Cradle-to-farm gate analysis of milk carbon footprint: a descriptive review

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

Abstract

Twenty-four life cycle assessment studies which estimated the carbon footprint of milk production in countries with modern dairy farming were examined. It proved difficult to compare the studies because of the strong discrepancies between them. The aim of this review was to examine the characteristics of LCA studies on milk production in order to understand how the variability of results can be explained. The main reason is the different methodologies adopted. However, other variables were considered: production system, stocking rate, milk productivity, mitigation strategies. Life Cycle Assessment is a promising tool for benchmarking carbon footprint among different countries or production systems. This approach could also be used as a mitigation indicator in the enforcement of political decision. Two major factors are needed for a practical application: i) a widely accepted methodology and ii) direct measurements of greenhouse gases in specific contexts.

Introduction

Over the last decades there have been various signs of changes in the earth’s climate such as increases in the average surface temperature and sea levels, and reduced snow and ice coverage. Meteorologists of the International Panel on Climate Change (IPCC) have also observed that extreme weather events (cyclones, typhoons, heat waves, drought, floods, etc.) have increased their intensity and frequency (IPCC, 2007). The same report (IPCC, 2007) identifies human activity as the main cause of climate changes, as this has determined a dramatic increase in atmospheric concentration of long-lived global warming gases (GHG): carbon dioxide, methane, nitrous oxide and halocarbons (gases containing fluorine, chlorine and bromine). The IPCC (2007) estimated an increase in GHG emissions from 28.7 Gt of CO2-eq/year in 1970 to 49.0 Gt of CO2-eq/year in 2004. There is increasing public concern about the effects of global warming on human health, food-supply, water resources, and other environmental issues, since dramatic events are expected in the future. For instance, an IPCC working group (Easterling et al., 2007) proposed a series of forecasts about climate changes and their effects (positive or negative) on food, fibre and forest productions. The working group predicted that food security (production and availability) will be strongly affected, but in such a way that the differences between developed and developing countries will increase rather than diminish. However, this is only a hypothesis since, according to other recent studies (Craine et al., 2010; Peltonen-Sainio et al., 2010), the probable increase in temperature and the frequency of intensive rain falls might have a negative impact on the productivity of some crops even in European regions.

This dramatic vision induced most governments to sign the Kyoto Protocol (1997) which was confirmed and strengthened by the European Community by the 2009/28/CE Directive.

Agriculture is not the main driving force of the increase in atmospheric GHG concentration, but it is considered one of the most important ones. On a global level, agriculture is estimated to be the fourth contributor of GHG after energy supply, industry, and forestry (IPCC, 2007). However, animal production is perceived to be much more harmful for global warming, probably as a consequence of the report issued by the FAO (Steinfeld et al., 2006) which identified livestock as being responsible for 18% of the world’s total GHG emissions. Most probably, public opinion has this perception of animal production because it has an impact not only on climate change, but also on acidification, eutrophication, ozone depletion, reduced water resources, loss of biodiversity and soil erosion. Also its fundamental role in the ecosystem has been quite forgotten; livestock allows the use of feed sources that cannot be used in any other way and transforms them into foods or leather. In developing countries, livestock represents the main or sometimes the only source of income and sustenance in pastoral systems. Livestock production contributes to global warming through three gases: i) CH4 which derives from enteric fermentation and from decomposition of organic matter of manure; ii) N2O which is primarily formed at the end of the denitrification and nitrification of organic N of manure and urine and of N of chemical fertilizers; iii) CO2 which is emitted with the combustion of fossil fuels used for moving tractors, heating, producing electricity and manufacturing chemical fertilizers, seeds, etc.

Alternative methods to assess the environmental impact of farming are available (Payraudeau and van der Werf, 2005). Life Cycle Assessment (LCA) is one of them and is considered a powerful tool for evaluating environmental effects of a product, process, or activity throughout its life cycle. This is also known as a from-craddle-to-grave approach. Life Cycle Assessment is a standardized method for calculating its impact and interpreting its results (ISO, 2006a,b). The impact categories which are typically analyzed are: land use, energy use, climate change, acidification, and eutrophication. These characteristics made it one of the most widespread instruments used by authorities, industries, and individuals in environmental sciences. It can be used in international benchmarking, economic and social planning, eco-labeling, verification of technical innovation, or evaluation of the results of the adoption of mitigation strategies. In many studies, the ISO standards are not strictly complied with; this does not necessarily make their scientific value void, but it simply...
means that they cannot be completely exploit-
ed through, for example, the Environmental
Product Declaration (EDP) that certifies reli-
bility of the LCA analysis.

The IPCC periodically publishes the GHG
emissions of seven categories: i) energy; ii)
industrial processes; iii) solvents and other
products use; iv) agriculture; v) land-use,
changes in land-use and forestry; vi) waste;
and vii) others.

Sub-categories of agriculture are: enteric
fermentation, manure management, rice culti-
vation, agricultural soils, prescribed burning
savannahs, field burning of agricultural
products. The IPCC methodology attributes
to agriculture only the CH4 and N2O emissions it
produces directly and excludes CO2 and N2O
deriving from fuel combustion or from produc-
tion of seeds, fertilizers, and machines. A com-
prehensive comparison between the applica-
tion of the IPCC and LCA approach to dairy cat-
tle production systems was made by Crosson
et al. (2011).

If climate change (or the global warming
potential, GWP) is the only impact category
considered in a study, LCA refers to carbon
footprint (CF). Although the CF of 1 kg of milk
is lower than those of pork, chicken, eggs and
beef (de Vries and de Boer, 2010), it receives a
particular attention because lactating cattle
are the main source of GHG of all livestock and
poultry. The FAO (2010) illustrated the main
traits of an LCA approach applied to dairy pro-
duction and compared the CF of 1 kg of Fat
Protein Corrected Milk (FPCM) among coun-
tries. The average GHG emission per 1 kg of
FPCM was 2.4 kg CO2-eq, with a great deal of
variation among countries (FAO, 2010). Many
LCA studies of milk production have been car-
ried out in several countries. However, these
studies have such different characteristics
that it is difficult to compare and interpret
their results, which are probably influenced,
not only by the characteristics of production
systems (i.e. milk productivity, stocking rate),
but also by the methodology adopted. This dis-
crepancy among the different analyses is a
major problem because one of the main appli-
cations of the LCA is benchmarking and also
because one of the main steps of an LCA analy-
sis is a comparison with the results obtained
by other authors. However, this is only possible
if there is a common method or, at least, a
common approach to their interpretation.

In this paper, some characteristics of the
LCA studies, which estimated the CF of milk,
were examined in order to understand how
this variability in results can be explained. The
studies considered are cradle-to-farm gate,
because they refer to milk production only and
do not include milk transportation to dairies,
processing or distribution.

Studies on milk carbon footprint

Using a combination of database searches
(PubMed, Medline, CABI, and Agricola) and
interactive screening of references, 34 papers
concerning LCA studies on milk production
were identified from 2000 to 2011. All of them
had been published in international peer-
reviewed journals, except those by Basset-
Mens et al. (2005), Fantin and Pergreffi (2010)
and FAO (20010). The phase of the life cycle of
milk that has been considered in this review is
that of a farm, so that the analysis concerns
milk production only and does not include milk
transportation to dairies, processing, distribu-
tion or consumption. There are some papers
which do not refer to farm phase only (Hagaa
Eide, 2002; Hospito et al., 2003; Fantin and
Pergreffi, 2010; Fantin et al., 2011); in those
cases, only data concerning the farm phase
were considered. Similarly, only emissions of
GHG (CO2, CH4 and N2O) were reviewed,
ignoring other environmental impacts. The
papers considered in the analysis had to refer
to a precise country and had to have sufficient
details. For these reasons, 7 papers were not
considered; another paper was eliminated
because it referred to a very small farm size in
a developing country and was considered to
not be comparable to that of modern milk pro-
duction systems. Finally, 2 studies could not be
used because they also took into account the
role of soil in carbon sequestration, which can
determine a considerable reduction in the
impact of the climate change associated to
milk. At the end of the process, 24 studies had
been selected and their main characteristics
are reported in Table 1. They were classified
according to country, farm data source (real
farms, simulated representative farms, national
statistics), allocation criteria, emission
inventory, gas GWP, method of comparison,
and functional unit (FU).

The studies were all performed in so-called
developed countries: 4 in the Netherlands, 3
each in Ireland and Sweden, 2 in the U.S.A,
New Zealand and Italy, one in Portugal, UK,
Germany, Spain, Denmark, Norway and France;
one other study was performed both in
New Zealand and Sweden. Data sources var-
ied. National statistics were used when (but
not always) geographical areas or different
years were being compared; in 4 cases, nation-
al statistics were used to estimate the effects
of a technical innovation. As data from real
farms cannot be easily gathered, in many LCA
studies a simulated representative farm used
instead, with the aim of simulating the effects
of alternative farming strategies, technical
innovations, etc.

Dairy farms produce not only milk, but also
meat, manure and in some cases crop com-
modities (cereals, soybean etc.). In cases of
multifunctional processes, the environmental
impact should be shared among the products.
Cederberg and Stadig (2003) define alterna-
tive co-product handling criteria: i) no alloca-
tion - when milk takes all the environmental
burden; ii) biological allocation - that consid-
ers the nutritional requirements for producing
milk and meat; iii) economic allocation - that
is based on the income from the two co-prod-
ucts; iv) system expansion - when the effects
of alternative ways to produce meat are consid-
ered.

Although with a small difference, an alterna-
tive method is the one proposed by Thomassen
et al. (2008a); however, these authors do not
indicate biological allocation but mass alloca-
tion if the environmental burden is shared
according to the quantity of co-products.

Life cycle assessment was often used to
compare the environmental effects of conven-
tional with that of organic dairy farming (5
papers). However, it was also used to evaluate
the effects of intensification or extensification
(5 papers), mitigation strategies (4 papers),
years (2 papers), genetic strain (2 papers), soil
(one paper) and allocation (one paper). In
some papers, no explicit comparison was made.

Definition of the FU is one of the main steps
of LCA methodology (ISO, 2006a,b). In the
studies examined, the FU is the GHG emission
associated to the production of one unit of milk
(kilogram or liter). In some cases, the unit of
measurement was much better defined as kilo-
gram of Energy Corrected Milk (ECM), Fat
Corrected Milk (FCM), or FPCM. In the present
review, only FU concerning measure of milk
was considered, and other FU, such as amount
of emissions of GHG from one hectare of cul-
tivated soil, were excluded.

Inventory analysis consists of collection of
data concerning resource use, energy con-
sumption, emissions and products from each
activity in milk production systems. Primary
sources of direct emissions (defined also sim-
ply as direct emissions) are those that are gen-
erated inside the system. In an LCA of milk
production, they are the CO2 emissions from
fuel combustion by tractor engines and other
| Authors                      | Country       | Farm data source | Allocation   | Emission inventory                                                                 | GWP                                      | Comparison | Kg GHG/UF |
|------------------------------|---------------|------------------|--------------|------------------------------------------------------------------------------------|------------------------------------------|------------|-----------|
| Basset-Mens et al., 2009     | New Zealand   | NS, RF and EF    | Biological   | OVERSEER (IPCC-NZ) SIMAPRO-Ecoinvent (Pre Consultants, 2008)                      | CO₂=1, CH₄=21, N₂O=310                   | Average NZ | 0.933     |
|                              |               |                  |              |                                                     | N₂O=310                                  | Low input | 0.646     |
|                              |               |                  |              |                                                     |                                        | N fertilizers | 0.762     |
|                              |               |                  |              |                                                     |                                        | Maize silage | 0.754/kg milk |
|                              |               |                  |              |                                                     |                                        | None       | 0.718/kg milk |
|                              |               |                  |              |                                                     |                                          |            |           |
|                              |               |                  |              |                                                     |                                          |            |           |
| Capper et al., 2009          | USA           | NS               | No           | IPCC, 2006; Bibliography                                                            | CO₂=1, CH₄=21                           | Year 1944 vs 2007 | 1944=3.66 |
|                              |               |                  |              |                                                     | N₂O=298                                  | 2007=1.35/kg milk |           |
|                              |               |                  |              |                                                     |                                          |            |           |
| Casey and Holden, 2005a       | Ireland       | RF (10)          | No, mass, economic | Bibliography                                                                                   | CO₂=1, CH₄=21                           | Conventional | 1.5       |
|                              |               |                  |              |                                                     | N₂O=310                                  | Efficient   | 1.26      |
|                              |               |                  |              |                                                     |                                          | Only diary  | 1.2       |
|                              |               |                  |              |                                                     |                                          | Integrated  | 1.05/kg ECM |
|                              |               |                  |              |                                                     |                                          |            |           |
| Castanheira et al., 2010     | Portugal      | SRF              | Economical   | Bibliography                                                                                        | CO₂=1, CH₄=25                           | Conventional | 1.09      |
|                              |               |                  |              |                                                     | N₂O=298                                  | Organic farming     | 0.90/kg ECM |
|                              |               |                  |              |                                                     |                                          | No allocation | 1.05      |
|                              |               |                  |              |                                                     |                                          | Economical    | 0.92      |
|                              |               |                  |              |                                                     |                                          | Biological    | 0.65      |
|                              |               |                  |              |                                                     |                                          | Expansion    | 0.6/kg ECM |
|                              |               |                  |              |                                                     |                                          | Fertilizing   | 0.93/l milk |
|                              |               |                  |              |                                                     |                                          | Diet         | 1.3       |
|                              |               |                  |              |                                                     |                                          | Whole system  | 1.28      |
|                              |               |                  |              |                                                     |                                          | Genetic      | 1.28      |
|                              |               |                  |              |                                                     |                                          | Large        | 1.28      |
|                              |               |                  |              |                                                     |                                          | Small farms  | 1.68/kg FPCM |
|                              |               |                  |              |                                                     |                                          | None         | 1.3kg     |
|                              |               |                  |              |                                                     |                                          | FPCM         | 1.3kg     |
| Del Prado et al., 2010       | UK            | SRF              | Not specified | SIMSDairy (del Prado et al., 2009)                                                                  | NS                                      |            |           |
|                              |               |                  |              |                                                     |                                          |            |           |
| Fantin and Pergreffi, 2010   | Italy         | RF (13)          | Mass         | IPCC, 2006 SIMAPRO-Ecoinvent (Pre Consultants, 2008)                                           | CO₂=1                                  | Conventional | 1.05      |
|                              |               |                  |              |                                                     | N₂O=298                                  | Organic farming     | 1.05/kg ECM |
|                              |               |                  |              |                                                     |                                          | None         | 1.05      |
|                              |               |                  |              |                                                     |                                          | Intensive    | 1.3       |
|                              |               |                  |              |                                                     |                                          | Extensive    | 1.0       |
|                              |               |                  |              |                                                     |                                          | Organic      | 1.3 kg/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.13 kg/kg ECM |
| Fantin et al., 2011          | Italy         | RF (6)           | No           | IPCC, 2006 SIMAPRO-Ecoinvent (Pre Consultants, 2008)                                           | CO₂=1                                  | Conventional | 1.05      |
|                              |               |                  |              |                                                     | N₂O=298                                  | Organic farming     | 1.05/kg ECM |
|                              |               |                  |              |                                                     |                                          | None         | 1.05      |
|                              |               |                  |              |                                                     |                                          | Intensive    | 1.3       |
|                              |               |                  |              |                                                     |                                          | Extensive    | 1.0       |
|                              |               |                  |              |                                                     |                                          | Organic      | 1.3 kg/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.13 kg/kg ECM |
| Flysjö et al., 2011          | New Zealand,  | NS               | No           | Bibliography                                                                                        | CO₂=1                                  | NZ grazing   | NZ 1.0     |
|                              | Sweden        |                  |              |                                                     | N₂O=298                                  | S indoors    | 1.16/kg ECM |
|                              |               |                  |              |                                                     |                                          | Intensive    | 1.3       |
|                              |               |                  |              |                                                     |                                          | Extensive    | 1.0       |
|                              |               |                  |              |                                                     |                                          | Organic      | 1.3 kg/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.13 kg/kg ECM |
| Haas et al., 2001            | Germany       | RF (18)          | No           | Bibliography                                                                                        | CO₂=1                                  | Intensive    | 1.3       |
|                              |               |                  |              |                                                     | CH₄=21                                   | S indoors    | 1.16/kg ECM |
|                              |               |                  |              |                                                     | N₂O=310                                  | Intensive    | 1.3       |
|                              |               |                  |              |                                                     |                                          | Organic      | 1.3 kg/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.13 kg/kg ECM |
| Henriksson et al., 2011      | Sweden        | NS               | No           | IPCC, 2006 and bibliography                                                                         | NS                                      | None        | 0.41/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 0.84/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.03      |
|                              |               |                  |              |                                                     |                                          | None         | 1.06/kg ECM |
| Hogdaas Erde, 2002           | Norway        | SRF              | Biological   | Bibliography                                                                                        | NS                                      | None        | 0.41/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 0.84/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.03      |
| Hospido et al., 2005         | Spain         | RF (2)           | Economical   | Bibliography                                                                                        | NS                                      | None        | 0.41/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 0.84/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.03      |
| Kristensen et al., 2011      | Denmark       | RF (67)          | Mass         | Bibliography                                                                                        | NS                                      | None        | 0.41/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 0.84/kg milk |
|                              |               |                  |              |                                                     |                                          | None         | 1.03      |

To be continued on next page.
Table 1. Continued from previous page.

| Authors            | Farm data source | Comparison | Country   | Farm data source | Allocation | Emission inventory | GWP           | Comparison | Kg GHG/UF |
|--------------------|------------------|------------|-----------|------------------|------------|--------------------|---------------|------------|-----------|
| Lovett et al., 2008 | SRF and RF (2)   | No         | Ireland   | Biological       | Not specified | DairyWise (Shalloo et al., 2004) | CO$_2$=1, CH$_4$=21 | None       | 1.383/kg FCM. |
| O’Brien et al., 2010 | No               | Biological | Ireland   | EF               | Not specified | Biological         | CO$_2$=1, CH$_4$=21 | None       | 1.116/kg milk |
| Phetteplace et al., 2001 | EF               | Biological | USA       | The Netherlands | No         | Farmsim (Phetteplace et al., 2006) | CO$_2$=1, CH$_4$=21 | None       | 1.082/kg FPCM |
| Schils et al., 2004 | SRF              | Biological | The Netherlands | The Netherlands | Not specified | DairyWise (Schils et al., 2004) | CO$_2$=1, CH$_4$=21 | None       | 1.072 |
| Thomasen et al., 2006b | SRF              | Economic   | The Netherlands | The Netherlands | Not specified | DairyWise (Thomasen et al., 2006b) | CO$_2$=1, CH$_4$=21 | None       | 1.1/kg FPCM |
| Thomasen and de Boer, 2005 | SRF              | Economic   | The Netherlands | The Netherlands | Not specified | DairyWise (Thomasen and de Boer, 2005) | CO$_2$=1, CH$_4$=21 | None       | 1.082/kg FPCM |
| Thomasen et al., 2009 | SRF              | Not specified | France     | EF               | Not specified | DairyWise (Van der Weerdt et al., 2009) | CO$_2$=1, CH$_4$=21 | None       | 1.082/kg FPCM |
| Van der Weerdt et al., 2009 | SRF              | Not specified | France     | EF               | Not specified | DairyWise (Van der Weerdt et al., 2009) | CO$_2$=1, CH$_4$=21 | None       | 1.082/kg FPCM |

RF, real farm (i.e., EF, experimental farm, NS, national statistic; SRF, simulated representative farm.

RF, real farm (i.e., EF, experimental farm, NS, national statistic; SRF, simulated representative farm.

Secondary sources of indirect emissions (or simply indirect emissions) are those coming from the production of fuel, machinery, fertilizer, pesticide, and plastic used in the production of feeds, nutrition of animals, and manure management. They also include those that are generated during the production of external replacement animals.

To perform an LCA study, a series of data in the farm (i.e., herd size, milk production, rations, manure management, tractors, yearly fuel and electricity consumption) needs to be collected. Specific emission factors (EF) are then associated to those data. There is a wide heterogeneity of systems to estimate direct and indirect emissions, and of EF among the LCA studies on milk production. Direct emissions of CH$_4$ and N$_2$O are often estimated through IPCC (2006) methodology. In the studies considered here, this is normally adapted to each specific country. In some studies, the authors did not refer to IPCC methodology, or at least not only, but adopted equations or EF found in the literature.

To estimate indirect emissions, extensive bibliography searches were often presented, but in many cases, some softwares (i.e. SimaPro, PRè, Netherlands, 2008) were used. These programs help the authors to estimate the mass flows and allow the access to some databases that can easily supply estimates of transport, extraction and processing raw materials, and production of usually used products, such as plastics, and their disposal.

Some whole-farm models were also developed to provide an estimate of both direct and indirect emissions of the milk production process: SIMSDairy (del Prado et al., 2009), DairyWise (Schils et al., 2007), MDSM (Shalloo et al., 2004), FarmGHG (Olesen et al., 2004), and DairyGHG (Rotz and Chianese, 2009).

Main factors affecting results of milk life cycle analyses

Comparison among countries

Probably, the use of several FU is extremely problematic in that it makes it difficult to compare the results of milk CF. To overcome this,
the studies were divided into four groups, taking into account the different EF: uncorrected milk, ECM, FPCM, or FCM. Among the studies in which uncorrected milk is adopted as FU, the highest value is that of Capper et al. (2009) and the lowest is that of Høgaas Eide (2002). With ECM as FU, the highest value was reported by Casey and Holden (2005a) and the lowest was that of Cederberg and Stadig (2003). On comparing studies with FPCM, the highest value was from Schills et al. (2006) and the lowest from van der Werf et al. (2009). One value only is available with FCM (Lovett et al., 2008). On the whole, there is a large variability among the studies that have been examined; if carbon sequestration is excluded, the lowest emissions of CO₂-eq associated to milk production are those from New Zealand, which has a production system characterized by low inputs and uses large areas of pasture. On the other hand, there are studies made in more intensive conditions, such as those carried out in the USA (Capper et al., 2009) or the Netherlands (Schills et al., 2006).

These observations are not easy to compare with other studies that, even if less detailed, used only one method to estimate the emissions from a number of countries. The FAO (2010) calculated that the average emission of GHG at the farm-gate is about 2.3 kg CO₂-eq per 1 kg of FPCM worldwide. However, its report showed great variations among different international areas. The highest value is that of sub-Saharan Africa and the lowest is that of North America. The study pointed out that emissions are lower in temperate regions, where industrial economies prevail, than in arid or humid zones, where there is little specialized farming and efficiency of livestock production is low. But there are also relatively large differences among the so-called developed countries (North America, Western and Eastern Europe, Russia, Eastern Asia, and Oceania): from 1 kg CO₂-eq per 1 kg of FPCM in North America to 1.9 kg CO₂-eq per 1 kg of FPCM in Eastern Asia. According to the scale of the FAO study (2010), the difference between GHG emissions associated to a grassland system, typical of New Zealand, and a mixed system, typical of the USA or Western Europe, is not measurable. At a European scale, Lesschen et al. (2011) reported that the GHG emissions associated to milk production in all the 27 countries of the European Union averaged around 1.3 kg CO₂-eq/kg of milk, varying between 1.1 and 2.2 kg CO₂-eq/kg in Denmark and Bulgaria, respectively. According to the study, these differences were mainly related to the efficiency of the cattle themselves, i.e. determined by the typical genetic levels and forage systems of each country. From these data, a benchmarking among countries that have specialized milk production systems, either extensive or intensive, is difficult to define.

Allocation

Milk production is typically a multipurpose production system. Although the main product is milk, an appreciable portion of the dairy farm income is the meat of male calves and culled cows. In some circumstances, further income can be derived from crops or replacement heifers. In most of the experiments reported in this review, the authors considered co-products and adopted mass, economic or biological allocation. Obviously, the choice of the allocation system has an important impact on results, raising critical questions about the comparisons made among studies. An example is given by that of Cederberg and Stadig (2003) who compared four allocation systems: no allocation, economic, biological, system expansion. The allocation system has dramatic effects on milk CF, which was reduced by 8, 15 and 37% in relation to an unallocated CF value with economic or biological allocation or system expansion, respectively.

Methodology

The papers presented in the list differ in many methodological aspects. Some papers treat data gathered in real farms, which often constitute a sample of a population of farms in a specific country or of a production system. Others employ a reference farm, that is a model that should be representative of a certain population. There will be obvious differences in the quality of the data and the results because of the difficulty of identifying a reference farm, especially if no details are given about the method adopted.

A great number of the papers in this review use EF estimated through IPCC (2006) methodology. Normally, country-specific EF are used, but there is hardly ever a clear declaration of which Tier (I or II) is given. Furthermore, whole-farm models often apply different procedures to estimate CH₄ or N₂O emissions from cows and manure (Schills et al., 2007; Rotz and Chianese, 2009). The absence of transparency and the variety of data sources are even greater with indirect emissions.

There is such a huge literature concerning direct GHG emission measurements from dairy cattle operations that it is difficult to find a relationship between FE used in LCA analyses and direct measurements. Of course, this is particularly true for those systems or countries (i.e. Italy) for which there are no or only a few specific experimental measurements. Furthermore, there is a large variety of measurement methodologies. For example, measuring methane gas from enteric fermentation probably presents the biggest problems. Most EF of enteric CH₄ have been estimated through respiration calorimetry chambers. One of the objections that is frequently raised is that this system requires the animal to be constrained, limiting the applicability of the results as a consequence. To measure emissions from grazing cattle, the tracer technique has been developed. This technique has some problems of reliability and repeatability (Lassey et al., 2011) and it is suspected to have a poor relationship with respiration calorimetry chamber technique (Pinares-Patiño et al., 2011).

Global warming potential is the ability of a gas to trap the heat and it is expressed as CO₂-eq. In all the CF studies examined in this review, the GWP of gases have a time horizon of 100 years and are those reported by Forster et al. (2007): CO₂=1 CO₂-eq; CH₄=25 CO₂-eq; and N₂O=298 CO₂-eq. There are some cases in which the authors used values that show little difference: CO₂=1 CO₂-eq; CH₄=21 CO₂-eq; and N₂O=310 CO₂-eq (reported as SAR values by Forster et al., 2007). Although small, the difference could have an appreciable effect when mitigation strategies are tested or when very different production systems are compared.

To overcome all these discrepancies and to have a useful tool for comparing different production systems, the International Dairy Federation has proposed guidelines for a standardized CF assessment for the dairy sector (IDF, 2010).

Organic vs conventional farming

Organic farming is considered much more environmentally friendly than conventional farming and several LCA studies aimed to demonstrate this hypothesis. Among those studies in the literature that have been examined there are 5 papers which compared the GHG emitted from a conventional with an organic dairy farming system. In 2 cases (Thomassen et al., 2008b; Kristensen et al., 2011), the GHG emission associated with organic milk was higher than that associated with conventional milk. In 2 cases it was similar (Haas et al., 2001; van der Werf et al., 2009), and in another it was lower (Cederber and Mattsson, 2000). In organic dairy farms, the indirect emissions are lower than in conventional dairy farms, because there is a reduced use of fossil fuel for the production and transport of concentrates and chemical fertilizers.
(Wood et al., 2006). On the contrary, direct emissions are higher: in particular, CH4 emission associated to 1 kg of milk increases in organic farms. Cows in organic farms are widely recognized to be less productive than cows in conventional farms (Roeesch et al., 2005). Organic breeders look for traits other than milk productivity in genetic selection and reduce concentrates in the diet of their cattle. However, higher milk productivity and higher feed digestibility is more favorable to a reduction in CH4 emissions per kilogram of milk (Boadi et al., 2004).

These inconsistent results only marginally weaken the idea that organic farming is more environmentally sustainable than conventional farming, because global warming is only one of the categories considered when evaluating the impact on the environment of any particular activity. In a recent Swiss study (Nemecek et al., 2011), organic farming was shown to reduce the environmental burden of many different agricultural production activities and, in at least 3 LCA studies (Cederberg and Mattsson, 2000; Haas et al., 2001; Thomassen et al., 2008b) organic milk production was shown to have a more positive impact, compared to conventional systems, on energy saving, acidification, eutrophication, photo-oxidant formation, ecotoxicity, and ozone depletion, which are the other great concerns of intensive dairy production.

### Intensive vs extensive farming

One of the greatest concerns about livestock farming is the production intensity per unit of land. However, it appears to be difficult to establish a unique relationship between production intensity and EF per unit of milk since this can be influenced in different several ways.

Crosson et al. (2011) correctly observed that intensification causes an increase in GHG emissions if these are expressed per land unit, while if they are expressed per kg of product this is much less obvious. Casey and Holden (2005b) analyzed a series of papers and found that a reduction in stocking rate allowed a decrease of CO2-eq per ha but it had a minimal effect on CO2-eq per kilogram of ECM.

In most of the studies examined, extensification was made through an increase in pasture utilization and a reduction in off-farm inputs, such as purchased concentrates and mineral fertilizers. In some examples, the extensification allowed a significant reduction of GHG emissions to be achieved (Haas et al., 2001; Basset-Mens et al., 2009). Similar indications are given by the simulations made by del Prado et al. (2010) and Lovett et al. (2008). However, there are other comparisons that came to opposite conclusions; when comparing conventional with organic systems, Thomassen et al. (2008b) and van der Werf et al. (2009) found that the reduction in milk production per land unit corresponded to a higher CF.

The stocking rate can determine the mass of nutrients (fertilizer and concentrates) and of energy used per unit of animal product. Some LCA studies highlighted this issue; O’Brien et al. (2010) simulated an increase of approximately 10-20% of the stocking rate and estimated a corresponding increase of approximately 5-6% of GWP associated to 1 hectare of land; in contrast, there was no effect on environmental burden of 1 kilogram of milk. There also are 2 studies in which the authors gathered data from real farms. Thomassen et al. (2008b) observed that the sample they took of conventional dairy farms had an average stocking rate of 2.13 LU/ha, whereas organic dairy farms averaged 1.7 LU/ha. As mentioned above, they observed an increase in the GWP per production unit from a conventional to an organic system, but a reduction in the environmental burden associated with the land unit. In this case, the authors observed a significant difference of milk production per cow. If there is no difference in respect to animal productivity, the reduction in the stocking rate does not influence the GWP of 1 kg of milk, but decreases the environmental burden associated to the land unit (Haas et al., 2001).

A point that some authors make is the rational and efficient use of N feed and N fertilizers. Excess nitrogen is often associated to high GHG emission per FU, because it indicates low efficiency of feeding, chemical and energetic resource utilization (Schills et al., 2006).

### Effect of milk productivity

The pivotal role milk productivity plays has already been mentioned. Gerber et al. (2011) analyzed the relationship between milk productivity and GHG per kilogram of FPCM and concluded that the emissions of CO2-eq decrease as milk production increases. In their simulation, O’Brien et al. (2010) did not find any difference in GHG emission per kilogram of milk among 3 Holstein-Friesian cattle strains. In this case, the differences in milk production were probably not big enough to be detected with the sensitivity of an LCA analysis. In contrast, in their historical analysis, Capper et al. (2009) showed that the increase in individual milk production from 1944 to 2007 resulted in a reduction in CF per kilogram of milk from 3.65 to 1.35 kg of CO2-eq, due to dilution of maintenance feed requirements. They also calculated that this reduction interested both CH4 and N2O.

The nutrient requirements for maintenance are very similar in cows of the same breed of high or low milk productivity. Also, cows with a high production have a higher metabolic ability to convert feed into milk. This means that the improvement in milk production has a direct positive effect on feed efficiency and, consequently, determines a reduction in the enteric CH4 emissions per kilogram of milk (Yan et al., 2010) because a cow with a high production eats proportionally less feed in relation to its produced milk; the same goes for the rumen fermentations. The improvement in milk production also has an indirect inverse effect on enteric CH4; higher production requires that cows are supplied with an elevated amount of energy, they are able to intake sufficient energy only if the diet has an elevated energy concentration and it is well documented that a reduction in the forage to concentrate ratio leads to less enteric CH4 being produced (Hindrichsen et al., 2006).

Theoretically, milk production should have the same effect on N2O emission (Gerber et al., 2011); however, this is not as obvious as in the case of CH4. In contrast to this gas, the animal emits only a negligible part of N2O, while most comes from manure during storing or after spreading, and its management strongly influences the pattern and amount of emissions (Külling et al., 2001; Monteny et al., 2001). In addition, higher milk production requires formulation of diets with higher protein concentration and, in any case, breeders prefer not to risk underfeeding their cattle, so that it is very difficult to maximize dietary N efficiency (VandeHaar and St-Pierre, 2006). Consequently, in order to achieve a significant reduction in GHG emissions, feeding strategies aimed at reducing N2O emissions should be accompanied by the adoption of strategies involving manure and fertilizer management which have a more effective and consistent effect on emissions of this gas.

Finally, the increase in milk production per cow means that, given the quota regimen as in Europe, the number of dairy cattle is reduced. In turn, the population of suckler cows should increase to meet the demand of meat, and an increase in GHG emissions from beef cattle is expected. However, Zehtemeier et al. (2012) showed that the increase in milk productivity determines a reduction in emissions, even when the expansion system is used and an increase in beef cattle population is hypothesized.
Effect of some mitigation strategies

There is plenty of literature regarding the possible strategies to reduce GHG emission from dairy farms. Some of them were submitted to LCA analysis. The simulations for reducing GHG emissions from dairy farms considered N management (Schils et al., 2005, 2006; Basset-Mens et al., 2009), length of the grazing season (Lovett et al., 2008), bovine somatotropine use in dairy production (Capper et al., 2008), herd size (Rotz et al., 2010) or had a more comprehensive approach, as that of del Prado et al. (2010), whose study examined fertilization, diet, intensification, and animal breeding value. In this regard, Beuken et al. (2010) emphasized the importance of a complete strategy that does not consider only one goal, but aims to improve at least cow efficiency, pasture management, and on-farm feed production.

There are several other strategies which have been proposed to be effective in mitigating GHG emission from dairy farms, but these have not yet been submitted either to a LCA simulation or to a LCA comparison. There are several reviews of the strategies to adopt for reducing emissions of CH4, N2O and CO2 from dairy cattle operations (Boadi et al., 2004; Eckard et al., 2010; Martin et al., 2010; Chadwick et al., 2011). Some of these strategies are the same as those followed to increase the biological efficiency of cattle and are pursued through genetic selection, improvement in feeding techniques and the increase in nutrient digestibility.

Some other strategies can be considered additional, because they could offer further help in reducing GHG emissions from dairy farms. Recently, some promising results were presented demonstrating the possibility of applying a specific genetic selection for reducing enteric CH4 emissions (de Haas et al., 2011). Some improvements have been made in reducing rumen methanogenesis by using oil seeds (Beauchemin et al., 2009; Grainger et al., 2010; Chung et al., 2011), ionophores (Odongo et al., 2007a), propionate enhancers such as encapsulated fumaric acid (Wood et al., 2009), nitrate and sulphate (van Zijderveld et al., 2010), myristic acid (Odongo et al., 2007a,b), tea saponins (Mao et al., 2010), essential oils (Calsamiglia et al., 2007), tannins (Anjum et al., 2008) and oregano leaves (Tekippe et al., 2011) in the diet of dairy cattle. Reduction of rumen degradable protein has positive effects on enteric and manure GHG emissions (Dijkstra et al., 2011)

Further improvement can come from rational management of manure. Covering of manure was seen to be very effective in reducing N2O emissions (Chadwick et al., 2011). Substantial reductions in N2O and NH3 emissions were obtained by treating manure with urease and nitrification inhibitors (Zaman et al., 2009). Nitrous oxide fluxes can be reduced by using enhanced-efficiency fertilizers (Sistani et al., 2011). Another option that was tried with positive results on N2O and CH4 emissions is the addition of straw to farmyard manures (Yamulki, 2006; Thorman et al., 2007). Soil N2O emissions can be cut by reduced manure application, corn-soybean rotation, and restoration of prairies (Hernandez-Ramirez et al., 2009). However, slurry application strategies can have variable results according to crop, soil type and slurry source (Velthof and Mosquera, 2011). Certainly, the most promising strategy is the anaerobic digestion of the manure, thanks to methane recovery (Amon et al., 2006). But probably there is also the need to use more appropriately the soil’s ability to sink the carbon, by adopting forage systems and agronomic techniques which preserve the soil’s organic carbon stocks (Soussana et al., 2010).

Conclusions

Life Cycle Assessment is an effective tool to evaluate the environmental impact of a product, process, or activity throughout its life cycle. For this reason, several LCA concerning milk production were made worldwide. In a moment when particular attention is being paid to GHG emissions by dairy farms, CF could be used for benchmarking by comparing GHG emissions from cattle from different countries or different production systems. It could also be used to evaluate the improvements of a farm, a region, or a state after the introduction of technical innovations or political strategies. It could be very effective as a mitigation indicator of results obtained from the enforcement of environmental political decisions.

From the literature examined, it appears that there is a wide discrepancy among studies, probably because the differences between the methodologies applied are too great. In addition, many mitigation strategies have not been tested in specific contexts and so there are no specific EF.

Two main things are needed to make CF a practical tool in dairy cattle production. The first is to have a widely accepted standardized methodology, and in this, the IDF’s initiative can be considered very promising (IDF, 2010). The second is to use EF obtained from direct measurements in the specific environmental conditions they are referred to; only then can LCA be sensitive enough to verify the effectiveness of a mitigation strategy in a specific context.

Finally, few LCA studies consider the role of soil in carbon sequestration, while it is generally recognized to be an important factor in the environmental sustainability of livestock systems.

References

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agr. Ecosyst. Environ. 112:153-162.

Amonit, G., Puchala, R., Goetsch, A.L., Patra, A.K., Sahlu, T., Varel, V.H., Wells, J., 2008. Methane emission by cows consuming diets with different levels of condensed tannins from lespedeza. Anim. Feed Sci. Tech. 144:212-227.

Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68:1615-1625.

Bassett-Mens, C., Ledgard, S., Carran, A., 2005. First life cycle assessment of milk production from New Zealand dairy farm systems. The Australia New Zealand Society of Ecological Economics Publ., Canberra, Australia. Available from: http://www.anzsee.org/anzsee2005_papers/Bassett-Mens_LCA_NZ_milk_production.pdf

Beauchemin, K.A., McGinn, S.M., Benchaar, C., Holtshauser, L., 2009. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: effects on methane production, rumen fermentation, and milk production. J. Dairy Sci. 92:2118-2127.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G., 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agr. Ecosyst. Environ. 136:358-365.

Boadi, D., Benchaar, C., Chiquette, J., Massé, D., 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Updated review. Can. J. Anim. Sci. 84:319-335.

Calsamiglia, S., Busquet, M., Cardozo, P.W., Castillejos, L., Ferret, A., 2007. Essential
oils as modifiers of rumen microbial fermentation. J. Dairy Sci. 90:2580-2595.

Capper, J.L., Cady, R.A., Bauman, D.E., 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87:2160-2167.

Capper, J.L., Castañeda-Gutiérrez, E., Cady, R.A., Bauman, D.E. 2008. The environmental impact of recombiant bovine somatotropin (rBST) use in dairy production. Proc. Natl. Acad. Sci. USA 105:9668-9673.

Casey, J.W., Holden, N.M., 2005a. Analysis of greenhouse gas emissions from the average Irish milk production system. Agr. Syst. 86:97-114.

Casey, J.W., Holden, N.M., 2005b. 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., Amaro, R., 2010. The environmental performance of milk production on a typical Portuguese dairy farm. Agr. Syst. 103:498-507.

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

Cederberg, C., Stadig, M., 2003. System expansion and allocation in life cycle assessment of milk and beef production. Int. J. Life Cycle Ass. 8:350-356.

Chadwick, D., Sommer, S., Thorman, R., Fangeüro, D., Cardenas, L., Amon, B., Misselbrook, T., 2011. Manure management: Implications for greenhouse gas emissions. Anim. Feed Sci. Tech. 168:167-514.

Chung, Y.-H., He, M.L., McGinn, S.M., McAllister, TA., Beauchemin, K.A., 2011. Linseed suppresses enteric methane emissions from cattle fed barley silage, but not from those fed grass hay. Anim. Feed Sci. Tech. 165:321-329.

Craine, J.M., Elmore, A.J., Olson, K.C., Tolleson, D., 2010. Climate change and cattle nutrition stress. Global Change Biol. 16:2901-2911.

Crosson, P., Shalloo, L., O’Brien, D., Lanigan, G.J., Foley, PA., Boland, TM., Kenny, D.A., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim. Feed Sci. Tech. 166:167-29:45.

de Haas, Y., Windig, J.J., Calus, M.P.L., Dijkstra, J., de Haan, M., Bannink, A., Veerkamp, R.F., 2011. Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. J. Dairy Sci. 94:6122-6134.

de Prado, A., Chadwick, D., Cardenas, L., Misselbrook, T., Scholefield, D., Merino, P., 2010. Exploring systems responses to mitigation of GHG in UK dairy farms. Agr. Ecosyst. Environ. 136:318-332.

de Prado, A., Scholefield, D., Chadwick, D., 2009. New integrated dairy production systems: specification, practical feasibility and ways of implementation. DEFRA Final Report ISO214. Available from: http://randd.defra.gov.uk/Document.aspx?Document=ISO214_7692.FRpdf

defries, M., de Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest. Sci. 128:1-11.

Dijkstra, J., Oenema, O., Bannink, A., 2011. Dietary strategies to reducing N excretion from cattle: implications for methane emissions. Curr. Opin. Environ. Sustain. 3:1-9.

Easterling, W.E., Aggarwal, P.K., Batíma, P., Brander, K.M., Erda, L., Howden, S.M., Kirilenko, A., Morton, J., Soussana, J.F., Schmidhuber, J., Tubiello, F.N., 2007. Food, fibre and forest products. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.) Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Eckard, R.J., Grainger, C., de Klein, C.A.M., 2010. Options for the abatement of methane and nitrous oxide from ruminant production: a review. Livest. Sci. 130:47-56.

European Commission, 2009. Directive of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. In: Official Journal, L 140, 05/06/2009, pp 16-62.

Fantin, V., Buttoli, P., Pergeretti, R., Masoni, P., 2011. Life cycle assessment of Italian high quality milk production. A comparison with an EPD study. J. Clean. Prod. (In press).

Fantin, V., Pergeretti, R., 2010. Studio di life cycle assessment (LCA) del latte alta qualità a marchio COOP. Report tecnico per la distribuzione pubblica. Centro Ricerche ENEA Ed., Bologna, Italy.

FAO, 2010. Greenhouse gas emissions from dairy sector: A life cycle assessment. FAO Publ., Roma, Italy. Available from: http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

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. Agric. 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 constituent and in radiative forcing. In: S. Salomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averitt, 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.

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

Grainer, C., Williams, R., Clarke, T., Wright, A.D.G., Eckard, R.J., 2010. Supplementation with whole cottonseed causes long-term reduction of methane emissions from lactating dairy cows offered a forage and cereal grain diet. J. Dairy Sci. 93:2612-2619.

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. 83:45-53.

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

Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scyoc, G.E., 2009. Greenhouse gas fluxes in an Eastern Corn Belt soil: weather, nitrogen source, and rotation. J. Environ. Qual. 38:841-854.

Hindrichsen, I.K., Wettstein, H.-R., Machmüller, A., Kreuzer, M., 2006. Methane emission, nutrient degradation and nitrogen turnover in dairy cows and their slurry at different milk production scenarios with and without concentrate supplementation. Agr. Ecosyst. Environ. 113:150-161.

Hogaaas 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.

International Dairy Federation, 2010. A carbon footprint approach for dairy. The IDF guide to standard lifecycle assessment methodology for the dairy sector. Bull. Int. Dairy Fed. 445:1-40.

IPCC, 2006. IPCC Guidelines for national greenhouse gas inventories. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

IPCC, 2007. Climate change 2007: synthesis report. Contribution of working groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Available from: http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

ISO, 2006a. Environmental management-life cycle assessment-principle and framework, ISO 14040. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b. Environmental management-life cycle assessment-requirements and guidelines, ISO 14044. International Organization for Standardization, Geneva, Switzerland.

Kristensen, T., Mogensen, L., Trydeman, A., Neftel, A., Krober, T.F., Menzi, H., Külling, D.R., 2007. 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.

Knudsen, M., Hermansen, J.E., 2011. Effects 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., 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.

Kyoto Protocol, 1997. Kyoto Protocol to the United States framework convention on climate change. Available from: http:// unfccc.int/resource/docs/convkp/kpeng.html

Lassay, K.R., Pinares-Patiño, C.S., Martin, R.J., Molano, G., McMillan, A.M.S., 2011. Enteric methane emission rates determined by the SF6 tracer technique: Temporal patterns and averaging periods. Anim. Feed Sci. Tech. 166-167:183-191.

Lesschen, J.P., van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. Anim. Feed Sci. Tech. 166-167:18-28.

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

Mao, H.L., Wang, J.K., Zhou, Y.Y., Liu, J.X., 2010. Effects of addition of tea saponins and soybean oil on methane production, fermentation and microbial population in the rumen of growing lambs. Livest. Sci. 129:56-62.

Martin, C., Morgavi, D.P., Doreau, M., 2010. Methane mitigation in ruminants: from microbe to the farm scale. Animal 4:351-365.

Monteny, G.J., Groenestein, C.M., Hilhorst, M.A., 2001. Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. Nutr. Cycl. Agroecosys. 60:123-132.

Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011. Life cycle assessment of swiss farming systems: I. Integrated and organic farming. Agr. Syst. 104:217-232.

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.

Ongono, N.E., Bagg, R., Vessie, G., Dick, P., Or-Rashid, M.M., Hook, S.E., Gray, J.T., Kebrab, E., France, J., McBride, B.W., 2007a. Long-term effects of feeding monensin on methane production in lactating dairy cows. J. Dairy Sci. 90:1781-1788.

Ongono, N.E., Or-Rashid, M.M., Kebrab, E., France, J., McBride, B.W., 2007b. Effect of supplementing myristic acid in dairy cow rations on ruminal methanogenesis and fatty acid profile in milk. J. Dairy Sci. 90:1851-1858.

Olesen, J.E., Weiske, A., Asman, W.A., Weihsberg M.R., Dijurhuus J., Schelde K., 2004. FarmGHG. A model for estimating greenhouse gas emissions from livestock farms. Documentation. Danish Institute of Agricultural Sciences. Available from: http://agrsci.au.dk/fileadmin/DJF/JPM/Klima/JOE/FarmGHG5Documentation.pdf

Payraudeau, S., van der Werf, H.M.G., 2005. Environmental impact assessment for a farming region: a review of methods. Agr. Ecosyst. Environ. 107:1-19.

Peltomaki, P., Jauhiainen, L., Trnka, M., Olesen, J.E., Calanca, P., Eckersten, H., Eitzinger, J., Golim, A., Kersebaum, K.C., Kozyra, J., Kumar, S., Dalla Marta, A., Micali, F., Schaap, B., Seguin, B., Skjelvag, A.O., Orlandini, S., 2010. Coincidence of variation in yield and climate in Europe. Agr. Ecosyst. Environ. 139:483-489.

Phetthave, 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.

Pinares-Patiño, C.S., Lassay, K.R., Martin, R.J., Molano, G., Fernandez, M., MacLean, S., Sandoval, E., Luo, D., Clark, H., 2011. Assessment of the sulphur hexafluoride (SF6) tracer technique using respiration chambers for estimation of methane emissions from sheep. Anim. Feed Sci. Tech. 166-167:201-209.

Roesh, M., Doerrh, M.G., Blum, J.W., 2005. Performance of dairy cows on Swiss farms with organic and integrated production. J. Dairy Sci. 88:2462-2475.

Rozt, 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/19920000/DairyGHHReferenceManual.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. 93:129-1282.

Schlis, R.L.M., de Haan, M.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C., Zom, R.L.G., 2007. DairyWise, a whole-farm dairy model. J. Dairy Sci. 90:5334-5346.

Schlis, R.L.M., Verhagen, A., Aarts, H.F.M., Kuikman, P.J., Šebek, B.L.J., 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Global Change Biol. 12:382-391.

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

Shalloo, L., Dillon, P., Rath, M., Wallace, M., 2004. Description and validation of the Moorepark Dairy System Model. J. Dairy Sci. 87:1945-1959.

SimaPro, 2008. Simapro 7.0. Life cycle assessment software. Amersfoort, The Netherlands. Available from: www.pre.nl

Sistiani, K.R., Jr-Baptiste, M., Lovan, N., Cook, K.L., 2011. Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. J. Environ. Qual. 40:1797-1805.

Soussana, J.F., Talec, B., Blanot, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal
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

Tekippe, J.A., Hristov, A.N., Heyler, K.S., Cassidy, T.W., Zhelezkov, V.D., Ferreira, J.F.S., Karnati, S.K., Varga, G.A., 2011. Rumen fermentation and production effects of Origanum vulgare L. leaves in lactating dairy cows. J. Dairy Sci. 94:5065-5079.

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

Thomassen, M.A., de Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agr. Ecosyst. Environ. 111:183-199.

Thomassen, M.A., Dolman, M.A., van Calker, K.J., de Boer, I.J.M., 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 68:2278-2284.

Thomassen, M.A., van Calker, K.J., Smits, M.C.J., Iepema, G.L., de Boer, I.J.M., 2008b. Life cycle assessment of conventional and organic milk production in the Netherlands. Agr. Syst. 96:95-107.

Thorman, R.E., Chadwick, D.R., Harrison, R., Boyles, L.O., Matthews, R., 2007. The effect on N2O emissions of storage conditions and rapid incorporation of pig and cattle farmyard manure into tillage land. Biosyst. Eng. 97:501-511.

VandeHaar, M.J., St-Pierre, N., 2006. Major advances in nutrition: Relevance to the sustainability of the dairy industry. J. Dairy Sci. 89:1280-1291.

Van der Werf, H.M.G., Kanyarushoki, C., Corson, M.S., 2009. An operational method for the evaluation of resource use and environmental impacts of dairy farms by life cycle assessment. J. Environ. Manage. 90:3643-3652.

Van Zijderveld, S.M., Gerrits, W.J.J., Apajalahti, J.A., Newbold, J.R., Dijkstra, J., Leng, R.A., Perdok, H.B., 2010. Nitrate and sulphate: effective alternative hydrogen sinks for mitigation of ruminal methane production in sheep. J. Dairy Sci. 93:5856-5866.

Velthof, G.L., Mosquera, J., 2011. The impact of slurry application technique on nitrous oxide emission from agricultural soils. Agric. Ecosyst. Environ. 140:298-308.

Wood, R., Lenzen, M., Dey, C., Lundie, S., 2006. A comparative study of some environmental impacts of conventional and organic farming in Australia. Agr. Syst. 89:324-348.

Wood, T.A., Wallace, R.J., Rowe, A., Price, J., Yáñez-Ruiz, D.R., Murray, P., Newbold, C.J., 2009. Encapsulated fumaric acid as a feed ingredient to decrease ruminal methane emissions. Anim. Feed Sci. Tech. 152:62-71.

Yamulki, S., 2006. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agr. Ecosyst. Environ. 112:140-145.

Zaman, M., Saggar, S., Blennerhassett, J.D., Singh, J., 2009. Effect of urease and nitrification inhibitors on N transformation, gaseous emissions of ammonia and nitrous oxide, pasture yield and N uptake in grazed pasture system. Soil Biol. Biochem. 41:1270-1280.

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.