded system, with a large consumption of straw.

**Table 4. Simulation of carbon footprint of 1 kg of fat protein corrected milk in four dairy farm models.**

| Cultivated area | Synthetic N fertiliser, N kg/ha | Cows, n | Calves and heifers, n | FPCM, kg/he/yr | Mechanisation | Pregnant heifers sold, n | Carbon footprint, kg CO₂eq/1 kg FPCM |
|-----------------|-------------------------------|--------|----------------------|----------------|--------------|-------------------------|-------------------------------------|
| High production. | High stocking rate. | Liquid/dung manure. | 60 | 50 | 50 | 115 | 160 | 120 | 11,250 | High | 0 | 0.97 | 0.90 | 0.94 |
| Average production. | High stocking rate. | Liquid/dung manure. | 60 | 50 | 50 | 115 | 160 | 120 | 8,000 | High | 10 | 1.11 | 0.89 | 1.04 |
| High production. | Low stocking rate. | Liquid/dung manure. | 100 | 0 | 100 | 40 | 160 | 120 | 11,250 | High | 0 | 1.05 | 0.98 | 1.02 |
| Average production. | High stocking rate. | Dung manure. | 60 | 50 | 50 | 115 | 160 | 120 | 8,000 | Medium | 10 | 1.22 | 0.97 | 1.14 |

FPCM, fat protein corrected milk; milk price: °0.40 €/kg; °.55 €/kg
Conclusions

We have prepared an electronic worksheet that can be used to estimate the CF of milk produced by cattle in typical intensive Italian systems. LatteGHG is user-friendly and can be used in field conditions. It is an effective tool that can be adopted to compare the ability of different farms to use natural resources and to reduce GHG emissions. It can also be used to evaluate the improvements made by a farm, a region, or a country after introducing some technical innovations or new government policies. Despite some limitations, because of the simplicity of the EF chosen, the tool was shown to be sensitive enough to point out differences between production systems. With some small changes, this tool can be used to estimate milk CF of other lactating ruminants, such as buffaloes.

However, further improvements are needed to address some remaining issues. These include: i) a more accurate estimate of enteric and manure CH4 emission to consider diet composition, animal performances and improved manure management systems; ii) a more direct and accurate estimate of the effects of reproduction performances on CF; iii) the introduction of LUC; iv) the introduction of an estimate of the effect of the forage system on the organic matter in the soil.

Solutions for the first two issues will soon be available whereas the incorporation of LCU and soil carbon budget into the LatteGHG will require further time and effort.

References

Agle, M., Hristov, A.N., Zaman, S., Schneider, C., Ndegwa, P., Vaddella, V.K., 2010. The effects of ruminally degraded protein on rumen fermentation and ammonia losses from manure in dairy cows. J. Dairy Sci. 93:1625-1637.

APAT, 2003. Analisi dei fattori di emissione di CO2 dal settore dei trasporti. Available from: http://www.ssc.it/pdf/2013/3906_Rapporti_03_28.pdf

APAT, 2008. Italian greenhouse gas inventory 1990-2006. Available from: http://unfccc.int/national_reports/annex1/ghg_inventory/national_inventories_submissions/Italy/4303.php

Asselin-Balençon, A.C., Popp, J., Henderson, A., Heller, M., Thoma, G., Jolliet, O., 2013. Dairy farm greenhouse gas impacts: A parsimonious model for a farmer’s decision support tool. Int. Dairy J. 31:S65-S77.

Baldwin, R.L., Thornley, J.H.M., Beever, D.E., 1987. Metabolism of the lactating cow: II. Digestive elements of a mechanistic model. J. Dairy Res. 54:107-131.

Bannink, A., van Schijndel, M.W., Dijkstra, J., 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. Anim. Feed Sci. Tech. 166-167:603-618.

Basset-Mens, C., Ledgard, S., Carran, A., 2005. First life cycle assessment of milk production from New Zealand dairy farm Systems. Available from: www.anzee.org/anzee2005papers/Basset_Mens_LCA_NZ_milk_production.pdf

Belflower, J.B., Bernard, J.K., Gattie, D.K., Hancock, D.W., Risse, L.M., Rotz, C.A., 2012. A case study of the potential environmental impacts of different dairy production systems in Georgia. Agr. Syst. 108:84-93.

Bell, M.J., Wall, E., Russell, G., Simm, G., Stott, A.W., 2011. The effect of improving cow productivity, fertility, and longevity on the global warming potential of dairy systems. J. Dairy Sci. 94:3662-3678.

Benchaar, C., Rivest, J., Pomar, C., Chiquette, J., 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. J. Anim. Sci. 76:617-627.

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. Int. Dairy J. 12:939-953.

Broderick, G.A., Stevenson, M.J., Patton, R.A., Lobos, N.E., Olmos Colmenero, J.J., 2008. Effect of supplementing rumen-protected methionine on production and nitrogen excretion in lactating dairy cows. J. Dairy Sci. 91:1092-1102.

Bussink, J.W., Oenema, O., 1998. Ammonia volatilization from dairy farming systems in temperate areas: a review. Nutr. Cycl. Agroecosys. 51:19-33.

Carè, S., Terzani, G.M., Pirlo, G., 2012. Milk production and carbon footprint in two samples of Italian dairy cattle and buffalo farms. Page 297 in Proc. 63rd Int. Meet. EAAP, Bratislava, Slovakia.

Casey, J.W., Holden, N.M., 2005. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. J. Environ. Qual. 34:429-436.

Castanheira, É.G., Dias, A.C., Arroja, L., Anaro, R., 2010. The environmental performance of milk production on a typical Portuguese dairy farm. Agr. Syst. 103:498-507.

Cederberg, C., Pïjsjo, Å., 2004. Life cycle inventory of 23 dairy farms in south-western Sweden. SIK Report No. 728. Available from: www.sik.se/archive/pdf-filer-katalog/SK728(1).pdf

Cederberg, C., Mattsson, B., 2000. Life cycle assessment of milk production – a comparison of conventional and organic farming. J. Clean. Prod. 8:49-60.

Ceschia, E., Bêziat, P., Dejoux, J.F., Aubinet, M., Bernhofer, Ch., Bodson, B., Buchmann, N., Carrara, A., Cellier, P., Di Tommasi, P., Elbers, J.A., Eugster, W., Grünwald, T., Jacobs, C.M.J., Jans, W.W.P., Jones, M., Kutsch, W., Lanigan, G., Magliulo, E., Marloie, O., Moors, E.J., Moreaux, C., Olioso, A., Osborne, B., Sanz, M.J., Saunders, M., Smith, P., Soegaard, H., Wattenbach, M., 2010. Management effects on net ecosystem carbon and GHG budgets at European crop sites. Agr. Ecosyst. Environ. 139:363-383.

Chadwick, D., Sommer, S., Thorman, R., Fanguiero, D., Cardenas, L., Amon, B., Mistlebrook, T., 2011. Manure management: Implications for greenhouse gas emissions. Anim. Feed Sci. Tech. 166-167:514-531.

de Boer, I.J.M., 2003. Environmental impact assessment of conventional and organic milk production. Livest. Prod. Sci. 80:69-77.

Dijkstra, J., Neal, H.D.St.C., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the ruminat: model description. J. Nutr. 122:2239-2256.

EEA, 2009. Annual European Community greenhouse gas inventory 1999-2007. An inventory report. EEA Technical report No. 4. European Environment Agency Publ., København, Denmark.

EMEP/EEA, 2009. 4.B Animal husbandry and manure management. Part B. Sectorial guidance chapters. Manure management GB2009 update June 2010. Available from: http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/4-agriculture/4-b

ENAMA, 2005. Prontuario dei consumi di carbonburante per l’impiego agevolato in agricoltura. Available from: http://www.enama.it/php/pageflip.php?pdf=enama_int_prontuario.pdf&dir=/it/pdf/manografie

Fantin, V., Buttol, P., Pergreffi, R., Masoni, P., 2012. Life cycle assessment of Italian high quality milk production. A comparison with an EPD study. J. Cleaner Prod. 28:150-159.

FIL-IDF, 2010. A common carbon footprint
approach for dairy. The IDF guide to standard lifecycle assessment methodology for dairy sector. Bulletin of the International Dairy Federation No. 445/2010.

Flysjö, A., 2011. Potential for improving the carbon footprint of butter and blend products. J. Dairy Sci. 94:5833-5841.

Flysjö, A., Cederberg, C., Henriksson, M., Ledgard, S., 2012. The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk. J. Cleaner Prod. 28:134-142.

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., Englund, J-E., 2011. The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agr. Syst. 104:459-469.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Climate Change 2007: the physical science basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp 131-234. Available from: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139:100-108.

González-García, S., Castanheira, É.G., Dias, A.C., Arroja, L., 2013. Environmental performance of a Portuguese mature cheese-making daily mill. J. Clean. Prod. 41:65-73.

Gräning, C. Beauchemin, K.A., 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? Anim. Feed Sci. Tech. 166-167:308-320.

Haas, G., Wetterich, F., Köpke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agr. Ecosyst. Environ. 83-83-53.

Henriksen, M., Flysjö, A., Cederberg, C., Swensson, C., 2011. Variation in carbon footprint of milk due to management differences between Swedish dairy farms. Animal 5:1474-1484.

Hogaae Eide, M., 2002. Life cycle assessment (LCA) of industrial milk production. Int. J. Life Cycle Ass. 7:115-126.

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

Husted, S., 1994. Seasonal variation in methane emission from stored slurry and solid manures. J. Environ. Qual. 23:585-592.

Intergovernmental Panel on Climate Change, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006a/g/

ISPARA, 2008. Agricultura. Inventario nazionale delle emissioni di disaggregazione provinciale. Rapporti 85. Istituto Superiore per la Protezione e la Ricerca Ambientale Publ., Roma, Italy.

ISO, 2011. Italian Greenhouse Gas Inventory 1990-2009. National Inventory Report 2011. Rapporti 139/2011. Istituto Superiore per la Protezione e la Ricerca Ambientale Publ., Roma, Italy.

ISO, 2006a. Environmental management – life cycle assessment – principles and framework. Norm ISO 14040:2006. International Organization for Standardization Publ., Geneva, Switzerland.

ISO, 2006b. Environmental management – life cycle management – requirements and guidelines, Norm ISO 14044:2006. International Organization for Standardization Publ., Geneva, Switzerland.

Kalscheur, K.F., Baldwin, R.L.VI, Glenn, B.P., Kohn, R.A., 2006. Milk production of dairy cows fed differing concentrations of rumen-protected protein. J. Dairy Sci. 89:249-259.

Kebrab, E., Clark, K., Wagner-Riddle, C., France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: a review. Can. J. Anim. Sci. 86:135-157.

Kirchgeessnner, M., Windisch, W., Muller, L.P., 1995. Nutritional factors for the quantification of methane production. pp 333-348 in Proc. 8th Int. Symp. Ruminant Physiology, Stuttgart, Germany.

Kristensen, T., Mogensen, L., Trydeman Knudsen, M., Hermansen, J.E., 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livest. Sci. 140:136-148.

Külling, D.R., Dohme, F., Menzi, H., Sutter, F., Lischer, P., Kreuzer, M., 2002. Methane emissions of differently fed dairy cows and corresponding methane and nitrogen emissions from their manure during storage. Environ. Monit. Assess. 79:129-150.

Külling, D.R., Menzi, H., Krober, T.F., Neftel, A., Sutter, F., Lischer, P., Kreuzer, M., 2001. Emissions of ammonia, nitrous oxide and methane from different types of dairy manure storage as affected by dietary protein content. J. Agr. Sci. 137:235-250.

Lee, C., Hristov, A.N., Dell, C.J., Feyerisen, G.W., Kye, J., Beegle, D., 2012. Effect of dietary protein concentration on ammonia and greenhouse gas emitting potential of dairy manure. J. Dairy Sci. 95:1930-1941.

Lovett, D.K., Shalloo, D., Dillon, P., O’Mara, F.P., 2008. Greenhouse gas emissions from pastural based dairying systems: The effect of uncertainty and management change under two contrasting production systems. Livest. Sci. 116:260-274.

Mc Gough, E.J., Little, S.M., Janzen, H.H., McAllister, T.A., McGinn, S.M., Beauchemin, K.A., 2012. Life-cycle assessment of greenhouse gas emissions from dairy production in Eastern Canada: a case study. J. Dairy Sci. 95:5164-5175.

National Research Council, 2001. Nutrient Requirements of Dairy Cattle, 7th rev. ed. National Academy Press, Washington, DC, USA.

Nguyen, T.T.H., van der Werf, H.M.G., Eugène, M., Veysset, P., Devun, J., Cheneau, G., Doreau, M., 2012. Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. Livest. Sci. 145:239-251.

O’Brien, D., Shalloo, L., Buckley, F., Horan, B., Grainger, C., Wallace, M., 2011. The effect of methodology on estimates of greenhouse gas emissions from grass-based dairy systems. Agr. Ecosyst. Environ. 141:39-48.

O’Brien, D., Shalloo, L., Grainger, C., Buckley, F., Horan, B., Wallace, M., 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. J. Dairy Sci. 93:3390-3402.

O’Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., Wallace, M., 2012. Evaluation of the effect of accounting method, IPCC vs. LCA, on grass-based and confinement dairy systems’ greenhouse gas emissions. J. Dairy Sci. 95:1564-1575.

Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agr. Ecosyst. Environ. 112:207-220.
Olesen, J.E., Weiske, A., Asman, W.A., Weisbjerg, M.R., Djurhuus, J., Schelde, K., 2004. FarmGHG. A model for estimating greenhouse gas emissions from livestock farms. Danish Institute of Agricultural Sciences. Available from: http://agrsci.au.dk/fileadmin/DJF/JPM/klima/JEO/FarmGHG5Documentation.pdf

Phetteplace, H.W., Johnson, D.E., Seidl, A.F., 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutr. Cycl. Agroecosys. 60:99-102.

Pirlo, G., 2012. Cradle-to-farm gate analysis of milk carbon footprint: a descriptive review. Ital. J. Anim. Sci. 11:e20.

Ramin, M., Huhatanen, P., 2013. Development of equations for predicting methane emissions from ruminants. J. Dairy Sci. 96:2476-2493.

Robinson, P.H., 2010. Impacts of manipulating ration metabolizable lysine and methionine levels on the performance of lactating dairy cows: A systematic review of the literature. Livest. Sci. 127:115-126.

Rotz, C.A., Chianese, D.S., 2009. The dairy greenhouse gas model. Reference manual, version 1.2. Pasture Systems and Watershed Management Research Unit. Available from: http://www.ars.usda.gov/sp2UserFiles/Place/19020000/DairyGHGReferenceManual.pdf

Rozt, C.A., Montes, F., Chianese, D.S., 2010. The carbon footprint of the dairy production systems through partial life cycle assessment. J. Dairy Sci. 93:1266-1282.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90:1-10.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Šebek, L.B.J., 2005. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. Nutr. Cycl. Agroecosyst. 71:163-175.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., De Haan, C., 2006. Livestock’s long shadow: environmental issues and options. FAO Publ., Roma, Italy. Available from: ftp://ftp.fao.org/docrep/fao/010/a0701e/a0701e.pdf

St-Pierre, N.R., Sylvester, J.T., 2005. Effects of 2-Hydroxy-4-(Methylthio) butanoic acid (HBM) and its isopropyl ester on milk production and composition by Holstein cows. J. Dairy Sci. 88:2487-2497.

Subbarao, G.V., Ito, O., Sahrawat, K.L., Bery, W.L., Nakahara, K., Ishikawa, T., Watanabe, T., Suenaga, K., Rondon, M., Rao, I.M., 2006. Scope and strategies for regulation of nitrification in agricultural systems – Challenges and opportunities. Crit. Rev. Plant Sci. 25:303-335.

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

Wall, E., Simm, G., Moran, D., 2010. Developing breeding schemes to assist mitigation of greenhouse gas emissions. Animal 4:366-376.

Weiss, W.P., 2004. Factors affecting manure excretion by dairy cows. pp 11-20 in Proc. Nat. Cornell Nutr. Conf., Ithaca, NY, USA.

Wheeler, D.M., 2012. OVERSEER® Technical manual. Calculation of methane emissions. AgResearch Ltd., Hamiltion, New Zealand. Available from: http://www.overseer.org.nz/Portals/0/Technical%20manual/OvrMethane%20H.pdf

Yan, M.J., Humphreys, J., Holden, N.M., 2013. The carbon footprint of pasture-based milk production: Can white clover make a difference? J. Dairy Sci. 96:857-865.

Zehetmeier, M., Baudracco, J., Hoffmann, H., Heißenhuber, A., 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. Animal 6:154-166.