UNIVERSITÀ DEGLI STUDI DI SASSARI

A.D. MDLXII

SCUOLA DI DOTTORATO DI RICERCA
Scienze e Biotecnologie
dei Sistemi Agrari e Forestali
e delle Produzioni Alimentari

Indirizzo di Scienze e Tecnologie Zootecniche

Ciclo XXVI

Estimation of carbon footprint in dairy cattle farms of Southern Italy

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Anno accademico 2012- 2013

A mia Madre, a mie Sorelle, e ad Alessandro,

con tanto affetto e gratitudine

"S'eliche non bocata castanza"

Acknowledgments

During my PhD I worked with a great number of people. Each one of them participated in a different way in my work, and it is a pleasure for me to express all my gratitude to them in my acknowledgments.

In the first place, I would like to express my deep and sincere gratitude to my supervisor Dr. Alberto S. Atzori. His wide knowledge, great patience, constant help, and friendship were fundamental for the realization of this thesis.

I am grateful to Professor Antonello Cannas for his personal guidance, detailed and constructive comments, and trust in me during these three years. I gratefully thank Professor Giuseppe Pulina for his precious advices and support. I express my gratitude to Prof. Nicolò P.P. Macciotta, Prof. Lelia Murgia, Prof. Francesco Giunta, Dr. Giovanni Pruneddu, Dr. Gianni Battaccone, Dr. Anna Nudda, and to Dr. Antonio Pais for their support and scientific help.

I would reserve a special thanks to Prof. Salvatore P.G. Rassu for his advices and friendship, and for everything he taught me during my bachelor; his teachings proved to be very useful during my PhD. I am also grateful to Prof. Laura Marongiu for her friendly help and complicity.

I gratefully thank Dr. Corrado Dimauro and Dr. Massimo Cellesi for their invaluable help in statistical analysis, and for making me love this so much feared topic.

My sincere thanks goes also to my friends Gavino Biddau and Emilio Usai for their constant presence, friendship, and indispensable help in bureaucratic matters. I am also grateful to Dr. Rita Marras and to Ms. Marina Pischedda for their constant help and support.

A special and big acknowledgment to Dr. Ana H.D. Francesconi for her friendship, infinite patience and understanding, and indispensable help for the editing of my thesis.

Antonio Mazza, Antonio Fenu, and Gesumino Spanu for their collaboration and friendship.

Roberto Rubattu, Dr. Roberta Boe and Dr. Maria Grazia Manca who taught me the basic techniques for chemical analyses.

I also thank my colleagues of the Section of Animal Science: Dr. Oscar Boaventura Neto, Dr. Gabriele Marras, Dr. Giuseppe Todde, Dr. Elisa Ortu, Dr. Osman Karimi, Dr. Rossella Manca, Dr. Maura Lovicu, Dr. Claudio Carzedda, Dr. Gianfranco Gaias, Dr. Maria Annunziata Pintus, Dr. Elia Pintus, Dr. Matteo Sini, Dr. Sara Saba, Dr. Fabio Correddu, Dr. Antonio Puledda, Dr. Caterina Canalis, Dr. Giustino Gaspa, Dr. Marco Giuseppe Pinna and Dr. Alessandra Marzano for their collaboration and friendship.

I convey a special acknowledgement to Professor Luis Orlindo Tedeschi for his hospitality and for the precious advices and teachings that he gave me during my period abroad in the Texas A&M University. A special thanks to Luigi, Mozart, Michele, Uyara, Marcia and Ana Virginia who made my American experience unforgettable.

I would like to reserve a special thank to the group that collaborated in the project "Indagine sulle emissioni di gas serra in aziende bovine da latte" for their professional and constant support: the director of the Filiera A.Q. s.r.l. Dr. Gianpiero Calzolari, and the responsibles Dr. Giampaolo Zanirato and Dr. Andrea Serraino; the director Dr. Francesco Casula and the technicians of the Cooperative 3A, Dr. Mauro Panetto, Dr. Antonio Schintu, Dr. Roberto Cocco, Dr. Agata Marongiu and Dr. Silvia Fiori; the director Dr. Andrea Breveglieri, and the technicians of the Cooperative Granlatte, Dr. Filippo Nettis and Dr. Marcello Pinto; the director Dr. Angela Zarro, and the technician of the Cooperative Asso.Lac., Dr. Arnaldo Perfetti; the director Dr. Salvatore Cascone, and the technician of the Cooperative Progetto Natura, Dr. Giovanni Capuzzello, and all the farmers of the 4 Cooperatives for the precious time that they have reserved to us and to our project.

My loving thanks to my mother and my sisters for their loving support, and to all my friends for their indirect contribution to my PhD.

Last, but certainly far from least, I would like to acknowledge my wonderful boyfriend Alessandro for his constant help, understanding, and accurate and interesting discussions about the work of my thesis. Without his encouragement it would have been impossible for me to finish this work.

ABSTRACT

This thesis focused on the global warming potential of dairy farms, using a sample of 285 farms which are members of 4 milk cooperatives operating in Southern Italy (3A - Sardinia, Granarolo - Puglia and Basilicata, Asso.La.C. - Calabria, Progetto Natura - Sicilia). The first study estimated the carbon footprint (CF) of milk collected from the member farms of the cooperatives and defined the incidence of the main emission sources in respect to total emissions. A weighted mean of 1.35 kg of CO_2eq per average kg of fat-and-protein corrected milk (FPCM) collected by the cooperative was obtained (1.66 kg as farm mean). Farms with the highest milk production level per cow (MYL) and high feed efficiency use had the lowest values of CF. The second study compared 8 approaches (different in number and type of predictors) to estimate enteric emissions for the same farms. All approaches were accurate for methane quantification, although more detailed approaches could be more informative for high-MYL farms. The third study analyzed the developed database with a multivariate approach (discriminant analysis). The most limiting factors for good environmental performance were herd profile, nutritional efficiency and diet digestibility, especially in farms with low MYL, and agronomic efficiency and herd management parameters in farms with high MYL. Further investigations on the same data is needed to identify the best strategies for mitigating GHG emissions in the studied cooperatives.

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INTRODUCTION

1.1. The Ecological footprint: a new method to estimate the environmental impact of human activities

The ecological footprint (EF), as firstly defined by Rees and Wackernagel, is "*a measure of the 'load' imposed by a given population on nature"* (Rees and Wackernagel, 1996a) expressed in terms of the area of productive land and water that is needed to sustain the rate of resources consumption and waste discharge of that population (Kitzes et al., 2008a).

Ecological footprint estimation is calculated to have an overview of global resources exploitation, to find critical points inside ecosystem balance and to find the sustainability level of Earth's population within the biosphere's regenerative capacity. Calculations used to estimate the EF are divided into two steps: the first step consists of the evaluation of the total amount of products consumed in a well-defined area divided by the population that lives there; the second step calculates the amount of land and water required to yield the products used and to assimilate the wastes that will derive from production processes and consumption. The assimilation of wastes is referred to the space needed for the disposal of every kind of waste that can derive from a production process; wastes can be represented by pollutant wastewaters, chemical substances, exhaust oils and lubricants, or garbage in general. Each one will require a special disposal system, and a specific surface area to realize the disposal (Rees and Wackernagel, 1996b).

Two concepts related to the EF are very important in ecosystems balance analysis: sustainability and carrying capacity. To ensure the sustainability of an ecosystem means that a defined population is able to live harmoniously with natural ecosystems, drawing food and all products needed without damaging the natural balance (Kitzes et al., 2008a).

Carrying capacity is closely related to sustainability, because this concept indicates the dimension of definite specific species population that can be supported for an undefined period of time in a limited space (Rees and Wackernagel, 1996b).

Ecosystem balance can be also supervised by analyzing its biocapacity. Materials, products and wastes produced in a defined place (city, district, region, nation, etc.) are compared with the dimension of that place in order to assess the biological productive capability of a certain land or water area. Biocapacity is divided into six categories, namely cropland, grazing land, fishing grounds, forest land, built-up area and fossil fuel area. Each one of these categories is able to produce services or products for human population; for this reason, all arid zones, open ocean areas and areas with very low productive potentiality are not considered in the total global biocapacity (Wackernagel et al., 2002).

The ecological footprint and the biocapacity are both measured in terms of global hectares (gha); one global hectare expresses the biologically productive capability of one hectare with a world average productivity (WWF, 2012). Total world biocapacity has been estimated at around 11 billion hectares of land and water areas, which represent ¼ of the total World surface (Kitzes et al., 2008a). During 1961, 70% of the total global biocapacity related to that specific year was consumed. In 2008, the world biocapacity was equal to 12.0 billion gha and the EF was equal to 18.2 gha; this fact means that during that year every person in the world had 1.8 gha available but, on the other hand, the same person was responsible for 2.7 gha of EF. Overexploitation of 0.9 gha per capita suggests that humans overtook annual biocapacity by 33% and Earth would need 1.5 years to regenerate the resources consumed in 2008 (WWF, 2012). In 1999, overexploitation was equal to 20% and this fact confirms the increasing trend of resources utilization that has been occurring in the world (Wackernagel et al., 2002). Reduced amount of fish ground in the oceans, climate changes, deforestation, reduction of arable lands because of erosion and salinity are all warnings which demonstrate that ecosystems are not able anymore to supply the amount of resources that humans have been trying to obtain during the last years.

Human requests are going beyond the regenerative potentiality of Earth’s ecosystems (Kitzes et al., 2008a). Considering that natural resources are essential and irreplaceable, overexploitation has to be solved because natural ecosystems output cannot be replaced by humans through artificial or synthetic products (Naeeda, 2007).

The excess in resources request, also called global overshoot, started in 1980, when Earth’s biocapacity was not able to sustain the increasing demand for resources by human beings. Overshoot cannot go ahead for ever because natural environment could reach a level of overexploitation that could lead to ecologic collapse.

Obviously, not every country is living in overshoot. East Europe respects the biocapacity of its area; however, its population is living using a level of exploitation that is not applicable at average global level. In the Asian continent, there is the opposite situation; this population is living in overshoot, considering the resources that are available in this area, but their consumption level is globally applicable. North America and west Europe show the worst situation; they are in overshoot conditions, and the application of their level of utilization of natural resources at global level would exploit 3-5 times the global biocapacity (Kitzes et al., 2008a). Even if some nations are respecting their biocapacity, it is impossible to consider them individually, because globalization unified all national productions and consumptions in such a way that actions of one nation affect in some manner all the others (Lustigová and Kušková, 2006).

Human population can expand the carrying capacity by removing species that hamper its survival and increasing the use of natural resources and technologies; considering this potentiality, it is possible to suppose that the concept of carrying capacity is a variable and infinitely expandable concept (Daly, 1986). For this reason, human population could think that its sustainability is not tied to the environment and natural resources. However, this is a distort vision because despite progress and big discoveries, humans are necessarily subjected to what the ecosphere produces and offers them (Rees, 1990).

Human population broke the balance of natural ecosystems by introducing industrial metabolism inside natural environment. Natural metabolism is composed of several flows of energy that come from nature and go into organisms (humans, animals, plants), and then come back to nature in other forms. Industrial metabolism presents a different flow of energy that humans created to satisfy the big request for resources caused by modern lifestyle. Industrial metabolism has only the requirement flow and consumes a big amount of natural resources, releasing as outflow tons of different kind of wastes that are not recyclable elements for ecosystems (Sterrer, 1993). Industrial metabolism, with its big request for energy, transformed natural resources into a "natural capital". This change inside the natural balance created the problem of system sustainability, which has to be solved by considering the carrying capacity in relation to not only the number of people that can survive in a specific place, but also the availability of resources. The forecast about the total depletion of natural resources is encouraging the world population to make a serious reflection on the overshoot problem in order to find a solution that ensures the survival of human population in harmony with biosphere resources (Kitzes et al., 2008a).

The first idea for overshoot solution regarded the reduction of greenhouse gases emissions; one approach to deal with this important environmental issue has been the application of the concept of "contraction and convergence". Contraction means to reduce emissions and convergence means to split the emission allocation between all world nations, in order to find responsibilities and to assign to every country which reduction level should be achieved (Global Commons Institute, 2000). The "contraction and convergence" solution has been widely accepted and the European Parliament in 1998 officially recognized this theory, inserting it inside the Parliament Basic Principles (European Parliament, 1998).

This theory was reconsidered by implementing its basic principles in the EF topic, resulting in the "Shrink and Share" concept; "shrink" refers to the reduction of the EF that is needed to not exceed the regenerative power of ecosystems; "share" is related to the system used to divide EF between people, regions, nations or continents (Kitzes et al., 2008a). Application of the "shrink" concept is easier than that of the "share" concept. In fact, it is more feasible to try to explain how to reduce the ecosystem exploitation than to decide how to share the responsibility of worldwide resources use. There are many theories about this issue. One solution could be to share the resources exploitation proportionally with national biocapacity; this system could have good implications on economy because trade between nations with a low biocapacity and nations with high biocapacity could be increased. Another solution is to forecast an equal share between people; this solution might appear politically correct because every person in the world will have the same responsibility, but using this method all differences related to regions, nations, continents, cultures and religions are standardized and there is not a "share" action associated with the actual sustenance capacity of nations (Kitzes et al., 2008a).

The adoption of the "shrink and share" theory by the agricultural sector will pose important problems: a constantly growing world population who asks for food and different kinds of land resources but also has to deal with the necessity of a reduction in biocapacity exploitation. If the agricultural sector increased its productivity, maximized water and fertilizers efficiency, and improved livestock management, it would be possible to satisfy population's requests, but it could also happen that the biocapacity limit would not be respected (Tilman et al., 2002). This could happen because, as explained before, not every region of the world is respecting its biocapacity; the attempt to obtain more and more resources from the same land could lead to overexploitation

(Kitzes et al., 2008a). Agricultural products request is not subjected to biocapacity, but it is subjected to population needs. The choice of intensive agricultural systems, implemented to produce the same amount of products, using fewer natural resources, may result in an increase of polluting emissions. Ethanol fuel produced from biomasses initially appeared as a good way of reducing GHG emissions from fossil fuel use and reducing fossil fuel exploitation (De Oliveira et al., 2005). However, several studies demonstrated that ethanol is not economically suitable because corn and sugar cane production systems are onerous and, even if the use of ethanol fuel can reduce GHG emissions from the transportation sector, resources used to cultivate biomasses for ethanol production originate new GHG emissions and, therefore, the problem of ecosystems exploitation still remains (Pimentel, 2003; De Oliveira et al., 2005). Furthermore, the use of arable land to produce biofuel causes reduction of forest areas and/or competition with natural resources used for human nutrition.

During the two-year period of 2010-2012, 870 million people in the World suffered from undernourishment (FAO, 2012a); introducing biomasses exploitation for fuel production is not only an economic and environmental issue but is also related to moral and ethical questions (Pimentel, 2003).

Reduction in forest areas is one of the consequences that arise from the increase in arable lands; arable lands are necessary to increase agricultural productivity but reduction in forest areas provokes a reduction in forest biocapacity (Houghton, 1994; De Oliveira, 2008).

Agriculture and forestry are only two of the different sectors that are involved in biocapacity and EF troubles; it is almost impossible to try to reduce EF and preserve ecosystems' biocapacity without analyzing all sectors at the same time and considering also the connections between them (Kitzes et al., 2008b).

1.1.1. Estimation of Ecological footprint

Ecological footprint is divided in seven footprints: Cropland footprint, Grazing footprint, Forest footprint, Fishing grounds footprint, Carbon footprint, Built-up land footprint, and Biocapacity footprint. This is described in detail in the NFA 2008 workbook published by Kitzes et al. (2008b), and summarized here.

Cropland footprint estimates the amount of land required to produce all agricultural products consumed by animals and humans; this estimation considers as products all crops cultivated for human or animal nutrition, like fruits, vegetables, cereals and grasses. Calculation of the Cropland footprint is done by dividing the amount of each product produced by the amount of land cultivated to produce it. In 2008, the National Footprint Accounts (NFA) made an inventory of products that come from the agricultural sector and that have to be considered in the Cropland footprint estimation: 149 categories of main products and 29 categories of secondary products were listed (Kitzes et al., 2008b).

Grazing land footprint estimates the amount of land needed to feed grazing animals. Calculation is complex because it is made by subtracting from the animal energy requirements the amount of energy provided by concentrates, hay and grasses. The result of this subtraction represents the energy supplied by grazing and is converted into the equivalent amount of grass. Grazing footprint will be equal to the amount of grass needed by animals divided by the average grass production of a grazing land (Kitzes et al., 2008b).

Forest footprint expresses the human population demand for regenerative capacity of forests; the forest sector demand is represented by wood used as fuel or as raw material for timber products or built materials. Calculation is performed by comparing the annual amount of wood products consumed with the net annual growth rates of world forests; there are 16 categories of main products derived from wood and 17 categories of secondary products derived from wood main products.

Fishing grounds footprint estimates the required surface area that supports human fishery demands in aquatic ecosystems. It includes all wild fish but it does not consider aquaculture production. Estimation is made for each fish species, by dividing the amount of primary production that it consumes during its lifetime by the average available primary production per hectare of marine or inland water area (Kitzes et al., 2008b). Average available production comes from a global estimation that calculated the consumable amount of several aquatic species (FAO, 2008). The NFA workbook reported the production of 1,538 marine and freshwater species (Kitzes et al., 2008b).

Carbon footprint represents the amount of forest area needed to absorb anthropogenic emissions of CO_2; even if emissions come from several sectors at different amounts, they are all summed up and converted into global hectares by applying the net annual rate of forest growth to find the level of carbon uptake. Carbon uptake rate is taken from the Intergovernmental Panel on Climate Change (IPCC, 2006b) data on the net annual growth of forests, and it is obtained considering that carbon makes half of the net increase in biomass. The amount of carbon uptake, adjusted by a forest equivalence factor, transforms tons of carbon dioxide into global hectares (Kitzes et al., 2008b). The NFA 2008 workbook adopted this Carbon footprint definition, expressing this footprint in global hectares. Carbon footprint is an important theme that has several implications; many solutions have been proposed during the last years for its estimation, using several units of measurement and several definitions. Currently, Carbon footprint is defined as "the net greenhouse gases (GHGs) exchange per unit of product or service" (Rotz et al., 2010) and it is measured in terms of kg of CO_2-equivalent per unit of product. This new approach considers emissions of all GHGs, including methane (CH_4) and nitrous oxide (N_2O), and not only CO_2. The carbon footprint is still an evolving topic and the solutions that can be used for its estimation continue to be discussed and modified (Kitzes et al., 2008b).

Built-up land footprint includes all lands that are occupied by human activities. There are two kinds of built-up land areas: i) infrastructure areas used to assemble buildings, streets, factories, farms and every kind of structures needed by humans; and ii) hydroelectric areas used to flood lands and make dams (Kitzes et al., 2008b).

Biocapacity footprint estimation expresses the total amount of available biological productive land and water; it is calculated for five different sectors: cropland, grazing land, fishing grounds, forest and built-up area (Kitzes et al., 2008b).

The EF does not include the *Water footprint* (WF), which is defined as the total amount of freshwater used to produce an asset or a service. WF can be measured in terms of volume of consumed water (liters or kilograms), that are consumed during the production process, or that are incorporated within the final product. WF is considered separately from EF because it is used mainly as a geographical indicator to quantify local water consumption, in order to control the available reserves. Nevertheless, WF can also be used as an environmental indicator to express the amount of freshwater used by a consumer, such as a city, a nation or a continent, or by a producer, such as a public institution or a private industry (Hoekstra et al., 2011).

1.1.2. Estimation of the environmental impact of a product by Life Cycle Assessment

The preservation of natural environment is possible only with an accurate knowledge of the amount of available resources, and an overview of human and animal requirements (Wackernagel et al., 2006). Environmental impact is a topical issue that involves many people; everyone knows that foods, products and services used daily are responsible for environmental impact, and consumers are more and more wishful to know how products are made and what is their environmental impact, following the "life cycle thinking" reasoning (De Leeuw, 2005; Thoma et al., 2013a). Recently, the concept of environmental sustainability was included in industrial management, considering low environmental impact as an added value for products (SETAC, 2011). Governments of several nations have already allocated public funds for sustainable industries that produce respecting environmental limits (Lubin and Esty, 2010), and some nations have also supplied consumers with handbooks that introduce guidelines on how to choose products with low impact (OECD, 2001). On the other hand, several industries have included environmental sustainability in their plans to improve company's competitiveness (Lubin and Esty, 2010). Some products are not directly involved in environmental impact, but their production process can have several phases that generate pollution; therefore, connecting pollutant emissions to the product that originates them, allows to estimate its environmental impact (PAS, 2011). Products also differ between regions and nations and the knowledge of their production processes can be used to determine the impact of every region or nation (SETAC, 2011).

The necessity to find critical points inside a product or service life, in order to improve its quality and reduce its environmental impact, inspired the idea of the Life Cycle Assessment method. The Life Cycle Assessment (LCA) is used to estimate the total environmental impact of products or processes, and it is based on a concept that considers different stages within a product or service life, following the basic theory of "from cradle to grave", e.g. the products followed from its production to its consumption or disposal. The first definition of LCA was created during the Society of Environmental Toxicology and Chemistry (SETAC) Congress in 1990. The SETAC is a no-profit organization interested in environmental problems. It describes LCA as a method that permits the estimation of environmental impacts correlated with processes or activities. Estimation occurs by identification and quantification of energy and raw materials consumption, by estimation of GHG emissions, and by evaluation of mitigation opportunities. LCA considers the life of a product or process starting from the raw materials used, continuing with the production system, transport, distribution, use or consumption, eventual reuse and its final disposal. LCA was standardized in 1998 by the ISO (International Organization for Standardization) with the redaction of the first regulation (UNI EN ISO 14040:1998, Evaluation of Life Cycle Assessment –

Principle and Framework). The regulation was revised in 2006 with the publication of the second edition (ISO 14040:2006 Environmental management – Life Cycle Assessment – Principle and Framework). The “cradle to grave” theory, which is the basis of LCA, has an important strong point: the analysis of the whole product or process life allows discover system’s performance (economic performance, energetic performance, environmental performance), in order to find the steps where the life cycle of the product or service can be improved (ISO, 2006a).

LCA estimation identifies:

- impact of product or process on environment and humans;
- environmental areas that are affected the most by production systems;
- impact variations during product life;
- technologies that can be used to reduce environmental impact;
- critical points for environmental impact in the production processes.

LCA estimation is associated with the collection of a large amount of data related to the considered system; the requested amount of data is obviously related to the level of accuracy that the LCA has to achieve (ISO, 2006a). Data collection needs a detailed knowledge of the considered system and a precise description of the analysis aims (SETAC, 2011). ISO 14040 regulates LCA estimation by dividing the analysis into 4 steps:

1. identification of the product, system or process that must be analyzed, definition of analysis aims and definition of the functional unit that will be used for the estimation of the environmental impact, considering that a comparison between different systems is possible only if the same functional unit is used (Ming-Jia et al., 2011);
2. inventory analysis with data collection taking into consideration geographical and temporal factors;
3. impact allocation by analyzing the results;
4. interpretation of the results.

During the 1st step, system boundaries are defined, to know which elements have to be analyzed and which elements should not be considered, and the detail level is also defined.

During the 2nd step, the life cycle inventory analysis (LCI) is carried out; input and output data are collected and classified. During this phase it is advisable to use a flexible approach, considering a future different use for the dataset, taking advantage of the possibility of analyzing an entire production process where a large amount of information can be collected and used later for a different type of analysis (SETAC, 2011). Information about system inputs is used to evaluate the impact of the product; however, when LCA is made on a multifunctional system, input can be also considered as a product that comes from a previous production system (Miettinem and Hämäläinen, 1997). The dairy sector is a typical multifunctional system where inputs (fertilizers, pesticides, fuel, animal feed, etc.) come from several production systems; for this reason LCA can be very complex sometimes and in these cases allocation is the most important step (Thomassen et al., 2008a; Flysjö et al., 2011; Thoma et al., 2013a; Thoma et al., 2013b). During this step, the life cycle impact assessment phase (LCIA) can also be performed to give additional information used to understand the LCI results and to estimate the environmental impact. In some cases, a simple data inventory is required and the LCA finishes in 2 steps; in other cases, the final purpose is the assignment of environmental impact between different products derived from the same process, and then the LCA finishes with the impact allocation step of the LCIA.

The impact allocation, that is the 3rd step, represents the most important phase and it shares input or output flows of a production system between the considered product or process and other products or processes (Thomassen et al., 2008a). Allocation can be performed in different ways. The attributional allocation allocates the impact within system boundaries, and it can be referred in terms of economic allocation or quantity of produced products. The consequential allocation performs the impact allocation without system boundaries, considering elements that can influence the production system, such as market perspectives or changes in consumer choices (Thomassen et al., 2008b). Consequential allocation can be very useful because it also considers what happens outside of the system and the results are more related to reality. However, sometimes the consequential allocation is not suitable, because market variations or changes in consumer choices do not have an immediate effect inside the considered life cycle, or they can influence just some steps of life cycle even without affecting allocation (Ekvall and Weidema, 2004).

The 4th and last step is represented by the interpretation of the results, which allows the individuation of the main factors influencing the environmental impact; the results can be then transformed into a report that can include advices for the reduction of environmental impact and for the general improvement of the system evaluated (ISO, 2006a).The interpretation of the results is usually related to an LCA that produces results used to inform consumers or to ameliorate a production process inside industrial improvement plans.

In conclusion, LCA can end with the LCI or the LCIA, without completing the subsequent phases; every LCA is different and the use of all or part of the 4 steps depends on the aim of the analysis.

1.2. Climate Change and Global Warming: the responsibility of human activities

Up to 250,000 years ago, before the existence of humans, all climate changes were provoked by natural events, such as modifications of solar activity, changes of Earth's orbit and volcanic eruptions. Afterwards, from the Industrial Era on, human activities have raised the amount of greenhouse gases (GHGs) in the atmosphere, thus activating the process of global warming. Rise in atmospheric temperatures recorded since the second part of the 20th century is correlated with human activities (EPA, 2013a); the gain of global temperature reflects the increasing concentration of GHGs in the atmosphere, especially in the northern hemisphere, where most dry lands and human settlements are located (FAO, 2013).

The climate change that happened during the last century is without precedent; the average global temperature increased by 0.6°C between the 20th and 21st centuries (FAO, 2013). The 12 years between 1995 and 2006 were the hottest ever recorded since 1850 and the International Panel of Climate Change (IPCC) forecasts an increase of 0.2°C per decade until 2030 (IPCC, 2007a). The variation of Earth's temperature can be considered as a consequence of climate change by itself, but at the same time it is also the cause of many other climate changes (EPA, 2013a). Episodes of high temperatures that exceed seasonal average have been occurring more and more often, causing serious losses in ecosystems and in the agricultural sector; in addition, these extraordinary events represent also a danger for human health (FAO, 2013). Climate changes include all variations in climatic parameters, such as atmospheric temperature, precipitations, wind. These changes have caused many extraordinary weather events, such as hurricanes, extended droughts, and rise in the oceans temperature, with the consequent rise in water acidity. They can condition human life in many ways: direct effects of climate changes are floods, droughts, tornados, and hurricanes that are dangerous for animals and humans; indirect effects could be correlated with the lack of food and water that may occur after those adverse climatic events.

Global warming is a sophisticated and complex terrestrial event that is associated with the rise in the average temperature on the Earth's surface (EPA, 2013a). Some evidences of global warming are the decrease of snow cover in the northern hemisphere mountains, melting of glaciers, reduction in the number of freezing days in mountain rivers and lakes, and decrease in permafrost extent. Rise in ocean water level is certainly one of the most alarming effects of global warming; it showed an average increase of 1.8 mm per year between 1961 and 2003, with an average of 3.1 mm per year during the last ten years of that period (i.e. from 1993 to 2003).

There are several problems correlated with the rise in ocean water level, such as risk of erosion in the coasts and flooding of little islands like those in the Caribbean, which have an average altitude close to sea level. Some ecosystems are going to risk their survival because of climate changes, floods, droughts, acidification of the oceans, land use change, fires, pollution and overexploitation of resources. If forecast about the rise in Earth's temperature will come true, we could have from 20 to 30% of animal and plant species at risk of extinction. Water scarcity could be another effect of global warming, resulting in the extension of drought periods; water scarcity is not a single problem but it is closely related to agriculture production, and affected countries could have troubles with crop production and food availability (IPCC, 2007a).

The effects of global warming will involve all continents but in different ways, as described in detail by IPCC (2007a). In brief, the African continent could experience an increase of drought periods, with the consequent reduction in water availability and agricultural production, which could worsen malnutrition problems already affecting this continent. The Asian continent could incur two opposite conditions. The center of the continent could have a rise in drought periods with consequences similar to those already described for the African continent, but with even worse implications because of the high rate of population growth of this continent and its huge food needs. Differently, the southern part of Asia could have a high risk of floods, and cities located near the delta of large rivers could be subjected to overflows (IPCC, 2007a). The Australian continent could have an increase in drought periods, with consequent reduction in water availability and decrease in agricultural productivity; Great Barrier Reef and Queensland Wet Tropics could be exposed to a high risk of biodiversity reduction, because of the rise in Earth's temperature and the increase of ocean acidity (IPCC, 2007a). In Northern Europe the risk of extinction of many species that live in mountain areas could increase because of changes in their ecosystems correlated with the melting of glaciers and perennial snow; in Southern Europe drought periods could be longer and more frequent with the consequences described above. Europe could be seriously affected by coastal erosion, with dangerous consequences because of the high level of urban settlements present in the coasts. In South America the rise in Earth's temperature could reduce the rain periods, with the resulting withdrawal of pluvial forest and enlargement of the savannah; this ecosystem change could increase the risk of extinction of many animal species that live in the pluvial forest. Reduction of rain could also provoke a decrease in the productivity of some crops and a reduction of livestock productivity. Global warming could affect glaciers and perennial snows of North America mountains, with an increase in their melting rate and in the risk of floods; in the south of North America drought periods could increase. Polar zones could be affected by the high risk of biodiversity reduction because of melting of glaciers and changes in the habitat of these regions (IPCC, 2007a).

Global warming does not generate only negative events (Glantz, 1995). Rise in Earth's temperature could ensure a warmer climate for those countries located in the Arctic, Antarctic and Siberian regions, such as Scandinavian countries and Russia; warmer temperatures favour the cultivation of a bigger variety of crops ensuring greater food self-sufficiency (Confalonieri et al., 2007). The melting of glaciers in the North Pole is going to create a new sea trade lane which could be used to rapidly connect Asia and Europe (Rosenberg, 2010). Warmer winters could lead to a reduction in the use of domestic heating systems, which in turn could reduce the use of fossil fuels and the emission of pollutants. The rise in fall and winter temperatures could cause a reduction in deaths and diseases related to cold weather (Christidis et al., 2010).

Among the several causes involved in all these events, the increase in the concentrations of GHGs in atmosphere is certainly one of the most influential (EPA, 2013a).

1.2.1. Origin and amount of greenhouse gas emissions

Earth's temperature is influenced by the balance between the energy that arrives from the sun, and the energy that is reflected from the Earth's surface and leaves the atmosphere. Solar energy that is absorbed by the Earth's surface increases Earth's temperature, thus causing global warming; solar energy that is reflected by the Earth's surface and leaves the atmosphere reduces Earth's temperature. Global warming is basically influenced by three actions: the solar activity, the variations of Earth's surface reflectivity and the greenhouse effect (EPA, 2013b).

The solar activity influences the amount of energy that reaches the Earth's surface and varies with the solar cycles. Each solar cycle has a duration of 11 years, during which the sun can show high or low activity associated with high or low energy production, respectively. Each solar cycle has a different level of activity and during the last 50 years there were not extraordinary activities that changed the amount of solar energy that reached the Earth's surface. In the past, solar activity was still unstable and, therefore, strongly influenced global temperature. Currently, solar activity is stable, being considered only a potential factor of global warming. The reflectivity of the Earth's surface is related mainly to the color of the surface reached by solar radiation; white and light surfaces, such as mountains covered by snow and glaciers, reflect more solar radiation than black or dark surfaces, such as forests, oceans and agricultural lands. The melting of glaciers and the expansion of agricultural lands that have been occurring during the last years has affected the reflectivity of Earth's surface, increasing the extension of the surfaces that are able to absorbing heat and reducing those that can reflect it (EPA, 2013b).

The greenhouse effect is the main factor responsible for global warming, considering that, first of all, it is an atmospheric and climatic phenomenon that allows to hold solar energy inside the atmosphere, regulating Earth's temperature and preventing thermal excursions. This natural phenomenon is guaranteed by the GHGs present within the Earth's atmosphere. The predominant gases within the Earth's atmosphere are nitrogen (N_2), which represents 78.08% of all gases, and oxygen (O_2), which represents 20.95% of them; the remaining percentage is represented by several gases, such as argon, water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2), ozone (O_3), and nitrous oxide (N_2O), which are present at different quantities. The main GHGs inside the atmosphere are H_2O, CO_2, CH_4, N_2O, O_3 and Fluorinated gases (EPA, 2013b). The solar energy reaches the Earth's surface especially in the form of ultraviolet (UV) and visible radiation and leaves the Earth's surface in the form of infrared (IR) radiation. The most part of these solar radiations cross the atmosphere without being absorbed and reach the Earth's surface, because GHGs are transparent to UV and visible radiations but can absorb IR radiations. Of all the energy emitted by the sun and that reaches the Earth's atmosphere, only 50% is absorbed by the Earth's surface. Considering that the Earth's surface is warm, it reflects solar energy by IR thermal radiations. Then, these IR radiations are absorbed by the GHGs, which slowly emit this energy, releasing heat in the atmosphere; solar energy absorption and heat releasing are not equal for each GHG, because they depend on the amount and chemical properties of each GHG present in the atmosphere (EPA, 2013b).

GHGs are characterized by molecular-spectroscopic properties that allow them to absorb and emit radiations within the thermal IR range. Molecular-spectroscopic properties are related to the distribution of positive and negative charges inside molecules chemical bonds, also called dipole moment. The molecules composed of two atoms of the same element, such as nitrogen (N_2) or oxygen (O_2), are more stable than those composed of different elements, such as methane (CH_4), nitrous oxide (N_2O) or carbon dioxide (CO_2); variations of dipole moment that happen inside these last three molecules make chemical bonds more unstable, and therefore more receptive to the infrared energy reflected by the Earth's surface. GHGs differ in chemical bonds, being characterized by different levels of energy. For this reason, each GHG has a different greenhouse effect, and some gases, such as N_2 and O_2, are not considered within the GHGs group, because of their almost fixed dipole moment, which does not allow them to interact with infrared radiations (Brau, 2004). The GHGs found within the atmosphere are present at a different concentration and differ in environmental impact. Indeed, the effect of GHGs on climate change derives from three main factors:

- the amount of GHGs in the atmosphere;
- the lifetime of GHGs in the atmosphere;
- the level of absorption and emission of IR radiation of each GHG.

Considering the different impact of each GHG on the atmosphere, a new measurement system, called Global Warming Potentials (GWPs), was introduced by the United Nation Framework Convention on Climate Change (UNFCCC) in 1995. This system expresses the GWP of each GHG using a new unit of measure, the CO_2-equivalent (CO_2-eq); the CO_2-eq is used to compare different GHGs based on their contribution to radiant forcing (UNFCCC, 2013). The CO_2 was chosen because of its stable presence within the atmosphere, compared to the large fluctuations of CH_4 and N_2O concentration over time and because of its long lifetime within the atmosphere, i.e. CO_2 concentration remains constant for thousands of years.

The GWP measures the total amount of energy that 1 kg of each GHG absorbs over a particular time interval in comparison to 1 kg of CO_2. The UNFCCC chose three different time intervals to analyze how the absorption activity of each GHG varies over

time; the selected time intervals where 20, 100 and 500 years because each of these intervals represents, on average, the lifetime of one of the considered GHG. Nevertheless, GWP are calculated referring to the average time interval of 100 years. *Carbon dioxide* (CO_2) enters the atmosphere by respiration of humans, animals and plants, by combustion of fossil fuels, trees or wood products, and as a result of some chemical reactions. The GWP value describes the impact of each gas: the CO_2 shows a GWP value of 1 and it is used as a baseline for all other GWP values (EPA, 2013b).
Methane (CH_4) present in the atmosphere comes from losses in the production system of natural oil and gas, from agricultural and livestock emissions (EPA, 2013b), from fugitive emissions in energy use and coal mining, from the decomposition of organic materials in rice fields, from anaerobic digestion of municipal and industrial solid waste in landfills and from wastewater treatment plants (Höglung-Isaksson et al., 2009). CH_4 absorbs more energy and has a 25-fold higher GWP than CO_2 and has an average permanence in the atmosphere of approximately 15 years (EPA, 2013b).
Nitrous oxide (N_2O) enters the atmosphere as a by-product of fuel combustion, from the industrial processes of nitric acid production, from the production and the utilization of anesthetic gases, from nitrification and denitrification processes that happen in soil and manure, and from wastewater treatment plants (Höglung-Isaksson et al., 2009). The average permanence of N_2O in the atmosphere is more than 100 years and its GWP is 300 times higher than that of CO_2 (IPCC, 2007a). The equivalences used to transform each GHG emissions into CO_2-eq are:

- 1 kg of CO_2 = 1 kg of CO_2-eq,
- 1 kg of CH_4 = 25 kg of CO_2-eq,
- 1 kg of N_2O = 298 kg of CO_2-eq.

Fluorinated gases (F-gases) are synthetic gases, such as hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride, which have a strong greenhouse effect. They are produced by some industrial activities, such as the aluminum production chain. The amount of their emissions is smaller than that of other GHGs, but they are more polluting because of their strong power to absorb solar energy. For this reason, F-gases are also called high global warming potential gases (High GWP gases) (Höglung-Isaksson et al., 2009).
Between 1970 and 2004, the increased demand for energy, food, buildings, transportation and industries by humans caused an increase in GHG emissions from 29 Gigatons (Gt) of CO_2-eq to 49 Gt of CO_2-eq/year. In the same period CO_2 emissions

increased from 21 to 38 Gt, with an average emission of 0.43 Gt between 1970 and 1994 and of 0.92 Gt per year from1995 to 2004 (Smith et al., 2007).

GHGs emissions can be divided according to the sectors from which they derive. The energy supply sector produces 26% of total GHGs emissions, the industry sector produces 19%, the land use, land-use change and forestry sector produces 17%, the agriculture sector produces 14%, the transportation sector produces 13%, the commercial and residential buildings sector produces 8%, and waste incineration and wastewater management and disposal produce the remaining 3% of total GHGs emissions (Smith et al., 2007).

The concentration of CH_4 increased from 715 ppm to 1,732 ppm during the years between the pre-Industrial Era and the 90's. In 2011 it reached 1,818 ppb, mainly because of fossil fuel use and agricultural emissions. Atmospheric concentration of N_2O was steady for approximately 100,000 years with an average of 280 ppb, but it started to increase from 1920 on and reached 324 ppb in 2011, mainly due to agricultural emissions (EPA, 2013b).

1.2.2. Environmental impact of the agricultural sector

The agricultural sector has a fundamental role in the availability of food for humans and animals and in the livelihood of millions of people. On the other hand, agricultural production impacts on ecosystems, introducing alien elements, such as fertilizers and pesticides, or causing high pollutant emissions during crop and livestock production (Tilman et al., 2002). In 2002 the amount of world's land surface occupied by agriculture was equal to 4,912 millions of hectares (Mha) (FAOSTAT, 2013), of which 3,359 Mha were represented by pastures and 1,539 Mha by croplands, corresponding to 40-50% of the total land surface. From 1960 to 2000 the agricultural sector increased its production level to follow the increase of human population and the improvement of its diet. The availability of calories per person followed the rate of human growth in almost all countries (Gilland, 2002), with the inevitable rise in the exploitation of natural resources (Tilman et al., 2001). An example of increasing food demand is represented by the rise in meat demand, which increased from 11 to 24 kg/yr/head between 1967 and 1997 and is supposed to increase until 2020 (Rosegrant et al., 2001).

Agriculture is an important source of greenhouse gases. Direct CO_2 emissions come from fossil fuel use, organic matter decomposition, microbial decay and plant litter burning (Janzen, 2004); CH_4 emissions come from ruminant enteric fermentation and the anaerobic decomposition of organic matter that occurs in manure storage and rice cultivation; N_2O emissions come from nitrification and denitrification of nitrogen compounds in soil and manure. In 2005 the amount of GHGs emissions from agriculture was equal to 6.1 Gt of CO_2-eq/yr, of which 3.3 Gt of CO_2-eq/yr were methane emissions and 2.8 Gt of CO_2-eq/yr were nitrous oxide emissions (Smith et al., 2007). Even if CO_2 emissions represent the largest percentage of GHGs emissions in the agricultural sector, they are often not considered during the CF estimation because CO_2 emissions generated by electricity and fossil fuel use are assigned to other sectors (industry, transport, buildings) and the remaining part, which derives from animal, plant and soil respiration and land use change, is absorbed by plants and soil in the carbon cycle, with a resultant break-even balance between emitted and absorbed CO_2 (Smith et al., 2007). According to 2005 estimations, the amount of CO_2 that is not balanced by the carbon cycle is equal to 0.04 Gt of CO_2-eq/yr (Smith et al., 2007).

During the last 40 years the agricultural sector increased the amount of pasture and croplands available by 500 Mha, in order to satisfy the increasing demand for food. Every year 7 Mha of forests and 6 Mha of other lands are transformed into croplands, especially in developing countries. The agricultural sector increased CH_4 and N_2O emissions between 1990 and 2005 by 17% and an additional increase has been predicted because of the rise in food demand. Increase in fertilizers use and in manure production correlated with an increased number of raised animals might cause an increase of 35% in N_2O emissions by 2030. Considering that CH_4 emissions are closely related to the number of raised animals, a high increase in these emissions could be expected. However, developments in animal nutrition and new technologies for manure management are going to help this sector and the US-EPA Agency forecasts an increase in methane emissions limited to 21% until 2030 (Smith et al., 2007).

1.2.3. Ecological footprint of the agricultural sector

Rural areas are inhabited by 3 billion people and this means that almost ½ of the world population lives around or far from cities. Besides, 2.5 billion people among those living in rural areas are closely connected with their places, because they work in the agricultural sector. Agriculture has always been the most important sector for human life and it is currently the main sector for economic and social growth of developing countries. Agriculture is strongly associated with the economic growth of countries. Developments and improvements in agriculture often preceded important historical events, such as the Industrial Revolution, which happened in Great Britain in 1760 after a considerable increase in agriculture production (FAO, 2013). Development of agriculture provided large benefits to human population; in fact, currently 6 billion people can live thanks to primary sector productions (Tilman et al., 2002). Changes in land use reflect the past and the future of human history; land use and agriculture are correlated with economic development, population growth, discovery of new technologies and environmental changes. Land use change rate is positively related to human population growth, but it decreases during economic development periods because of the introduction of new productive activities. Agriculture development and land use changes that happened thousands of years ago in all continents were really important because they allowed the development of new populations and the birth of large Empires, such as those of Egyptians, Maya and Romans. A large difference between past and current agriculture is that all changes and developments which happened in the past influenced only the regions where they occurred, whereas those happening nowadays influence all regions and all countries of the world because of their dimensions and because of globalization (Hougton, 1994). Crop cultivation and livestock production are certainly the main sectors of agriculture. Wheat, corn and rice cultivation systems represent the basis of human nutrition and supply 2/3 of human dietary energy. The amount of production per hectare of these cultivations increased greatly from the 60's to the 90's, thanks to genetic improvement, fertilizers and pesticides use, irrigation and new cultivation technologies (Cassman, 1999). Increase in these cultivations was also favoured by the expansion of cultivated lands at the expense of natural ecosystems (Waggoner, 1994). Increase in land-use change and in inputs for cultivation caused water, land and air pollution, reduction in biodiversity and reduction in forest areas (Matson et al., 1997). During the last years agriculture productivity exceeded the population growth, increasing the availability of calories per person from 2200 kcal/d in 1960 to 2900 kcal/d in 2009, with Europe showing an even higher value, equal to 3370 kcal/d. However, there are several differences among regions and undernourishment still remains unsolved in many countries. Growth in food production is not always connected with greater food availability, because undernourishment is often related with lack of access to food (FAO, 2013). Populations that live in several underdeveloped nations cannot access food because of lack of appropriate economic resources, infrastructure and technology (Alexandratos, 1999). During the last 50 years, global arable lands increased by 67 million hectares, because 107 million hectares of new arable lands were introduced in developing countries and 40 million hectares of arable lands were dismissed in developed countries (FAO, 2013).

Agriculture has responsibility for natural resources management. Indeed, 30% of the land surface is used for crop cultivation and animal pasture, and 70% of spring water is used in crop irrigation. The forestry sector plays an important role in climate change and mitigation, considering that trees absorb CO_2 from the atmosphere and are considered the most important Earth's active carbon sink. Deforestation, which is strongly connected with climate changes, is done to supply raw materials essential for human needs, and to increase the availability of arable lands.

Deforestation rate decreased during the last decades, passing from 16 million ha/yr in 1990 to 13 million ha/yr in 2010 of harvested forest areas. Reforestation was also considerable, with 5.2 million ha/yr of trees being planted between 2000 and 2009. The problem is that deforestation occurs mainly in tropical areas, whereas reforestation is mostly done in temperate and boreal areas. Therefore, there is a global improvement but overshoot of tropical forests still remains. Between 2000 and 2010, South America and Africa lost 4 million ha/year and 3.4 million ha/year of forest areas, respectively. In the same period, forest areas showed an increase in of about 0.7 million ha/year in Europe, and a net increase of more than 2.2 million ha/year in Asia despite the high level of deforestation that is still affecting the south of this continent. Oceania had a net loss of approximately 0.7 million ha/year during the same period, with a worsening situation between 2005 and 2010, because drought and fires caused the loss of millions of hectares of forest areas in Australia. North and Center America showed a steady situation between 2000 and 2010 (FAO, 2010a).

Livestock systems are the biggest users of arable lands; most deforestation actions in Latin America and Caribbean were carried out to obtain new pasture areas, and when deforestation was no longer possible overgrazing happened (FAO, 2013). Between 1961 and 2009, livestock products showed different trends following consumer choices: beef production showed a decrease of 2%, whereas swine production is still following a positive trend, even if its growth rate decreased from 4% to 0.8% (FAO, 2013).

Between 1961 and 2011 global milk consumption doubled, and the productivity of the dairy sector followed this trend (Figure 1); however, the increment of milk production was higher in developing countries than in developed countries (FAO, 2012b), following the human population growth and the changes in nutritional habits (FAO, 2013).

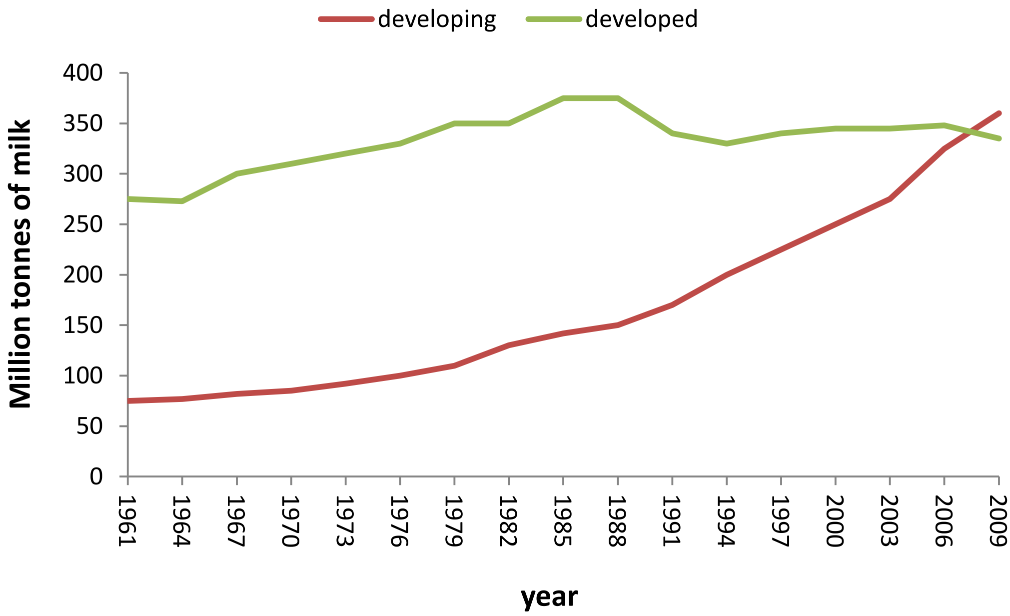

Figure 1.1: World milk production from developing and developed countries between 1961 and 2009 (FAOSTAT, 2013).

Approximately 85% of total milk produced in the world comes from dairy cows; the remaining percentage comes from goats, sheep, buffalos and camels, at different production levels depending on the world area considered (FAO, 2012b).

Only the poultry meat production sector showed a constantly increasing trend during the last 50 years. Meat consumption is not globally shared: there are more than 20 developing nations with an average meat consumption of 10 kg/head/yr, whereas developed countries have an average meat consumption of 80 kg/head/yr (FAO, 2013).

All activities included in the agriculture sector generate pollutant emissions that contribute to global environmental impact (FAO, 2013). During the last years, among agricultural activities, the livestock system was often blamed for a high environmental impact because of different events correlated with it, such as land use change, overexploitation of water resources, nutrient excretion in soil and groundwater, fossil fuels overexploitation, GHG emissions and competition with humans for environmental resources. However, livestock systems are also responsible for important benefits, such as production of human food, preservation of ecosystems and recycling of natural nutrients. Despite all these positive benefits, livestock activity cannot occur in every region of the World, because of environmental limitations (Janzen, 2011). Humans have always shared their life with animals, giving them feed and refuge and obtaining food, wool and leather for clothes, work power and company (Shusky, 1989). This old relationship between humans and animals is even stronger if we consider ruminants species. Nevertheless, the “ancient contract” is currently in a critical condition because humans are trying to obtain from their animals more resources than they can truly produce in natural conditions (McAlpine et al., 2009; Wirsenius et al., 2010).

1.2.4. LCA application on agricultural systems

Study of the environmental impact related to one specific product is often complex, because in most cases the final product comes from different production chains, and it is almost impossible to estimate its impact without considering all its life cycle (IDF, 2010). The dairy production sector represents a good example of a complex production system because within a dairy farm a multiple flow of materials and products occurs, involving many different sectors, such as crop cultivation, fertilizers and pesticides production, energy production and many others. Agricultural productions are influenced not only by human demand for food but also by livestock requirements, and some cultivations like soybean are strongly affected by animal consumption (FAO, 2013).

The LCA method was initially designed for industrial systems, but several modifications applied to the original method made its utilization possible in many other systems. The estimation of GHGs emissions in agriculture is currently achievable thanks to LCA application. This type of research on agricultural products is complex because of the simultaneous existence of a main product and one or more secondary products (IDF, 2010).

Global ecological footprint estimation is useful to achieve an overview on World’s environmental impact, but only if we analyze environmental conditions of countries and regions we can obtain useful and explanatory results that can be used to identify overshoot conditions and find their causes (Wackernagel et al., 2005).

1.3. The Carbon footprint of the dairy sector

The latest FAO report (Gerber et al., 2013) affirmed that 7.1 Gt of CO_2-eq/year are currently emitted from the livestock sector, which represents 14.5% of total anthropogenic emissions. Of these emissions, beef cattle are responsible for 41%, dairy cattle for 20%, pig meat for 9% and poultry meat and eggs for 8%.

All the products that derive from the livestock sector, such as milk, meat and eggs, are essential for human life. On the other hand, their production also causes pollution and, therefore, generates a lot of public interest in this sector. However, it is fundamental to make a distinction between the different livestock sectors and between the different world regions within each sector; in fact, GHGs emissions vary substantially depending on the animal species reared, on the level of technology adopted in the farm, and on farm location (FAO, 2010).

In 2010, the GHG emissions from the global agricultural sector were equal to 4,689,940 Gigagrams (Gg) of CO_2-eq, out of which 2,359,183 Gg (i.e. 50%) derived from the livestock sector, being 85.6% of them produced by animal fermentations and 14.4% derived from manure management (Table 1) (FAOSTAT, 2013).

Europe has a high level of livestock activity, which contributes to 26%, 13%, 22%, 12% and 11% of global production of milk, beef meat, pork meat, poultry meat and eggs (FAO, 2008). In 2010, the GHG emissions of the Europe's livestock sector were equal to 308,655 Gg of CO_2-eq, out of which 37.16% was due to the dairy sector (FAOSTAT, 2013).

Table 1.1. Greenhouse gases emissions from agriculture and livestock sectors in 2010 for different geographic areas. Emissions attributed to CH_4 and N_2O are reported within parentheses and expressed as percentage (FAOSTAT, 2013).

GHGs emissions	WORLD	EUROPE	ITALY
	Gg of CO_2-eq	*Gg of CO_2-eq*	*Gg of CO_2-eq*
Total Agriculture emissions	4'689'949	534'977	28'747
CH_4 from agriculture emissions	2’714’324 *(57.88%)*	279’020 *(52.16%)*	17’732 *(61.88%)*
N_2O from agriculture emissions	1975617 *(42.12%)*	255956.94 *(47.84%)*	11014.7 *(38.32%)*
Total Livestock emissions	2’359’184	308’655	17'322.15
Enteric CH_4 from Livestock emissions	2018899 *(85.58%)*	223’870 *(72.53%)*	11’925 *(68.84%)*
Manure CH_4 from Livestock emissions	180’440 *(7.65%)*	46’980.7 *(15.22%)*	3’099 *(17.89%)*
N_2O from Livestock emissions	159’845 *(6.78%)*	37’805 *(12.25%)*	2’298 *(13.27%)*

In developed countries, from 78 to 83% of GHGs emissions occur inside the farm, and the remaining emissions derive from the transportation sector, animal feed production, fertilizers and pesticides production, and the milk processing chain; in developing countries, the percentage of on-farm emissions is higher, reaching 90-99% of the total GHGs emissions. This happens because in developed countries farms are technologically more advanced and productive and, therefore, the dairy production chain releases a low amount of emissions per unit of product (Figure 1.2) (FAO, 2010).

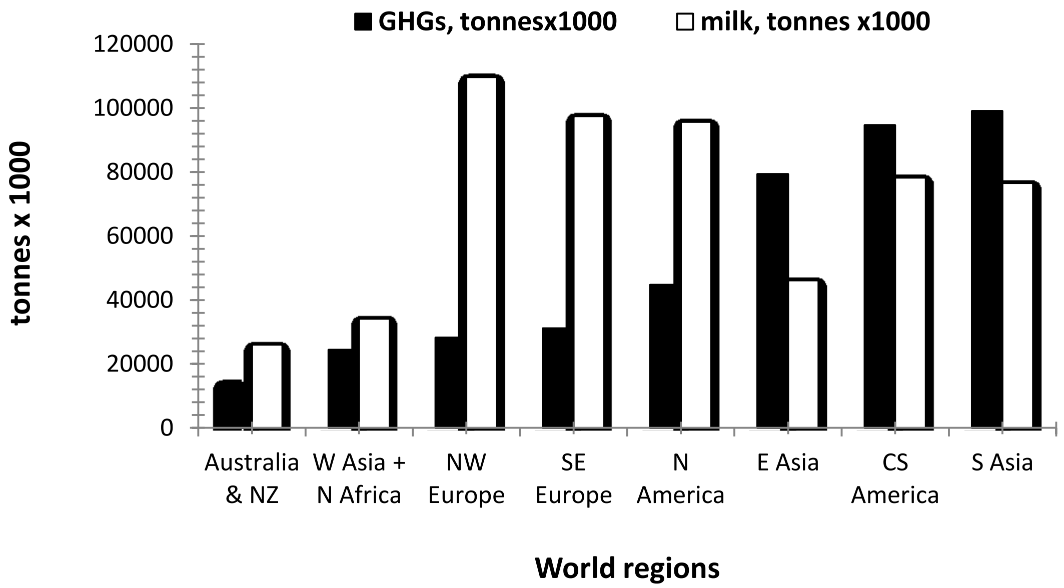

Figure 2.2. GHG emissions from the dairy cattle sector in 2010 and milk production levels from the main World regions (FAOSTAT, 2013).

This fact is confirmed by the different amounts of CO_2eq that are emitted for every kg of fat and protein corrected milk (FPCM) produced. The world range is between 7.5 and 1.3 kg of CO_2eq/kg of FPCM, with an average of 2.4 kg of CO_2eq/kg of FPCM. The highest value of 7.5 kg of CO_2eq/kg of FPCM was recorded in the Sub-Saharan Africa farms, followed by the South Asia farms, which produced 4.6 kg of CO_2eq/kg of FPCM, and by the North Africa and East Europe farms, which produced 3.7 kg of CO_2eq/kg of FPCM. The lowest value of 1.3 kg of CO_2eq/kg of FPCM is the average level of GHG emissions that occurred in Europe and North America (FAO, 2010).

1.3.1. GHG emissions sources in the dairy sector

Emissions of the dairy system come from several phases of the production process, and each of them contributes differently to total emissions. Generally, approximately 2/3 of dairy sector emissions are related to the crop cultivation sector, which provides feeds for animals (Casey and Holden, 2005). Considering that crop cultivation is associated with water consumption, energy consumption, pesticide and fertilizer use and many other production chains, it is easy to understand the noticeable dimension and complexity of the dairy sector.

Rotz et al. (2010) classified the GHGs emissions produced within dairy farm boundaries into two main groups: primary emissions and secondary emissions (Table 1.2). Primary emissions refer to gases directly emitted by the milk production process (e.g. CO_2 emitted during fuel consumption), whereas secondary emissions refer to gases emitted by sectors which produce products that are then used in the milk production process (e.g. CO_2 emitted during fuel production). The IDF (2010) classification is made considering the emissions produced in the entire dairy sector, and dividing the GHGs emissions into two different groups: farming and processing. Farming emissions are produced within farm boundaries; processing emissions derive from all processes related to the dairy industry (Table 1.2).

IDF (2010) classification also regrouped farm emissions according to the GHG produced. The CO_2 emissions are caused by the combustion of fuel used in deforestation and by biogenic C contained in plastic, paper and carton used for packaging. CH_4 emissions come from animal enteric fermentation and from anaerobic microbial activities within manure. N_2O emissions come from fertilizer and pesticides, replacement animals production processes, and from direct and indirect emissions from manure (IDF, 2010).

Emissions related to milk transportation and transformation have to be considered in a "cradle to grave" LCA; milk transformation factories generally produce more than one product (milk, milk powder, cheese, yogurt, butter), and, therefore, it is recommended sharing the emissions coming from all these products according to the production process used for each one of them. Meat production is often a co-product of dairy farms: it comes from cull cows and male calves raised inside the farm, whose emissions have to be considered in LCA estimation (IDF, 2010).

When dairy carbon footprint estimation is made within farm boundaries, animal and manure management, on-farm feed production and energy consumption have to be considered (Asselin-Balençon et al., 2013), whereas emissions from meat production, milk processing and feed production have to be measured only if they occur inside the farm (Browne et al., 2011).

Estimation of carbon footprint related to feed production processes can be divided into different steps. Animal feeds can derive directly from the crop cultivation sector, but also from feed mills that transform different crops into concentrated feeds.

Table 1.2. Classification of GHGs emissions within the dairy sector (Rotz et al., 2010; IDF, 2010).

GHG	**FARMING EMISSIONS**		**PROCESSING EMISSIONS**
	Primary Emissions	*Secondary Emissions*	
CO_2 (carbon dioxide)	Plant respiration, soil respiration, manure fermentation, animal respiration, feed production, fuel consumption for machinery use	Fuel production, machinery production, fertilizer and pesticide production, plastic production, replacement animals	Transport of milk and dairy products, production of operating and packaging materials, delivery of operating and packaging materials, consumption of operating and packaging materials, wastewater treatments, releases from industrial processes, waste production and disposal
CH_4 (methane)	Animal enteric fermentation, manure anaerobic fermentation	Replacement animals	Releases from industrial processes, waste production and disposal
N_2O (nitrous oxide)	Manure aerobic fermentation, nitrification and denitrification processes within the soil	Replacement animals, fertilizer and pesticide production, plastics production	Releases from industrial processes, waste production and disposal

Emissions correlated with animal nutrition have to be studied at different levels and feed mill processes and crop cultivation processes are considered as secondary emissions (Rotz et al., 2010), when animal feed is not produced within farm boundaries. Feed mill emissions come from transportation of raw materials to the feed mill and transportation of animal feeds to the farm, fuel use for energy production, and emissions from crop cultivation. Adom et al. (2013) estimated the carbon footprint of a US feed mill located in Michigan and showed that 88-92% of carbon footprint came from raw materials cultivation, and only 8-12% of emissions were caused by energy consumption and transportation.

N_2O is the most produced GHG within the agricultural sector, and soybean and corn cultivation produce the biggest world amount of this GHG as compared with all other cultivations (Del Grosso et al., 2005). N_2O emissions that occur during crop cultivation derive from nitrification and denitrification of inorganic N in the soil; these emissions can also occur from manure stored in aerobic conditions (Cadwick et al., 2011). Manure stored in anaerobic conditions is instead a source of CH_4 (Møller et al., 2004; Burton and Turner, 2003). Carbon soil sequestration should be taken into account in a "cradle to grave" LCA (Franzleubbers and Follet, 2005).

1.3.2. Physiological basis of carbon dioxide, methane and nitrous oxide production

Carbon dioxide, methane and nitrous oxide production from dairy farms can take place from several processes; however, the main sources are animal enteric fermentation, manure fermentation and soil emissions.

1.3.2.1. Carbon dioxide production

Carbon dioxide emissions that happen within the dairy sector derive from many processes which can be considered or not when estimating CF, depending on the method adopted. In general, three main sources of CO_2 in the dairy sector can be identified: animal management, crops and soil, and fuel use.

Animals: CO_2 production related to animals can derive from animal respiration and manure decomposition. Ruminants remove C from the ecosystem through feeding and emit CO_2 through respiration. During a one-year interval, the amount of C removed by animal feeding is balanced by the amount of C contained in the CO_2 emitted by respiration (IPCC, 2007b). The process of manure decomposition can produce different amounts of CO_2, depending on the organic matter (OM) content and on the oxygen content of manure. CO_2 production from manure is an aerobic process, and solid manure can generate more CO_2 than liquid slurry, because anaerobic conditions are difficult to obtain. Therefore, housing solutions that generate solid manure (e.g. bedded pack) can produce more CO_2 emissions than those that produce liquid slurry (e.g. cubicles) (Chianese et al., 2009a).

Crops and soil: CO_2 emissions from crop cultivation and soil are affected by several factors. The Carbon © balance that exists within the ecosystem is regulated by the amount of C absorbed by plants and soil, and by the amount of C released during the mineralization of the organic matter. Soil tillage, plant biomass production and cultivation management can influence this balance. For example, corn and soybean are two kinds of plants that can have a great C input because of their high biomass production. The amount of C that effectively remains within the ecosystem will be affected by the harvesting solution. Cultivations that leave part of their biomass in the soil after harvesting procedures (e.g. corn grain) lead to a larger C output than those that have all their biomass harvested (e.g. corn silage). No-till practices reduce the microbial activity in the soil, thus reducing soil mixing, oxidation processes, organic matter mineralization and gas exchange, and leading to lower CO_2 production and emission (Chianese et al., 2009a). C absorbed by plants and C absorbed and emitted by animals is considered neutral within a short-term time interval (e.g. one year) and it is not contemplated by LCA because it is quickly and easily released into the environment by respiration, excretion, decomposition and incineration processes. The short-term carbon flux of most ecosystems is equal to the net ecosystem production (NEP); the NEP is obtained by subtracting the CO_2 absorbed by the photosynthesis from the CO_2 emitted by plant and soil respiration. The result of this calculation, made within a time interval of 12 months, has a negative value. This means that, within a year, plants and soil can absorb more CO_2 than they emit (Chianese et al., 2009a). However, using a long-term approach, the NEP is different, because more elements have to be considered within the ecosystem, such as the CO_2 emitted by animal respiration, C applied to the soil by land-applied manure, C removed with harvested feeds, CO_2 emitted from fuel use, and, in particular, modifications of the C content of the soil. The C content of the soil change sharply in the case of land use changes (Chianese et al., 2009a; Rotz et al., 2010). The land use change occurs when there is a change in the utilization of a land (e.g. from natural vegetation to cropland cultivation, from cropland cultivation to forest). This shift affects the soil carbon content, in a positive or negative way, depending on the original and the new use of the land area. A land area where natural vegetation is converted into crop cultivation will incur in a loss of soil carbon due to higher rates of mineralization, higher harvest of organic matter and lower biomass accumulation on site; conversely, a cropland area converted into natural vegetation will accumulate carbon within the soil (Post and Know, 2000).

Fuel use: fossil fuels contain different amounts of carbon, depending on their origin (e.g. petroleum, natural gas, coal). CO_2 emissions from fuel use originate from carbon combustion done to generate mechanical energy used for different activities. The amount of CO_2 emitted depends on the carbon content of the fossil fuel used and on the type of the combustion. In dairy farms, the CO_2 emissions related to fuel use are considered proportional to the amount and type of fuel used for all farm activities, such as crop cultivation, animal feeding, transport of feed and milk, water heating and water pumping (Rotz et al., 2010). Rotz et al. (2010) reported that each kg of fuel used in the farm can generate an average of 3.54 kg of CO_2-eq. as primary emissions.

1.3.2.2. Methane production

Animal enteric fermentation and microbial processes within manure stored in anaerobic conditions are the main sources of CH_4 within a dairy farm. Low amounts of methane can also derive from manure applied to the soil or filed by animals on pasture; however, these emissions are not considered because of their almost negligible percentage within the total CH_4 emissions of a dairy farm (Chianese et al., 2009b).

Animal enteric fermentations**:** Methane is a secondary product that derives from ruminal fermentation of feeds. The amount of methane produced is affected by several factors, such as feed and ration characteristics, number of rumen bacteria, number of methanogens among ruminal bacteria population, and rumen pH. Methane emissions can be considered at the same time an energy loss for animals and a source of environmental pollutant (Vercoe, 2007). Ruminal fermentation affects environmental pollution and animal productivity; feeding animals with balanced feed ration can improve the amount of feed energy that is converted into animal product (milk or meat). This is an essential factor in animal breeding because almost 2/3 of farm costs derive from feeds (Szumacher-Strabel and Cieślak, 2012).

Ruminant nutrition is based on–plants, such as grass, forages and seeds, which derive from several species and that can be distributed in different forms. Plant cells cannot be digested by humans and by many animals that are not able to produce the appropriate enzymes; conversely, microbial rumen population that colonizes the ruminant digestive system is composed of different classes of microorganisms that are able to ferment the plant cell walls (Szumacher-Strabel and Cieślak, 2012). Short-chain volatile fatty acids are the final product of microbial fermentation and are immediately available for animal needs (Kamra, 2005).

Rumen microbial population is composed of bacteria (10^{10}cells/ml), ciliate protozoa (10^4-10^6 cells/ml), anaerobic fungi (10^3-10^5 zoospores/ml) and bacteriophages (10^8-10^9 cells/ml); each group of rumen microorganism has different species present at different ratios, depending on diet characteristics, rumen temperature, rumen pH and many other factors (Kamra, 2005).

Rumen bacteria can be classified according to their metabolic activity and the energy substrate (Hungate, 1966):

- cellulolytics hydrolyze cellulose and hemicelluloses;
- amylolitics hydrolyze starch;
- methanogens produce methane;
- lipolytics hydrolyze triglycerides producing glycerol and free fatty acids;
- proteolytics hydrolyze proteins peptides bonds of proteins providing free amino acids.

Differently from other animals, ruminant species have a peculiar digestive system that has 4 fermentative chambers: reticulum, rumen, omasum and 30bomasums. Abomasum, which can be compared to human stomach, is where the real digestive process takes place trough secretion of acids and digestive enzymes. Rumen is the biggest fermentative chamber, where the microbial population lives in a stable environment with pH, temperature, oxygen and other factors are closely regulated in order to preserve optimal fermentation conditions (Bortolami et al., 1997).

Microbial rumen population ferments plant material to produce energy and carbon that are used for its own growth and for animal requirements (Bortolami et al., 1997). Monosaccharides, disaccharides, polysaccharides, cellulose, hemicelluloses, pectic substances, and lignin are introduced inside the forestomach apparatus by feed rations of plant origin. Lignin cannot be fermented and, therefore, passes undigested in the feces; all the other compounds are broken up into simple monosaccharides by the enzymes produced by rumen bacteria. The monosaccharides that derive from this first digestive phase are then transformed by rumen microorganisms into fructose 1,6-diphosphate (Aguggini, 1998). Volatile fatty acids, methane, carbon dioxide, and hydrogen are the final microbial fermentation products (Bortolami et al., 1997).

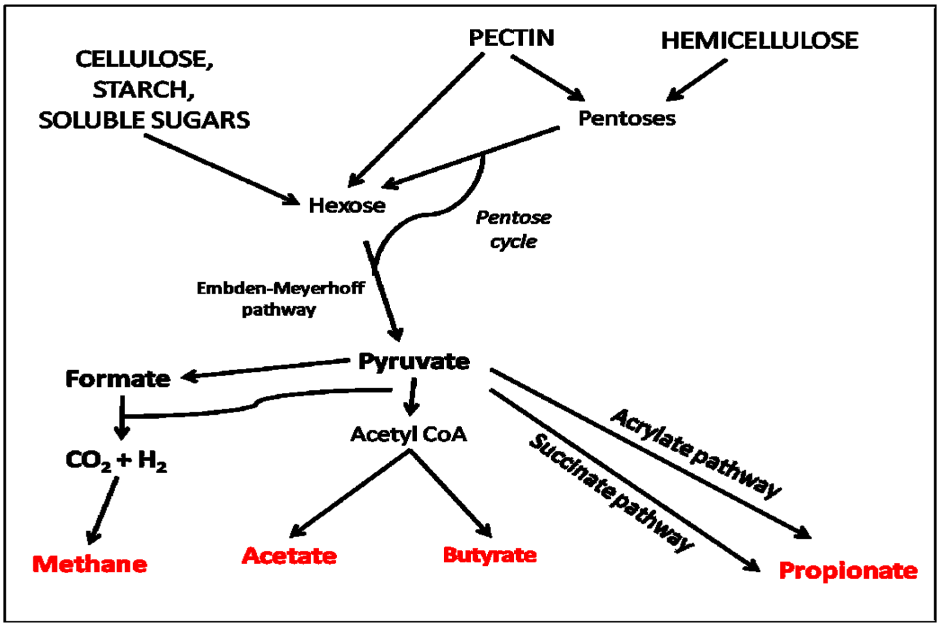

Figure 1.3. Schematic representation of the major pathways of carbohydrate metabolism in the rumen (Aguggini et al., 1998).

Acetate, propionate and butyrate are the main volatile fatty acids produced within the ruminant digestive apparatus (Figure 1.3) and derive from the fermentation of plant carbohydrates; isobutyrate, valeric, pyruvic, and lactic acid derive from the digestion of different compounds and are produced in very low quantities. Acetate, propionate and butyrate are generated from different biochemical reactions; the pyruvic acid is the common and obligated intermediate compound, derived from the anaerobic demolition of glucose, from which the three main volatile fatty acids are produced (Aguggini et al., 1998). One molecule of glucose can generate acetate, propionate or butyrate, according to the following stoichiometric reactions (Moss et al., 2000):

- Acetate = $C_6H_{12}O_6 \rightarrow 2\ C_2H_4O_2 + 2\ CO_2 + 8\ H$;
- Butyrate = $C_6H_{12}O_6 \rightarrow C_4H_8O_2 + 2\ CO_2 + 4\ H$;
- Propionate = ½ $C_6H_{12}O_6 \rightarrow$ pyruvate + $CO_2 \rightarrow$ fumarate + 2 H $\rightarrow C_3H_6O_2 + CO_2$;
- Propionate = ½ $C_6H_{12}O_6 \rightarrow C_3H_6O_2$ (lactate) + $H_2O \rightarrow$ acrylate + 2 H $\rightarrow C_3H_6O_2$.

Volatile fatty acids are absorbed through the rumen walls and are used by the the animals as a primary source of carbon and energy (Bortolami et al., 1997).

Production and elimination of methane is considered a physiological need of ruminants (Moss et al., 2000). In fact, methane production helps to maintain oxidative conditions in the rumen anaerobic environment through reoxidation of electron carriers cofactors, such as NADH, FADH2 and ferredoxin; on the other hand, it represents a loss of energy for animals, which can lose 6% of ingested energy due to removal of CH_4 from their bodies by belching and flatulence (Johnson and Johnson, 1995). Methanogenic archaea are highly specialized microorganisms responsible for methane production. They are characterized by slow development and strict anaerobic conditions, and they are responsible for the final step of feed degradation. The various phases of fermentation are closely connected to each other; in fact, the metabolic efficiency of each group of microorganisms group depends on what other groups do. The methanogenic bacteria use primarily molecular hydrogen and carbon dioxide as substrate for the synthesis of methane, according to the following equation (Moss et al., 2000):

- $CO_2 + 8\ H \rightarrow CH_4 + 2\ H_2O$.

However, they are also able to use as substrate formate and other less important elements, such as acetate and short-chain primary alcohols, including methanol formed during pectin degradation, and n-butanol. Formate may be directly used by methanogenic bacteria or may be used after degradation into carbon dioxide and hydrogen by other bacteria (Bortolami et al., 1997).

CH_4 enteric emissions are mainly affected by feed characteristics, animal production level, animal management and genetic characteristics (Monteney et al., 2006). Hydrogen rumen production is closely connected with feed characteristics because VFA derive from feed fermentation; acetate, butyrate and propionate are produced from different feed substrates and lead to the production of different amounts of H_2. As a consequence, feeding animals with products that lead to lower H_2 productions reduces CH_4 emissions (Boadi et al., 2004). Concentrates ration level affects CH_4 enteric emissions by increasing rumen propionate synthesis which, in turn, leads to have lower H_2 production (Aguerre et al., 2010). Grasses with C4 metabolic pathway lead to higher CH_4 enteric emissions than C3 grasses, probably because of their high fiber content (Archimede et al., 2011).

Forage quality and maturity also affect enteric emissions: animals fed fresh forages emit less CH_4 because of the lower content of fiber, N and organic matter (OM). Legume forages reduce CH_4 enteric emissions because of their content of tannins, which inhibit methanogenic bacteria (Tamminga et al., 2007). The amount of starch and other nonstructural carbohydrates in animal feeds positively affects rumen propionate production, link reducing animal methane emissions (Boadi et al., 2004). Rumen pH influences the amount of methanogens bacteria, considering that their survival is guaranteed within the pH range 6–8 (Jones et al., 1987); feed rations with high grain content can lower rumen pH to levels below those required by methanogens, thus reducing methane emissions (Hegarty, 1999).

Feeding frequency can influence rumen pH and enteric methane emissions: rumen pH fluctuations, which derive from low meal frequency, cause a reduction in number and activity of methanogens in the rumen, causing a reduction in methane emissions (Sutton et al., 1986). Feed intake level negatively affects CH_4 production in the rumen: high feed intake levels increase the feed passage rate, thus reducing rumen fermentation and methane emissions (Johnson and Johnson, 1995; Mathison et al., 1998). Feeding animals with ground or pelleted forages can reduce methane emissions. This happens because grinding and pelleting processes reduce forage digestibility and, consequently, increase the propionate:acetate ratio within the rumen, thus causing a reduction in methane production. Grinding and pelleting forages also increase the feed passage rate, thus reducing rumen fermentation and, consequently, reducing methane emissions (Johnson et al., 1996; LeLiboux and Peyround, 1999).

Addition of fat to the ration can reduce CH_4 emissions by several actions: decrease of OM fermented in the rumen, reduction of methanogens number of ruminal bacteria activity, and reduction of H_2 availability through biohydrogenation of unsaturated fatty acid (Beauchemin et al., 2005; Beauchemin et al., 2007; Beauchemin et al., 2009; Chung et al., 2001; Moate et al., 2011). Sometimes fat addition does not result in CH_4 reduction, but it can cause an increase of milk production link achieving a dilution effect; in this case, methane emissions produced after fat addition to the diet will be divided by a higher amount of milk than the amount that would have been produced without fat supplementation, and the final CF value will be lower (Johnson et al., 2002).

<u>Microbial processes within manure</u> – Methane production can also occur by action of methanogenic bacteria in manure stored in anaerobic conditions (Monteny et al., 2006). Manure fermentation is similar to rumen fermentation and is affected by organic matter content of manure, animal feed intake, feed ration characteristics and oxygen concentration (Boadi et al., 2004). The first phase of methane production from manure is represented by the growth of acidogenic bacteria, which are able to ferment the organic matter (OM) of manure and produce organic acids, hydrogen and CO_2.

Acidogenic bacteria can survive within a large temperature range (3–70 °C), but they show the maximum fermentative activity at 30 °C. The second phase is performed by three groups of methanogenic bacteria (psychrophilic, mesophilic and termophilic) that are able to produce methane in different thermal conditions. Manure methane production derives from organic acid, hydrogen and CO_2 produced by different classes of bacteria: hydrolytic, acidogenic, acetogenic and methanogenic (Monteny et al., 2006). Acetogenic and methanogenic bacteria survive only in anaerobic conditions, whereas hydrolytic and acidogenic bacteria can live even in aerobic conditions. This fact allows active fermentation in presence or absence of oxygen, but methane production still remains an anaerobic process. Each class of bacteria carries out a specific step inside the fermentation process, producing compounds that will be used in the following steps as energy source for microorganisms (Ciborowski, 2001).

In manure, methane production derives from organic matter (OM) digestion and from fermentation of straw, which is usually added to litter. Bedding management can affect methane emissions: manure stored at low temperatures (<10 °C) and low pH (<6) can lead to a reduction of methane emissions, because acidogenic and methanogenic bacteria cannot perform their fermentative activity in those conditions. The frequent addition of straw to bedding and manure can prevent compaction, thus preventing the anaerobic conditions that favor the activity of methanogenic bacteria (Monteny et al., 2006). Manure storage can also affect methane production: manure that is stored in open tanks, being mixed and often managed in the presence of oxygen,, results in lower methane emissions because of the absence of anaerobic conditions (Møller, 2003).

1.3.2.3 Nitrous oxide production

In a dairy farm, N_2O emissions derive from soil, cropland and manure, either deposited on pasture and on barn floor or stored. The N content of substrates affects the amount of N_2O emissions produced.

Even if nitrogen can come from different substrates, N_2O emissions can originate from the same biochemical process. Denitrification and nitrification are two subsequent chemical reactions included within the nitrogen cycle that can lead to N_2O production. These reactions are always present within the soil, but they can also take place in manure stored under aerobic and anaerobic conditions, in manure applied on soil, and after fertilizer application on croplands (Chianese et al., 2009c). The N_2O production can derive from two different processes:

- Nitrification: transformation of ammonium into nitrate under aerobic conditions;
- Denitrification: production of nitrogen gas from nitrate reduction under anaerobic conditions (Monteny et al., 2006).

Nitrification is performed by nitrosating bacteria, a particular class of microorganisms that can oxidize ammonia (NH_3) and ammonium ions (NH_4^+) into nitrite (NO_2^-) and nitrate (NO_3^-) under aerobic conditions. Denitrification occurs under anaerobic conditions and consists of a reduction process performed by denitrificating bacteria that leads to the production of N_2, starting from the nitrate (NO_3^-) produced during the previous process. These two processes can take place continuously, because the N_2 that reaches the atmosphere can be transformed into NH_3 by the nitrogen-fixing bacteria of the soil (Smil, 1996).

As reported in the conceptual model of Davidson et al. (2000), N_2O and NO derived from the nitrification and denitrification processes are considered losses that can happen from the N flow that takes place within the “pipe”. Denitrification and nitrification can occur simultaneously and have common intermediary. The soil water content and the soil acidity, which affect the availability of oxygen and of electron donors and acceptors, influence the amount of N_2O and NO produced and transported out of the soil. Within dry and aerated soils, nitrification represents the predominant process and, therefore, NO is the most emitted nitrogen oxide, whereas in soils with a high water content, NO is reduced to N_2O because of anaerobic conditions (Davidson et al., 2000).

Soil and cropland: N content in the soil and cropland depends on several factors, such as amount and type of fertilizers, organic matter content, and amount of manure applied or deposited by animals (Chianese et al., 2009c). Main N_2O sources in soil are fertilizers and manure applied to soil (Brown et al., 2001). Nitrous oxide emissions from soil and cropland are mainly affected by the N concentration and oxygen concentration in the soil. These two elements are more present in croplands because of fertilization and tillage processes performed to increase crop production. Oxygen affects N_2O emissions, because N_2O production requires both aerobic and anaerobic conditions (Chianese et al., 2009c). Leaching, immobilization by plants and microbiota utilization indirectly affect N_2O production. Therefore, soil and meteorological factors may strongly control, directly and indirectly, the production, transport and emissions of N_2O.

<u>Manure management:</u> N present in manure derives from animal excretions. Nitrogen contained in proteins and in non-protein compounds of animal feeds is degraded mostly by rumen microorganisms, producing ammonia and free aminoacids in the rumen. These compounds are then used by the microorganisms to produce bacterial proteins, which are almost completely digested once they arrive in the intestine. Part of the rumen ammonia is absorbed by the rumen wall and, after being transformed into urea, is excreted with the urine. Of the share of N from feeds which is not fermented in the rumen, one part is digested in the intestine and the other part excreted. Nitrogen of feed and microbial origin which is absorbed by the intestine is then used in various metabolic processes, with a variable efficiency according to the physiological process considered. Part of the N is then transferred to the animal tissues or to the milk. The remaining part is excreted, in the form of urea, in the urine.

Nitrogen present in feces and in urine differ for biological origin and chemical composition. Fecal nitrogen is composed of: 1) microbic protein, which cannot be digested in the gastro-intestinal tract; 2) protein of endogenous origin, i.e. residues of enzymes and of the turnover of epithelial cells of the digestive system; and 3) undigestible dietary protein (Mason, 1969). Urinary N is made up prevalently of urea (50-90% of the total), ippuric acid (2-8%), allantoin (2-22%) and other N derivatives of degraded nucleic acids.

On average, about half of fecal N is of endogenous origin, and the other half is of feed and microbic origin (Tamminga, 1992, cited by Bussink and Oenema, 1998). The N concentration in feces is generally quite constant, ranging between 60 and 90 g of N/kg dry feces, with average values of 75 g of N/kg dry feces (Bussink and Oenema, 1998). Differently, the concentration of N in urine is extremely variable, ranging from 1 to 20 g of N/l (Bussink and Oenema, 1998).

N excretion always increases proportionally to the increase of the percentage of dietary CP. The N quantity that should be given to the animals with the ration is then determined taking into account their ability to digest N and the efficiency of N use in several metabolic processes. In well-balanced rations, even if total N excretion varies with diet, the ration between fecal N and urinary N tends to be relatively constant (Haynes and Williams, 1993). In case of an exceeding N contribution, the share of excreted N with feces varies only in small quantities, because an excess of N is expelled mainly in the urine (Frank et al., 2002), and, to a much lower extent, in the milk (in the form of urea).

Tomlinson et al. (1996), in agreement with Frank et al. (2002), showed that dairy cows fed rations with 12%, 15% and 18% of CP produce fecal and urinary excretions which resulted in slurries with a N content of 3.2 %, 4.2 % and 5.3 % of total DM, respectively. Gaseous N emissions from manure are mainly represented by ammonia emissions and are highly influenced by air temperature and other meteorological variables (Atzori, 2008). Ammonia volatilization from animal manure can generate indirect emissions of N_2O after redeposition of ammonia in the soil and subsequent nitrification (EPA, 2013a). Direct emissions of N_2O are the smallest part of total gaseous N emissions from manure and correspond to 1% and 2% of total N gaseous compounds in liquid and solid manure, respectively (Webb, 2001).

Considering manure management types:

- slurry or liquid manure (produced in free-stall barns with concrete floor areas managed without bedding materials) produces negligible amounts of N_2O emissions in the housing phase of manure management, because the nitrification processes have not started yet, and very low amounts in storage tanks, because the manure is almost always in anaerobic conditions, and inside the storage facilities (Groenestein and Van Faassen, 1996); however, nitrous oxide emissions can also be produced from slurry stored in uncovered tanks, depending on the crust density and dimension, and the area that is exposed to the air (Olesen et al., 2006).
- solid manure (produced in bed-pack barns, in farmyard or in stockpile solid manure storage), in contrast, is often stored in aerobic conditions, because of the large amount of bedding material mixed with dung and urine, and can produce relevant amounts of N_2O. Chemical and physical characteristics of manure can positively or negatively affect N_2O emissions in bed-pack farms that are not frequently renewed or in stockpile manure not closely compacted (Groenestein and Van Faassen, 1996; Yamulki, 2006).
- dung and urine excreted at pasture generate emissions that are often considered as emissions from not managed manure, allowed to lies as deposited (IPCC, 2006). However, excreted nitrogen can be considered as a N applied to the soil in form of dung and urine. Allen et al. (1996) showed that N_2O emissions from dung and urine varied considerably, depending on grazing season, deposition time and type of grazed soil.

Mechanisms that control nitrous oxide emission from excreta of grazing animals are affected by the biochemical conditions that influence the transformation of nitrogen compounds in feces and urine via nitrification and denitrification processes. A major influence is associated with soil microbiota; in fact, a momentary increase in NO_2^- in urine patches might be caused by nitrite-oxidizing bacteria which can increase the emission of N_2O via nitrification (Oenema et al., 1997). On the other hand, higher emissions are generally observed during and after rainfall periods (Allen et al., 1996). Autumn and winter anaerobic soil conditions favor denitrification and lead to higher emissions than summer conditions (Yamulky et al, 1998).

According to Yamulki et al. (1998), data on N_2O emissions from animal excreta in grazed grasslands are few and not consistent, because of the interactions among excreta, microbiota, environmental conditions and global N_2O flux. The same authors measured N_2O emission from cattle dung and urine applied through a simulated seasonal grazing pattern and found that the average emission from the urine patches was more than five times greater than that from the dung, probably for the larger amounts of mineral-N available in urine. In addition, low temperatures inhibit ammonia volatilization (Much, 1982) reducing the completion for N among grasses and soil microbiota leading to more N available for emissions. Soil type, pasture intake, excreta C-to-N ratio, and grazing environmental conditions can increase the variability in emission patterns.

Methane emissions and nitrous oxide emissions could also be related with each other because N manure content limits the development of archaea bacteria and is considered a factor that decreases methane emissions from manure (Bryant, 1974). Soil N_2O emissions generally start from NO_3^- compounds and are often affected by N leaching processes and N plant absorption (Yamulki et al., 1997).

As explained above, GHG are produced by various sources which are sometimes correlated, such as methane emissions that derive from enteric fermentation and manure. On the other hand, sometimes these sources are antagonists and, therefore, the production of one GHG can impede the production of others. Studies on mitigation strategies have to consider this correlation because, in most cases, it is not feasible to obtain a decrease in GHG emissions by reducing simultaneously all GHGs (Table 1.3).

Table 1.3. Emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from soil, manure, manure management and feed using different feeding solutions and housing types. The symbols indicate the effect of every action on each greenhouse gas (GHG) emission (↑ = increase; ↓ = decrease; - = no effect or not considered) .

	GHGs		
ITEMS	**CO_2**	**CH_4**	**N_2O**
Slurry manure decomposition	↓	↑	↓
Manure on pasture	↑	↓	↑
Soil tillage	↑	↓	↑
Fuel use	↑	↑	-
Soil fertilization	-	-	↑
Feeding management			
% of concentrates	-	↓	-
Grasses: C4 vs. C3	-	↑	-
Forage maturity	-	↓	-
Starch ration content	-	↓	-
Low meal frequency	-	↓	-
High feed intake	-	↓	-
Grinded and pelleted feeds	-	↓	-
Addition of fats	-	↓	-
Reduction of diet N content	-	↑	↓
Housing and manure management types			
Bedded pack	↑	↓	↑
Pasture	↑	↓	↑
Cubicles	↓	↑	↓

1.4. Estimation of Carbon footprint

The estimation of CF is a complex issue that should be examined carefully.

The systems used to estimate the CF of every GHG can be divided into three main groups: *in vivo* estimations, *in vitro* estimations, and estimations by prediction equations (Storm et al., 2012). *In vivo* estimations are obtained by measuring the emissions directly from the source that produces them; *in vitro* estimations are made mainly in laboratory conditions by measuring the GHG emissions within a controlled environment; prediction equations result from mathematical calculations based on direct estimations results transferred to large scale.

The choice of the estimation method depends on the GHG analyzed, emission sources, experiment purposes, acceptable estimation accuracy level, and available economic resources (Bhatta et al., 2007). A deep knowledge of the advantages and disadvantages related to the various estimation systems is useful to compare the results that derive from different estimations, as reviewed by Storm et al. (2012).

The large amount of methods that exists for the CF estimation from dairy farms is justified by three main objectives that this research area is trying to reach: 1) to achieve a deeper and more accurate level of knowledge of the biological and physical mechanisms that control the GHGs production; 2) to quantify accurately all types of GHGs emissions by referring to different breeds and species, located in different regions of the world, and considering different time intervals; 3) to extend the GHGs estimations, made on a limited sample, to a wide scale by developing equations that relate the measured inputs to the calculated emissions.

1.4.1. *In vivo* estimation of methane

Respiration chambers, ventilated hoods, open-circuit face mask respirometry, tracer gas techniques and meteorological techniques can be considered the most known systems used for in vivo methane measurements because of their extended use and results reliability.

Respiration chambers. This system was originally created to study the energy metabolism of animals. The respiration chamber is a box that can be built with different materials, such as glass, plastic or steel, and monitors one animal at a time. It is totally isolated from the outside environment and has a constant flow of monitored air inside; temperature and humidity are kept constant and the animal is monitored 24 hours per day, in order to measure its feed intake, urine and feces excretion, and quality and quantity of emitted gases (Moe and Tyrell, 1979; Miller and Koes, 1988; Soliva and Hess, 2007). Recently, Hellwing el al. (2012) fabricated a transparent polycarbonate chamber to measure O_2, CO_2, CH_4 and N_2O emissions; the building materials used allowed animals to see each other and produced a functional and cheap measurement system. Respiration chambers allow to obtain reliable and comprehensive results on animal emissions and metabolism, but it has some serious limitations. For example, the isolation could influence animal feedback by making them exhibit behaviors that are different from those that they would show naturally (Storm et al., 2012). Another limitation is that it is not feasible to apply this system on grazing animals (Harper et al., 1999).

Ventilated hoods. Place et al. (2011) built a methane measurement system by modifying the original system developed by Kelly et al. (1994). The ventilated hood can be considered as a small respiration chamber that encloses the head of the animal to collect and analyze all gases emitted by respiration and belching. A negative characteristic of this system is that it does not measure all animal emissions, because it does not collect rectum gases emissions. Place et al. (2011) made the ventilated hoods by using transparent polycarbonate, in order to allow the animals to watch outside, and to have a cheaper and lighter hood than the one made of wood by Kelly et al. (1994). Air flow control and gases analysis are performed similarly to those of respiration chambers, but ventilated hoods are an encumbrance for animals, which can make only some movements, like stand up, lie down, eat and drink. On the other hand, the preservation of visual and physical contact with the surrounding environment is more feasible in the ventilated hoods, because they can be placed inside the barn and thus animals subjected to the test can still remain within the herd (Place et al., 2011).

Open-circuit face mask respirometry. This system was introduced by Liang et al. (1989) for methane estimation in cattle. Expired gases are collected into a plastic bag by using a plastic funnel; the plastic funnel is connected to the plastic bag through a tube that sucks the air. Samples of gases contained within the plastic bag are then analyzed by gas chromatography or other techniques. This solution is currently used often for methane estimation in small ruminants (Fernàndez et al., 2012), and it can be considered as an alternative solution to the ventilated hoods.

Tracer gas techniques. This group of gas measurement method includes several techniques characterized by the same main principle: measurements are made through the assessment of the amount of a tracer gas emitted from animals characterized by a constant tracer gas:methane emission ratio.

The *sulfur hexafluoride (SF_6) technique* is the most known tracer gas technique. It was developed by Johnson et al. (1994) and consists of a small permeation tube that contains a known amount of SF_6 that is inserted into the rumen. SF_6 was chosen because it has no effects on rumen microbial population. Before rumen insertion, SF_6 permeation ratio is checked in order to know the amount of the tracer gas released per unit of time. Expired gases are collected from the animal mouth by a tube positioned on the animal head and connected with a sampling canister fixed to the neck of the animal. Concentrations of CH_4 and SF_6 inside the canister are then analyzed by gas chromatography, considering that CH_4 and SF_6 are emitted with a fixed ratio. This system is suitable for *in vivo* methane estimation considering that it can be used on grazing animals and allows gas estimation for many animals at a time; however, it should be taken into account that only expired gases can be collected (Johnson et al., 1994; Zimmerman, 1992).

CO_2 is another gas used as tracer in methane estimations; in this system samples of expired air are taken near the animals, usually during milking procedures. The CO_2:CH_4 release ratio is known, because it has been calculated by several simultaneous direct measurements of CO_2 and CH_4 emissions within respiration chambers. The emitted amount of CH_4 is calculated through a mathematical proportion based on CO_2 recorded emissions (Madsen et al., 2010).

Meteorological techniques. All these techniques are based on direct measurement of flow of gases from the atmosphere; the amount of GHGs emitted by the animals is calculated comparing the GHGs concentrations of air collected in the presence of animals with those present in a sample of air collected without the animals (Harper et al., 2011).

The *tunnel method* was originally made for sheep and is composed of a big tunnel made of plastic that can be placed in a specific position in the pasture to measure the air flow temperature, velocity and composition while animals are grazing inside it. Air samples taken inside the tunnel are analyzed by gas chromatography or by infrared technique. This method can be easily used on grazing animals, it is not expensive and it can be used with many animals at the same time. Samples of outside air flow need to be analyzed periodically to know the characteristics of the air (Lockyer and Jarvis, 1995; Murray et al., 2007).

The *micrometeorological mass difference technique* was used by Harper et al. (1999). The methane estimation is made in the field, by placing several pipes, at different height levels from the ground, around the boundaries of the pasture where animals are grazing. Air samples can be taken and analyzed automatically following pre-determined intervals; gas analysis is performed by gas chromatography. It is a good estimation system for grazing animals because it is absolutely not invasive; however, velocity and direction of the wind strongly influence the results and unexpected changes of these meteorological elements can distort the final results.

1.4.2. In vitro estimation of methane

In vitro fermentation, measurement of archaeol concentration, rumen volatile fatty acid production, and milk fatty acid profile are four of the most used indirect methods for methane estimation. All these techniques need to be used in a laboratory, by estimating methane emissions from samples taken from animals or by recreating natural conditions in an artificial environment, to reproduce physiological reactions under controlled and monitored conditions.

In vitro *fermentation*. This technique, originally used to analyze rumen feed fermentation, feed digestibility and feed metabolizable energy (Goering and Van Soest, 1970; Menke et al., 1979), allows to estimate methane emissions of animals by reproducing rumen fermentations in artificial conditions. A sample of rumen fluid is collected from the rumen of the animal and is stored in anaerobic and monitored conditions, in order to maintain microbial activity. A fluid medium that contains several elements which promote microbial activity is prepared and added to the rumen fluid. The substrate that has to be fermented is prepared and added to the mixture. In vitro fermentation takes place within an incubation chamber where pressure, gases concentrations and temperature are kept constant. Samples are kept within hermetically sealed bottles, where gas samples are extracted through a needle. Gas samples are collected following regular intervals throughout fermentation and can be analyzed using several systems, such as infrared photo acoustic spectrometry-trace gas analyzer, mass spectroscopy, tunable diode laser absorption spectroscopy and gas chromatography. In vitro fermentation is a good method for methane estimation because the fermentation chamber can contain several samples at the same time and reliable results can be achieved in a short time, without using animals. However, in vitro fermentations do not mirror exactly what happens inside the rumen, because the interaction between the animal and the environment cannot be reproduced (Tedeschi et al., 2008a; Tedeschi et al., 2008b; Lopez and Newbold, 2007).

Archaeol concentration measurement. This is an indirect technique that measures archaeol (2,3-diphytanyl-O-*sn*-glycerol) concentration within animal feces, in order to determine the concentration of methanogens bacteria inside the rumen and, consequently, estimate the potential methane production. Archaeol is a lipid membrane that is present in methanogens Archaea and its concentration is measured by gas chromatography. Gas chromatography is performed after extraction, separation from the total lipid extract of feces, and trimethylsilylation of isolated alcohol fraction (MacCartney et al., 2012). The relationship between archaeol feces concentration and methane production was studied by Gill et al. (2011), who measured methane emissions from steers fed different forage/concentrate ratios by using the SF_6 technique and comparing CH_4 emissions rate with the archaeol concentration in the feces. The authors found a weak positive relationship between CH_4 emissions and archaeol concentration of feces ($r=0.55$; $P=0.05$), and suggested that more studies need to be conducted before implementing this estimation method.

Volatile fatty acid production. Volatile fatty acids (VFA) are some of the final products of rumen fermentation. The injection of ^{14}C-labelled VFA inside the rumen allows to calculate the VFA production rate; a stoichiometric relationship is applied in order to calculate the methane production level that can be achieved with a determined VFA synthesis level. VFA production inside the rumen generates different amounts of H_2, depending on what kind of VFA is produced. Acetate, butyrate and propionate are synthesized through several chemical reactions that produce different quantities of H_2; the amounts of each VFA produced are used to estimate the hypothetical methane production with an equation developed by Demeyer et al. (1975). This system is based on some principles: VFA are considered the only products that originate from CHO rumen fermentations; free H_2 that escapes from the rumen is not considered; only anaerobic processes can take place within the rumen; and H_2 is not used for other reactions in the rumen. Obviously, these principles are not always true and cannot happen simultaneously; as a consequence, this method tends to overestimate methane production from the rumen (Hegarty and Nolan, 2007).

Milk fatty acid profile. Dijkstra et al. (2011) made an indirect estimation of methane enteric emissions from dairy cows by comparing the milk fatty acid profile with the methane enteric emissions, directly measured in an open-circuit indirect respiration calorimetry chamber. Milk used for the fatty acid profile analysis was collected while the cow remained within the respiration chamber, to ensure a temporal correspondence between methane production and milk fatty acids synthesis. The CH_4 enteric emissions were correlated positively ($P<0.05$) with C14:0 iso, C15:0 iso, and C17:0 anteiso fatty acids and negatively ($P<0.05$) with several milk fatty acids that derive directly from ruminal biohydrogenation (e.g. C17:0 iso, cis-9 C17:1, cis-9 C18:1).

1.4.3. Estimation of nitrous oxide

Nitrous oxide measurements are taken directly in the emissions source, by measuring the gas production from manure, stored under different conditions or applied on pasture, and from cultivated soils or pasture lands. Slurry tanks and the chambers method are the most used systems for N_2O estimation and can also measure CH_4, O_2, CO_2 and many other gas emissions.

Slurry tanks. Several tanks are filled with manure and buried into the ground protruding 5 cm above the ground level; tanks are contained in an open dynamic chamber where incoming and outgoing air is collected and analyzed to measure gas emissions arising from manure (Amon et al., 1996).

Chambers method. Soil gas emissions can be detected by using three types of chambers: open chambers, closed static chambers and closed dynamic chambers. All of these chambers have the same structure: a box made of fiberglass and aluminum, which can have several dimensions (depending of the soil area that has to be analyzed), does not have an inferior base, and is inserted into the ground to a depth of 4.5 cm. *Open chambers* have a system of pumps that draws air inside the chambers, and then directs air outside, where there is a probe that extracts the gas samples for the analysis. *Closed static chambers* are placed on the ground and contain a chemical trap that absorbs for 24 hours the gas that must be analyzed. After 24 hours the amount of gas that was absorbed is determined, and divided by the soil surface and by the absorption time. *Closed dynamic chambers* are equal to the previous system with the difference that the amount of gas that is absorbed is checked following several time intervals (Li et al., 2000).

1.4.4. Analytical estimation of GHGs by equations and mathematical models

In vivo or *in vitro* measurements of GHGs are not always feasible, especially when estimations are referred to big areas, such as regions, countries or continents, because the application of in vivo or in vitro methods would be expensive and would require too much time. Equations and mathematical models allow the estimation of GHGs emissions when a large amount of animals and farms are considered. Analytical estimation methods are based on datasets derived from in vivo or in vitro measurements that are performed on a restricted sample; by applying regression equations, the amount of gas measured is associated with various predictors and then extended to many more animals or farms (Storm et al., 2012).

Table 1.4. The main GHGs within the atmosphere.

Name	Symbol
Carbon Dioxide	CO_2
Methane	CH_4
Nitrous Oxide	N_2O
Hydrofluorocarbons	**HFCs** (e.g., HFC-23 (CHF_3))
Perfluorocarbons	**PFCs** (CF_4, C_2F_6, C_3F_8, C_4F_{10})
Sulphur Hexafluoride	SF_6
Nitrogen Trifluoride	NF_3
Trifluoromethyl Sulphur Pentafluoride	SF_5CF_3
Halogenated Ethers	e.g., $C_4F_9OC_2H_5$, $CHF_2OCF_2OC_2F_4OCHF_2$
Other halocarbons	e.g., CF_3I, CH_2Br_2, $CHCl_3$, CH_3Cl, CH_2Cl_2

Many regression equations to estimate GHGs emissions have been published. They all derive from data obtained in respiration chambers, or from measurements of SF_6 or other direct estimations. The equations differ for the variables taken into account and for the predictions made (Bhatta et al., 2007).

Despite the large number of methods available for the CF estimation, there is still some confusion about the systems that can be used for this environmental issue. One of the main points of disagreement is the number of GHGs that has to be considered in the CF estimation (Pandey et al., 2011). The IPCC (2006a) classification includes the main greenhouse gases in Earth's atmosphere (Table 1.4). As explained before, each gas has a different greenhouse effect, and each one is emitted from different sources and at different amounts. Consequently, the selection of the GHGs that have to be considered within the CF estimation is affected by the emission sources present in the sector considered (Pandey et al., 2011).

Several methods of CF estimation do not have a specific sector of application. In this case, they can be considered as general models that contain rules and equations for the CF estimation, applicable to any kind of production sector. Within this group, the main differences between models concern the GHGs considered, and the origin of the equations present in the model (Table 1.5).

Table 1.5. Carbon footprint estimation methods applicable on all sectors.

MODEL	EMISSIONS	EQUATIONS
GHG Protocol of WRI	CO_2, CH_4, N_2O	IPCC (1997)
Annual GHG Inventory (EPA method)	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6	EPA (2013c)
ISO 14064/14065	CO_2, CH_4, N_2O	-
PAS 2050	CO_2, CH_4, N_2O	IPCC (2006 a), BS EN ISO 14021, BS EN ISO 14044
IPCC 2006	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3, SF_5CF_3, Halogenated Ethers, Other halocarbons	IPCC (2006a)

The IPCC 2006 method considers all of the most important GHGs within the atmosphere (Table 3). The Annual GHG Inventory, also named EPA (Environmental Protection Agency of United States) method, considers only CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (EPA, 2013c). The GHG protocol of the WRI (Word Resources Institute; WBCSD, 2012), the PAS 2050 model (PAS, 2011), and the ISO 14064/14065 normative (ISO, 2006b) considers only the three major GHGs (CO_2, CH_4, and N_2O).

The IPCC 2006 and the EPA methods contain only their own equations and coefficients; the GHG protocol of WRI is based on IPCC (1997) equations; the PAS 2050 model (PAS, 2011) is based on IPCC (2006) equations and on several ISO normatives (e.g. BS EN ISO 14021, BS EN ISO 14044), and the ISO 14064/14065 presents a set of rules for the CF estimation without providing specific equations.

1.4.5. The IPCC 2006 method

The "2006 IPCC Guidelines for National Greenhouse Gas Inventories" were developed by the Intergovernmental Panel on Climate Change (IPCC) to make an officially recognized system for GHGs estimation that could be used to measure the environmental impact from several sectors. An official method was required to compare different data calculated in different countries. The Guidelines are composed of 5 volumes: general guidance, energy, industry, agriculture and waste. Each volume of the IPCC Guidelines is divided into several chapters: chapter 10 of volume 4, entitled "Emissions from livestock and manure management", contains the equations and the coefficients used to estimate GHGs emissions from dairy farms. CH_4 emissions resulting from animals and manure, and direct and indirect N_2O emissions derived from manure can be calculated using this method. Each emission can be estimated using three different levels of accuracy. In fact, the IPCC method has three levels of analysis: Tier1, Tier 2 and Tier 3. The Tier system is equal for each sector and allows to obtain estimations with different levels of accuracy, depending on the number of variables that are considered.

Tier 1 is a synthetic estimation which uses a limited amount of information; estimations made with Tier 1 can be referred to big areas, such as countries and continents, and have a low level of accuracy. The Tier 2 estimation level can be used when more information is available; it can be used to reach a higher level of accuracy, and its estimations can be referred to smaller areas, such as regions, districts, cities, or even single industries. Tier 3 has basically the same equations and coefficients of Tier 2; however, it allows the insertion of equations of different origin and the use of coefficients related to the considered area on which estimation is going to be made (IPCC, 2006a).

1.4.6. The application of the IPCC 2006 method to the dairy sector

CH_4 emissions are calculated in Tier 1 using as inputs only the gross energy intake (GE) and the number of animals present in the farm. Tier 2 includes several equations that allow to obtain specific emission factors for CH_4 emissions, considering the feed and ration characteristics, animal characteristics, milk production, atmospheric temperature and manure management.

N_2O emissions are calculated with the Tier 1 using information about the GE, the number of animals and the manure management system. The Tier 2 considers also feed and ration characteristics, atmospheric temperature and many other variables that allow to obtain specific GHG estimations that can be referred even to single farms (IPCC, 2006b).

CH_4 and N_2O emissions can be calculated using the Tier 3 by replacing equations and coefficients of the IPCC (2006b), with equations calculated by different authors, equations created specifically for the considered analysis, and coefficients referred to the considered area.

CO_2 emissions from animals are not considered by the IPCC 2006 method; however, this method estimates the CO_2 emissions from crops and soils, realizing this estimation with the same three levels of accuracy described before (IPCC, 2006c).

1.5. CF estimation methods for the dairy sector

There is a large number of CF estimation approaches expressly realized for the dairy sector (Table 1.6). They basically differ for the selected boundaries within the entire dairy sector, for the measured GHGs, for the allocation system, for the functional unit, and for the equations and coefficients used for the estimation.

This review considers 27 CF estimations realized in different world regions, by several authors, in order to obtain a general overview on the approaches used to realize the CF estimation from the dairy sector (Table 1.6). Estimations were realized in different countries, analyzing different kinds of animals, farm characteristics, climate conditions, and managements.

The results showed that the CF was comprised between 0.37 and 13.78 kg of CO_2eq/kg of milk (Table 1.6). The high variability existing between these CF estimations can be explained comparing the models on the basis of the factors considered for the grouping realized in the Table 1.6, and on the basis of the amount of milk produced per cow recorded in each experiment (Table 1.6).

The CF is generally obtained dividing the GHGs emissions produced from a specific dairy system by the total amount of milk produced within that system; the milk production level is useful to compare different farms or systems, but it is also connected with different variables, such as nutrition, fertility, breed, quality of feeds, feed cultivation technologies, and many more, which can indirectly affect the final CF result.

It is a common practice to compare the CF results even if they are calculated using different functional units; however, within the Table 1.6, the CF results and the milk production levels of each farm are expressed in terms of fat and protein corrected milk (FPCM), by applying the IDF (2010) formula, in order to realize a valid comparison between these CF results.

Some authors, already comprised within the Table 1.5.1, were not considered within the Table 1.6, because information on milk production per cow and on milk characteristics (e.g. fat and protein content) were not available, and the FPCM could not be calculated.

1.5.1. The selection of the boundaries

One of the most important steps within CF estimation is represented by the selection of the farm boundaries; with this step it is possible to decide the emission sources that have to be considered. Within the selected approaches, two solutions for the farm boundaries selection were used: "from cradle-to-farm-gate" and "from cradle-to-grave". The first solution considered only the emissions that happen within farm boundaries; the second solution considered the entire dairy supply chain, following the product from its production to its consumption and disposal (ISO, 2006a).

Between the 27 estimations (Table 1.5.1), only 6 were realized using the "from cradle-to-grave" solution: Eide (2002), which obtained a CF equal to 500-650 kg CO_2 eq/FU; Fantin et al. (2012), which obtained a CF equal to 1.30 kg of CO_2eq/l of high quality (HQ) milk; Gerber et al. (2011), which obtained a CF equal to 0.50-0.65 kg of CO_2eq/kg of FPCM; Guerci et al. (2013a), which obtained a CF equal to 1.72 kg of CO_2eq/kg of milk; Thoma et al. (2013b), which obtained a CF equal to 1.77 kg of CO_2eq/kg of milk consumed by US consumer; Vitali et al. (2013), which obtained a CF equal to 1.10-1.22 kg of CO_2eq/l HQ milk.

It must be taken into account that the models were realized in different countries, using different emission factors, and the variability that exists between them can be correlated with these two elements. Between the 27 CF estimations considered, the preference observed for the "from cradle-to-farm-gate" boundaries solution (21 vs. 6) reflects a general trend existing within the CF estimation system.

In fact, as suggested by the IDF (2009), 80% of the GHGs emissions, on average, happen within the farm boundaries; this consideration has led many authors to restrict the boundaries of their analysis, considering only the emission sources within the farm. However, the selection of the boundaries can be affected by many other factors, such as the research funding, or the interests of the authors on specific steps of the milk supply chain (e.g. farm level if the estimation is realized to provide information for the farmers, milk processing level if the estimation is realized for the consumers or for the entire milk supply chain sector).

These differences can be observed comparing the estimation realized by Gerber et al. (2011) on the global dairy sector, with the estimation realized by Casey and Holden (2005) on the Irish dairy sector; obviously, the aims and the economic availabilities related to these 2 estimations were different.

The estimation of Gerber et al. (2011) required the largest amount of information, considering that analyzed the dairy sector on a global scale; this fact suggests that the financial resources used for this experiment could have been high, especially considering that the collection of the information used to estimate the CF on a global scale required the cooperation of several scientists from several nations. No mitigation solutions or suggestions were provided by Gerber et al (2011), considering that their research was realized to assess the GHGs emissions arising from the global dairy sector, and to assess the relation between the milk production level and the CF. The results can be used to inform people involved within the global dairy sector (e.g. farmers, managers, technicians of the dairy industries) on the environmental impact of the global dairy supply chain, considering that the estimation of Gerber et al. (2011) was realized with a "from cradle-to-grave" solution.

Casey and Holden (2005) realized a CF estimation on a representative Irish farm, using the average data referred to the Irish dairy system, in order to obtain a CF that could be applied to the entire national dairy sector; they also proposed 3 different mitigation solutions, simulating 3 "scenarios", each one texting a different mitigation solution. The simulations realized to investigate the mitigation solutions for the Irish dairy sector CF, made this research more complex than the one realized by Gerber et al. (2011). The results can be used to inform national farmers and consumers on the environmental impact of the Irish dairy sector, by referring only to the GHGs emissions that happen within the farm.

Thoma et al. (2013a) and Thoma et al. (2013b) used the same farms and the same model to predict the CF of the dairy sector. In the first experiment they chose the "from cradle-to-farm-gate" solution, obtaining a CF equal to 1.23 kg of CO_2eq/kg of FPCM; in the second experiment they chose the "from cradle-to-grave" solution, obtaining a CF equal to 1.77 kg of CO_2eq/kg of milk consumed by US consumers. The CF measured in the first experiment represents the 70% of the CF obtained in the second estimation, reaching a percentage below the IDF (2009) estimation.

Fantin et al. (2012) obtained a CF value equal to 1.30 kg of CO_2eq/l of HQ milk, analyzing the LCA of the HQ milk in Italy; they chose the "from cradle-to-grave" solution, following the life cycle of the HQ milk until the delivery to the distribution centers. However, they also calculate the percentage of the different impact categories that were attributable within the farm boundaries; the 82% of the GHGs emissions produced during the production processes of 1 liter of HQ milk derived from the farm boundaries.

Between the estimations that adopted the "from cradle-to-farm-gate" solution anyway exists a high variability, because within the farm there are many sources of emission that can be included or not. Bartl et al. (2011), Basset-Mens et al. (2009), and Capper et al. (2009), Guerci et al. (2013b), Guerci et al. (2013c), Guerci et al. (2013d), Penati et al. (2010), Thomassen et al. (2008), applied the IDF (2009) classification for the GHGs emissions, considering separately the emissions that happened on-farm and those happened off-farm, which have to be included using different emission factors. Rotz et al. (2010) used their own classification by dividing into primary and secondary the emissions that happened within the farm. Browne et al. (2011), Casey and Holden (2005), Cederberg and Flysjö (2004), Chianese et al. (2009), Flysjö et al. (2011), Haas et al. (2001), Hagemann et al. (2011), Kristensen et al. (2011), Lesschen et al. (2011), Pirlo and Carè (2013), Thoma et al. (2013a), and Vergé et al. (2007) did not use a different organization for the emissions estimated within the farm.

The CF range measured with the estimations listed above using the "from cradle-to-farm-gate" was included between 0.37 and 13.78 kg of CO_2eq/kg of milk.

1.5.2. The selection of the allocation system

The allocation, which represents the third step in the LCA procedure, is used to assign the GHGs emissions measured from a production system, to the products that are produced within it and that are responsible for those emissions (ISO, 2006a).

Within the dairy sector, more than one product is generally produced; besides the milk, many other products derive from this sector, such as meat from culled cows and surplus calves, manure sold outside of the farm, crops, and many more. Within the 19 approaches analyzed in this review (Table 1.5.1), many allocation solutions are used;

however, a comparison between the different CF on the basis of the allocation system is not feasible, because each model has its own dataset and the allocation is realized using different equations.

The allocation systems used for the 27 estimation approaches of the Table 1.5.1 were the no allocation system, mass allocation, economic allocation, biological allocation, physical allocation, system expansion allocation, and protein mass allocation.

Nevertheless, the researches of Casey and Holden (2005), Flysjö et al. (2011), Guerci et al. (2013d), Kristensen et al. (2011), Pirlo and Carè (2013), and Rotz et al. (2010) are different than the others; these authors realized the CF estimation testing more than one allocation system, in order to find which may be more suitable. For example, Casey and Holden (2005), estimating the CF of the Irish dairy sector, tested 3 different allocation systems between milk and meat. The no allocation solution involves assigning all the GHGs emissions to the milk; with this system Casey and Holden (2005) obtained a CF value equal to 1.50 kg of CO_2eq/kg of ECM. The economic allocation involves the distribution of the CF between milk and meat on the basis of their market prices; using this solution the authors obtained a CF equal to 1.30 kg of CO_2eq/kg of ECM. The mass allocation is applied distributing the CF between milk and meat on the basis of their produced quantities; Casey and Holden (2005) obtained a CF value equal to 1.45 kg of CO_2eq/kg of ECM by applying this last solution.

Kristensen et al. (2011), estimating the CF from 35 conventional and 32 organic dairy farms, applied 5 different allocation systems: mass allocation calculated with a model developed by the authors, protein mass allocation (distribution of the CF between milk and meat on the basis of their protein content), biological allocation (distribution of the CF between milk and meat on the basis of the energy required to produce them), economic allocation, and system expansion (distribution of the CF between milk and meat, comparing the CF produced from the meat production of other animals).

For the conventional and organic farms analyzed by the authors, the average CF was equal to:

- 1.04 kg of CO_2eq/kg of ECM applying the mass allocation model;
- 1.00 kg of CO_2eq/kg of ECM applying the protein mass allocation;
- 0.905 kg of CO_2eq/kg of ECM applying the biological allocation;
- 1.08 kg of CO_2eq/kg of ECM applying the economic allocation;
- 0.95 kg of CO_2eq/kg of ECM applying the system expansion allocation.

In both publications, the main difference can be observed between the CF obtained with the economic allocation, and the CF obtained with the biological allocation. These two solutions take into account two totally different elements, which are the economic value of the final products, and the amount of energy required for their production. The economic value is related to the market trends, the amount of energy required for milk and meat production is influenced by several physiological and chemical variables. These differences can explain the gap between the CF results obtained with these allocations.

1.5.3. The selection of the emission sources

Within all the factors considered in the classification of the 27 estimations (Table 1.5.1), the selection of the emission sources represents one of the most important factors that influenced the final CF result. The LCA of a dairy farm can take into account several environmental parameters, such as global warming potential, acidification, eutrophication, and many more. The global warming potential expresses the amount of GHGs emissions produced within a farm or within the dairy supply chain, and it is not influenced by the other environmental parameters, which are expressed with different unit of measure, and related to different sources of emissions. As a consequence, the inclusion of different environmental parameters within the CF estimation does not represent a factor that can change the final result.

Within the global warming potential, the number of emission sources considered can affect the final result. Chianese et al. (2009) obtained one of the lowest CF values between the 27 CF analyzed models, equal to 0.5-1.2 kg of CO_2eq/kg of milk. This result can be explained with the inclusion of the carbon sinks.

The carbon sinks are represented by all those biological elements that can absorb C from the environment. Crops, forests, and soils can be considered as carbon sinks, because by plants and soil respiration, and by the biomass crop accumulation, they can subtract CO_2 and CH_4 from the atmosphere (Chianese et al., 2009). Chianese et al. (2009) considered the soil and crops respiration within his CF model, providing two carbon sinks that allowed to reduce the final GHGs emissions amount.

Rotz et al. (2010) considered the CO_2 emitted by the animals for their respiration (that is an emissions source almost ignored by many authors, since it is considered equivalent to the carbon absorbed by plants), and they considered also the C balance that exists between the croplands and the atmosphere, obtaining a CF value equal to 0.37-0.69 kg of CO_2eq/kg of ECM.

Flysjö et al. (2011) and Guerci et al. (2013d) considered within the CF estimation the land use change factor (LUC), obtaining a CF value equal to 0.49-2.11 kg of CO_2eq/kg of ECM and 1.55-1.72 kg of CO_2eq/kg of FPCM, respectively; this factor estimates the CO_2 emissions that arise from a land use change. These emissions can be positive, when a natural land is transformed into a cropland (e.g. forest into soybean production land); it can be negative when a cropland is transformed back into a natural land.

Many other elements can be considered within the CF estimation, and their inclusion within the calculations can affect the final result; Rotz et al. (2010) included within the secondary emissions the GHGs that derived from the production of plastics, seeds, energy, fertilizers, and pesticides. On the other hand, several authors such as Cederberg and Flysjö (2004) and Besset-Mens et al. (2009) did not consider the secondary emissions that derived from the production processes of these materials; besides, Besset-Mens et al. (2009), Casey and Holden (2005), and many more authors did not consider the emissions related to the plastic use or to the seeds use, considering only the emissions that derived from the use of fertilizers and pesticides.

Guerci et al. (2013c), included the emissions that derived from the production of purchased feeds, but they did not used a default emission coefficient; a detailed dataset on the off-farm feed production processes was realized in order to obtain an accurate estimation regarding the production of the feeds (concentrates and seeds) realized outside of the farm boundaries. The information was referred to local animal feed factories, and the use of energy (electricity and fuels) was also considered.

1.5.4. The selection of equations and coefficients for the CF estimation

The choice of the equations and coefficients that have to be used for the CF estimation represents a crucial point within all the estimation phases. The IPCC (2006) method, as explained above, presents three levels of accuracy correlated with 3 levels of required information.

Among the 27 estimations selected for this review, Rotz et al. (2010), Gerber et al. (2011), and Lesschen et al. (2011) followed the IPCC (2006) method, using all its equations and coefficients. They obtained different CF values, equal to 0.37-0.69, 1.6-1.8, and 1.3 kg of CO_2eq/kg of milk, respectively. The CF estimation of Gerber et al.

(2011) was a large inventory referred to the global dairy sector, and the CF estimation of Lesschen et al. (2011) was also a large inventory referred to the Europe livestock sector; the choice of the Tier 2 was justified by the large amount of farms and animals considered, which did not allow the possibility to collect more information to realize a Tier 3. Rotz et al. (2010) realized the CF estimation of the dairy farms of Pennsylvania (USA) using the IPCC (2006) Tier 2 for the CH_4 and N_2O emissions calculation; however, they integrated the IPCC (2006) method by using different coefficients (gathered from literature) to estimate the primary and secondary emissions arising from the use of the energy within the farm, and from the production of fertilizers, pesticides, plastics, energy, and seeds used within the farm. The IPCC (2006) was used by Rotz et al. (2010) for the estimation of the N_2O produced from manure; the IPCC (2006) method suggests to multiply the amount of N excreted by the animals by different emission factors (EF) calculated by the IPCC (2006) on the basis of the atmospheric temperatures, and on the basis of the manure management solution adopted by the farm. To estimate the N_2O emissions produced from bedded pack and drylot surfaces Rotz et al. (2010) used the IPCC (2006) EF, whereas to estimate the N_2O emissions produced by slurry or liquid manure they used the coefficient of Olesen et al. (2006), which calculated the N_2O emissions on the basis of the m^2 of manure storage facilities. Rotz et al. (2010) obtained the lowest values considered in this review; it was due by the fact that they studied farms with high production level but moreover because their calculations accounted for many carbon sinks in the on farm production of animal feeds and soil organic matter (Chianese et al., 2009).

A modification of the Tier 2 was used by several authors, such as, Bartl et al. (2001), Basset-Mens et al. (2009), Guerci et al. (2013c), Kristensen et al. (2011), and Thomassen et al. (2008), who obtained a CF value included between 0.90 and 13.78 kg of CO_2eq/kg of milk. Within each one of these estimations, some IPCC coefficients and equations were substituted by coefficients referred to the farms or to the regions/nations considered, and by equations created by different authors that allowed to obtain a higher level of accuracy.

The difference that can be obtained using different accuracy levels in the CF estimation was verified by Guerci et al. (2013b); they realized the CF estimation on 29 dairy Italian cattle farms using the IPCC (2006) Tier 1 method, and a modified IPCC (2006) Tier 2 method. They obtained a CF equal to 1.15 kg of CO_2eq/kg of FPCM using the 1st solution, and a CF equal to 1.26 kg of CO_2eq/kg of FPCM using the 2nd method. The accurate method demonstrated to be more suitable when a complex and heterogeneous system has to be analyzed, because it allows to consider more variables that can affect the final result. The Tier 1 is more usable when the considered system does not present a high variability between the farms, and the research does not contemplate a deep accuracy level to achieve.

1.5.5. Milk production level and CF

As mentioned above, among the several factors that can affect the CF result, milk production level, in terms of kg of milk/year per cow, represents one of the most important factors. This fact is due to 2 main reasons: i) the CF of the dairy sector is expressed in terms of kg of CO_2eq per kg of milk (milk, ECM, FPCM, etc.), and considering that the CF is negatively correlated with the amount of milk produced (Figure 1.5.1), the amount of milk will influence the CF; ii) the amount of resources used to produce the milk (e.g. seeds, fertilizers, and energy used for crops production, kg of feed required by the animals for their maintenance and for their productions) can affect the CF considering that each one of them produce GHGs emissions.
This last concept was analyzed and explained by Capper et al. (2009), who compared the environmental impact of the US dairy sector between 1944 and 2007; among all the differences that the authors pointed out, the improvement of the productive efficiency between the two dairy system provided the most important factor that explained the reduction of the CF recorded between the two considered years. The amount of energy that one cow requires for its maintenance does not change when the cow improves its milk production level; there will be only an increment for the energy required for the production of the milk, and this increment will provoke a reduction in the percentage of the maintenance energy within the total requirements of the dairy cow.
Between 1944 and 2007 the number of dairy cows raised in the US decreased from 25.6 to 9.2 millions, but the amount of milk produced increased from 53 to 84 billion kg; this huge increment was provoked by the genetic improvement, by the selection of specialized breeds for milk production (e.g. Holstein vs. Jersey and Guernsey), by the introduction of feed rations specifically realized to optimize milk production. At the same time, the milk production gain was accompanied by a reduction of the CF (3.83 vs. 1.27 kg of CO_2eq/kg FPCM); this reduction was not only caused by the gain of milk production or by the reduction of the raised dairy cows. The introduction of the mixed

rations and the reduction in the use of pasture allowed to obtain a reduction of CH_4 enteric fermentations, and an increment of the amount of feed energy used for milk production instead of that used for methane production. The improvement of the agriculture sector allowed to produce more crops using a lower amount of land and other inputs, reducing the emissions of CO_2 and N_2O that are related with these practices.

The Table 1.5.2 reports 15 CF estimation results with their correspondent milk production levels; it is possible to observe that within the same milk production level, different CF were obtained. The explanation for this trend must be found analyzing all the differences that exist between the farms that obtained these different results.

The estimations realized by Capper et al. (2009) for the farms of 1944, Guerci et al. (2013d) for the Italian farms that practice the summer grazing in the Alps (SG), and Besset-Mens et al. (2009) showed a milk production level included between 2173 and 4218 kg of FPCM/year per cow, and a CF value included between 3.83 and 1.04 kg of CO_2eq/kg FPCM. The highest CF value of this subgroup was recorded by Capper et al. (2009) on the US dairy farms of 1944, and the explanation for of this result was already exposed above.

The remaining 2 CF results presented an high difference (1.04 vs. 1.72) even if they showed the same milk production level; however, Guerci et al. (2013d SG) realized in their estimation an accurate analysis on the off-farm feed production emissions, considering many more variables and emission sources compared to Besset-Mens et al. (2009), who did not consider all these factors, adopting only default coefficients.

Bartl et al. (2011) that measured the CF in the coastal farms of Perú, Casey and Holden (2005) and Penati et al. (2010) presented the same milk production level, which was include between 5041 and 5868 kg of FPCM/year per cow. The CF measured in these 3 researches was included between 1.14 and 3.15 kg of CO_2eq/kg FPCM. There is a large difference between the CF obtained by Bartl et al. (2011) and the CF obtained by Penati et al. (2010); in fact, these 2 research presented the same milk production level (5016 vs. 5868 kg of FPCM/year per cow), but a different CF result (1.14 vs. 3.15 kg of CO_2eq/kg FPCM). The estimation of Bartl et al. (2011) was realized in the coastal regions of Perú, on not specialized cows, raised within farms that presented a low technology level.

Guerci et al. (2013d) with the estimation of the CF realized on the no summer grazing Italian dairy farms (no SG), Pirlo and Carè (2013), Kristensen et al. (2011), Rotz et al.

(2010), Thomassen et al. (2008), Cederberg and Flysjö (2004), Capper et al. (2009) with the estimation of the CF on the US farms of 2007, Flysjö et al. (2011), and Guerci et al. (2013c) obtained a CF included between 0.55 and 1.55 kg of CO_2eq/kg FPCM, with a milk production level included between 7016 and 10299 kg of FPCM/year per cow.

Rotz et al. (2010) obtained the lowest CF value (0.55 kg CO_2eq/kg FPCM), but they did not obtained the highest milk production level, as it was expected. This fact can be explained considering the C sinks included in this estimation that allowed to reduce the final CF result.

Besides, Guerci et al. (2013c), as explained before, did not used default coefficients to estimate the emissions that were produced during the off-farm feed production processes, but they realized an accurate estimation on the entire process including many more emission sources, that probably influenced the final CF result.

The CF obtained by Kristensen et al. (2011) was equal to 0.92 kg CO_2eq/kg FPCM, and it was similar to the CF estimation obtained by Besset-Mens et al. (2009) that was equal to 1.04 kg CO_2eq/kg FPCM. However, the milk production levels obtained in these 2 estimations were different (4218 vs. 8300 kg of FPCM/year per cow), and the milk production level measured by Kristensen et al. (2011) was the 50% higher than the one measured by Besset-Mens et al. (2009), despite a difference between the CF values equal to the 11%. The result obtained by Besset-Mens et al. (2009) represents the average CF calculated for the dairy cow systems of New Zealand; the coefficients used for this estimation were the same for the 4 systems because the authors applied only default values selected from the IPCC-NZ methodology, from national inventory data, and from national literature. They used one coefficient for the enteric CH_4 emissions, one coefficient for the manure CH_4 emissions, and a fixed N amount of fertilizers per hectare, on the basis of national inventories.

The result obtained by Kristensen et al. (2011) represents the average CF calculated comparing 35 conventional dairy farms with 32 organic dairy farms in Denmark. The CH_4 estimation was realized using the IPCC (2006) on the basis of the DMI measured each month for each farm; the DMI of the animals that were partially feed on pasture was measured by subtracting the amount of DMI provided with the supplement from the total DMI that the animal should receive daily on the basis of its energy requirements. The amount of excreted manure was estimated on the basis of the DMI, and the amount of manure deposited on pasture was estimated considering the time spent outside by the animals. The N_2O emissions from manure were estimated on the basis of the N excreted, calculated considering the N intake and the N contained in the animal productions (milk and meat). The N_2O emitted from the soils was estimated using different coefficients on the basis of the different N sources applied to the soil (fertilizers, manure, crop residues). Secondary emissions from land use and imported feeds were also considered.

The more detailed estimation realized by Kristensen et al. (2011) considered many more variables compared to the one realized by Besset-Mens et al. (2009), and this fact can justifies the higher CF value obtained by Kristensen et al. (2011), despite the higher milk production level recorded in their farms.

Furthermore, the estimation of Besset-Mens et al. (2009) presents a CF result close to the one obtained by Cederberg and Flysjö (2004), that was equal to 0.97 kg CO_2eq/kg FPCM, who however presented a milk production level equal to 8529 kg of FPCM/year per cow. Even in this case, the explanation for these similar results, obtained despite a huge difference between the milk production levels, can be related to the amount of variables considered by the authors. Cederberg and Flysjö (2004) considered the same variables of Kristensen et al. (2011), calculating the GHGs emissions using the IPCC (1996) method. Besides, they realized the CF estimation accounting all the animal categories of the farm (dairy cows, young heifers, older heifers, calves), considering also the estimations that derived from pesticides and plastic production and use, and realizing a different estimation for the emissions that derive from the production processes realized for the production of the feed concentrates on-farm and off-farm.

Different CF values can be compared only if there is a similarity between the characteristics of the considered farms, including even the raised breeds, the climate conditions, the technology level, and the time interval.

The very large difference that exists between the CF obtained by Rotz et al. (2010), equal to 0.55 kg of CO_2eq/kg of FPCM, and the CF obtained by Capper et al. (2009) in the US farms of 1944, equal to 3.83 kg of CO_2eq/kg of FPCM, can be explained analyzing all the characteristics of the farms, and considering the dramatic discrepancy that exists between the considered systems. A valid comparison between CF results can be obtained considering similar estimation conditions; if the conditions are not similar, it could be appropriate to exclude all the variables that are not present in all the estimations compared.

Table 2.6. Overview of some models for the greenhouse gases estimation from the dairy cow sector.

Author & Country	Method	Boundaries	Considered emissions	References	Allocation system	Functional unit	Result
Bartl et al., 2011 (Perú)	LCA applied to two smallholder milk production systems in Perú (highlands and coast)	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication	IPCC (2003) and various authors	Economic allocation	1 kg of ECM (ALP, 2006)	3.18-13.78 kg CO_2eq/kg ECM (coast farm vs.highlands farm)
Basset-Mens et al., 2009 (New Zealand)	LCA applied to four dairy farm systems	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication, energy use, and land use	MfE (2006) and various authors	Biological allocation	1 kg of milk; 1 hectare	0.64-0.93 kg CO_2eq/kg milk
Browne et al., 2011 (Australia)	Agricultural GHGs emissions modeled for 14 representative farms	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (1997), DCCEE (2009)	Mass allocation	1 kg of MFP (Sjaunja et al., 1991)	0.85-0.94 kg CO_2eq/kg MFP
Capper et al., 2009 (USA)	Comparison between the environmental impact of modern and historical dairy production practices (1944 vs. 2007)	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006), US EPA (2007), USDA/NASS (2006), USDA/NASS (2007)	No allocation	1 kg of milk	3.66 vs. 1.35 kg CO_2eq/kg milk

Table 1.6. (continued).

Author & Country	Method	Boundaries	Considered emissions	References	Allocation system	Functional unit	Result
Casey and Holden, 2005 (Ireland)	Partial LCA applied to the Irish dairy system	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (1996b), EPA (1998), and various authors	No allocation, mass allocation, and economic allocation	1 kg of ECM (Sjaunja et al., 1991)	1.30-1.50 kg CO_2 eq/kg ECM
Cederberg and Flysjö, 2004 (Sweden)	LCA applied to 23 dairy farms	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication, energy use, and land use	IPCC (1996b), IPCC (1997), IPCC (2000), and various authors	Economic allocation	1 kg of ECM	0.76-1.26 kg CO_2 eq/kg ECM
Chianese et al., 2009 (USA)	Estimation of GHGs emissions from a representative dairy farm	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O), and soil respiration	Various authors	No allocation	1 kg of milk	0.5-1.2 CO_2 eq/kg milk
Eide, 2002 (Norway)	Total LCA of Norwegian dairy farms	From cradle-to-grave	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication, depletion of stratospheric ozone, ecotoxicity	IPCC (1996b), EPA (1998), and various authors	Biological allocation	1,000 liters of drinking milk brought to the consumers	500-650 kg CO_2 eq/FU

Table 1.6. (continued).

Author & Country	Method	Boundaries	Considered emissions	References	Allocation system	Functional unit	Result
Fantin et al., 2012 (Italy)	LCA of Italian high quality milk (HQ) production	From cradle-to-grave	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication, ozone depletion, resources with or without energy content, photochemical oxidation	IPCC (2006), and various authors	no allocation	1 liter of HQ milk	1.3 kg CO_2eq/ l of HQ milk
Flysjö et al., 2011 (Sweden)	Partial LCA applied to 23 dairy farms to investigate the link between milk and beef production	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O), land use change	IPCC (1996b), IPCC (1997), IPCC (2000), and various authors	Economic allocation by system expansion	1 kg of ECM	0.49-2.11 kg CO_2eq/kg ECM
Gerber et al., 2011 (World)	LCA on 155 countries to assess the GHG emissions of the dairy system on a global scale	From cradle-to-grave	Global warning potential (CO_2, CH_4, N_2O	Various authors	Protein mass allocation	1 kg of FPCM	1.6-1.8 kg CO_2eq/kg FPCM
Guerci et al., 2013a (Italy)	Carbon footprint of pasteurized liquid milk	From cradle-to-grave + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006), Ecoinvent (2007)	Biological allocation	1 kg of pasteurized milk	1.72 kg CO_2eq/kg milk

Table 1.6. (continued).

Model & Country	Method	Boundaries	Considered emissions	References	Allocation system	Functional unit (FU)	Result
Guerci et al., 2013b (Italy)	Estimation of Carbon footprint using different methods	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006), and various authors	Biological allocation (IDF, 2010)	1 kg of FPCM	1.15-1.26 kg CO_2eq/kg FPCM
Guerci et al., 2013c (Italy)	Environmental impact of 41 intensive dairy farms	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)Acidification, Eutrophication, energy use, and land use	IPCC (2006), and various authors	Economic allocation	1 kg of FPCM	1.30 kg CO_2eq/kg FPCM
Guerci et al., 2013d (Italy)	Effect of summer grazing on carbon footprint of milk in Italian Alps	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O) and land use change	IPCC (2006), and various authors	No allocation, economic, nitrogen mass, and mass allocation	1 kg of FPCM	1.55-1.72 kg CO_2eq/ kg FPCM
Haas et al., 2001 (Germany)	LCA for 18 grassland farms in three different farming intensities	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O), Acidification, Eutrophication	IPCC (1996)	Protein mass allocation	1 tonne of milk	1.0-1.3 t CO_2 eq/ tonne of milk
Hagemann et al., 2011 (World)	Quantification of GHGs emissions of bovine milk production systems of 38 countries	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (1996), IPCC (2007), and various authors	Biological allocation	1 kg of ECM (GFE, 2001)	1.0-3.07 kg CO_2 eq/kg ECM

Table 1.6. (continued).

Model & Country	Method	Boundaries	Considered emissions	References	Allocation system	Functional unit (FU)	Result
Kristensen et al., 2011 (Denmark)	Partial LCA to estimate the GHGs emissions and the land use on commercial dairy farms	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O) and land use	IPCC (2006), and various authors	Protein mass, economic, biological, system expansion	1 kg of ECM (Sjaunja et al., 1991)	0.9-1.10 kg CO_2 eq/kg ECM
Lesschen et al., 2011 (Europe)	GHGs emissions in the 27 Members States of the European Union (EU-27)	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	MITERRA-Europe, CAPRI, GAINS and IPCC (2006)	Mass allocation	1 kg of milk	1.3 kg CO_2eq/kg milk
Penati et al., 2010 (Italy)	Effect of farming system changes on LCA indicators for dairy farms in the Italian Alps	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)acidification, eutrophication, non-renewable energy use, and land use	-	Economic allocation	1 kg of FPCM	1.13 kg CO_2eq/kg FPCM
Pirlo et al., 2013 (Italy)	GHGs emission estimation of 4 simulated Italian dairy farm models	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006), ISPRA (2008), and various authors	No allocation, physical, and economic allocation	1 kg of FPCM	0.89-1.22 kg CO_2eq/kg FPCM
Rotz et al., 2010 (USA)	Partial LCA for dairy farms of various size	From cradle-to-farm-gate + primary and secondary emissions	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006), and various authors	Economic allocation	1 kg of ECM	0.37-0.69 kg CO_2eq/kg ECM

Table 1.6. (continued).

Model & Country	Methodology	Boundaries	Considered emissions	References	Allocation system	Functional unit (FU)	Result
Thoma et al., 2013a (USA)	Partial LCA of GHGs emissions from 536 dairy farms	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006)	Biological allocation (IDF, 2010)	1 kg of FPCM (NRC, 2001)	1.23 kg CO_2 eq/kg FPCM
Thoma et al., 2013b (USA)	Total LCA of GHGs emissions from 536 milk supply chains	From cradle-to-grave	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2006)	Different allocation systems, depending on the considered product	1 kg of milk consumed by US consumers	1.77 kg CO_2 eq/FU
Thomassen et al., 2008 (Netherlands)	Partial LCA of environmental impact from 21dairy farms	From cradle-to-farm-gate + on-farm and off-farm emissions	Global warning potential (CO_2, CH_4, N_2O)acidification, eutrophication, energy use, and land use	IPCC (2006), and various authors	Economic allocation	1 kg of FPCM	1.4-1.5 kg CO_2 eq/kg FPCM
Vergé et al., 2007 (Canada)	GHGs emission estimation of dairy system for 5 regions	From cradle-to-farm-gate	Global warning potential (CO_2, CH_4, N_2O)	IPCC (2000), and various authors	No allocation	1 kg of milk	1.02 kg CO_2 eq/kg milk
Vitali et al., 2013 (Italy)	LCA of HQ bovine milk	From cradle-to-grave	Global warning potential (CO_2, CH_4, N_2O), acidification, eutrophication, water footprint	IPCC (2006), ISPRA (2011), CRPA (2001)	mass allocation	1 liter of HQ milk	1.10-1.22 kg CO_2 eq/l HQ milk

Table 1.7. Milk production level per cow and Carbon footprint results for 14 CF estimation approaches.

Author	Milk production (kg FPCM*/year per cow)	CF (kg CO_2eq/ kg FPCM)
Capper et al., 2009 (farms of 1944)	2172.9	3.83
Guerci et al., 2013d (SG farms)	4131.5	1.72
Besset-Mens et al., 2009	4217.7	1.04
Casey and Holden, 2005	5041.5	1.42
Bartl et al., 2011 (coastal)	5815.8	3.15
Penati et al., 2010	5868.4	1.14
Guerci et al., 2013d (noSG farms)	7016.2	1.55
Pirlo and Caré, 2013	8097.1	1.05
Kristensen et al., 2011	8300.6	0.92
Rotz et al., 2010	8307.5	0.55
Thomassen et al., 2008	8478.5	1.49
Cederberg and Flysjö, 2004	8528.6	0.97
Capper et al., 2009 (farms of 2007)	8664.2	1.27
Flysjö et al., 2011	10222.6	1.40
Guerci et al., 2013c	10298.8	1.30

*milk yield per cow was standardized at 4% fat and 3.3% protein using the IDF (2010) formula for the fat and protein corrected milk.

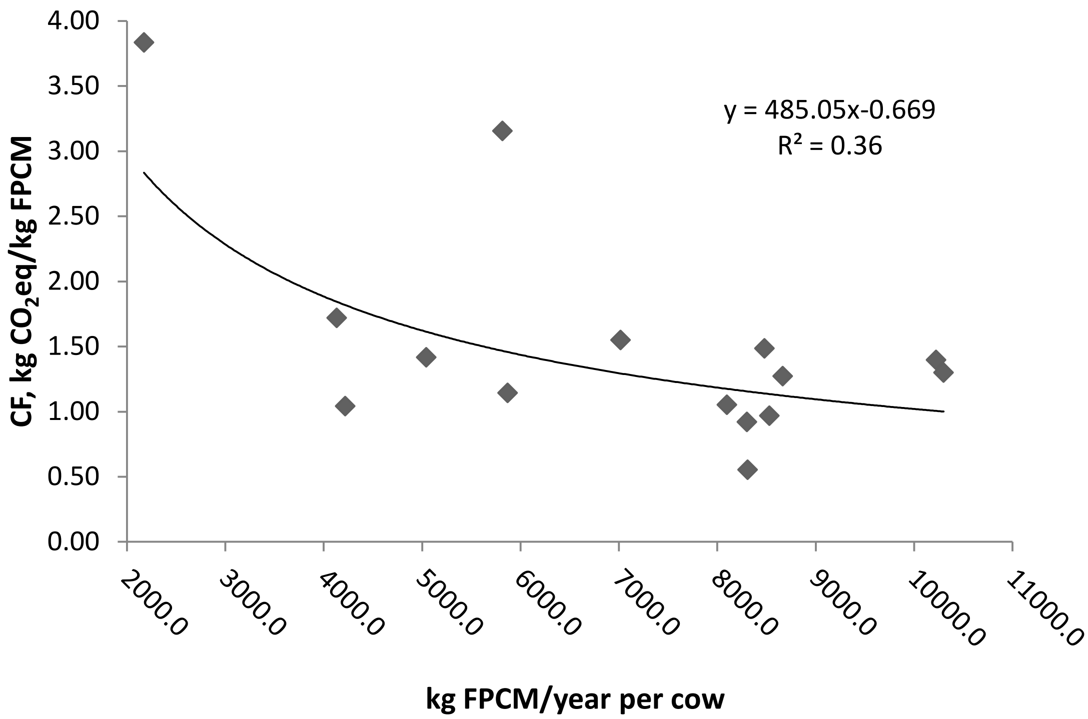

Figure 3.5. Regression of CF on milk production level observed by 14 authors.

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Chapter 2

Carbon Footprint of Southern Italy dairy cattle farms

2.1 Introduction

The dairy chain represents a good example of complex production system set to produce milk as final output. Within a dairy farm a multiple flow of materials and products occurs, involving many different areas such as animal feed production, herd turnover, manure management, crop fertilization and energy consumption (FAO, 2013). Similarly, the quantification of the environmental impact attributable to one defined product is often complex because, in most cases, the final product comes from different production chains, and it is almost impossible to estimate its impact without considering all its life cycle (IDF, 2010). The measure of the environmental impact of a given product (or process) in terms of CO_2 equivalent (CO_2eq) emissions in the unit of time is called Carbon footprint (EPA, glossary). Several studies (e.g. Cederberg et al., 2004; Casey and Holden, 2005; Thomassen et al., 2008; IDF, 2010; Penati et al., 2010; Pirlo and Carè, 2013; Rotz et al., 2010; Gerber et al. 2011; Guerci, 2012; Guerci et al., 2013a) were realized to measure the greenhouses gases (GHGs) emissions resulting from the production of a liter of milk in different countries, production areas and livestock systems within areas. If large inventories are needed to quantify the livestock contribution to anthropogenic emissions, the quantification at local level is furthermore necessary to quantify the contribution of the farms and their products to atmospheric pollution (Browne et al., 2011), to plan mitigation strategies to be applied by different livestock systems (Phetteplace et al., 2001), and to obtain large information to perform analysis of economic and environmental costs and benefits related with GHGs reduction plans and social benefits (Thoma et al., 2010b).

Milk production and GHG emissions of dairy farms are strongly affected by raised breeds, dairy herds feed and management, barn facilities and housing type, manure management, crop cultivation techniques, energy consumptions (Cederberg and Flysjö, 2004; Besset-Mens et al., 2009; Capper et al., 2009). In addition, local climate characteristics and meteorological variables, such as high temperature and humidity, have direct effects on CO_2, CH_4 and N_2O emissions that derive from manure management and crops (Yamulki, 2006), indirect effects on emissions due to the strongly influence on animal performances (feed intake and/or milk production and quality, and nitrogen excretion; Bouraoui et al., 2002) and on crop production (yield, fiber quality).

The dairy sector of Southern Italy (Basilicata, Calabria, Campania, Molise, Puglia, Sardegna, and Sicilia), includes 1/3 of the total number of Italian dairy farms; among these farms, 10% of the Italian bovine milk is produced (CLAL, 2013). The south of Italy also presents specific climatic conditions that are different than the rest of national territory (CMI, 2012); winds, floods, hot and dry summers, and extended drought periods can negatively affect crops productions and animal performances, influencing also the production levels and the environmental impacts. In this area farm management is really connected with local productions and local traditions, and sometimes farm's productivity is not affected by the competition that exists between national and global markets (Boccaletti and Moro, 2012). However a large part of the produced milk is collected by large cooperatives, processed within innovative plants, and sold in regional target markets or exported in the world trade. These cooperatives are currently pursuing some common production objectives, which include improvements of farm production efficiency, standardization of the product quality and quantification and amelioration of environmental performance, in order to allow to the local milk supply chain to get standards of production similar to other strategic production areas of the world. In this context, a partial evaluation of the environmental performances of these systems can be calculated quantifying the CF of the produced milk.

Equations and mathematical models allow to estimate GHGs emissions when a large amount of animals and farms are considered (Storm et al., 2012). The IPCC (2006a) suggests a standard method that can be used to perform the CF estimation at farm level, in order to estimate the emissions from the main farm emission sources and compare the results with estimations completed elsewhere in the world. The integration of the IPCC (2006a) method with equations adapted for local conditions might: i) help to highlight the differences between the observed GHGs emissions, which can be caused by different techniques and strategies adopted for animals and crops management, and for the energy use within the farm; ii) favour the elaboration of emission mitigation strategies.

The aim of this work was to estimate the CF in terms of CO_2eq emissions per liter of FPCM sold, in a sample of dairy farms selected from 4 milk cooperatives operating in the South of Italy. A more specific objective was to define the incidence of the main emission sources in respect to total emissions, the range of variability of the emissions and to obtain indication and useful information for the future mitigation strategies planning at farm level.

2.2. Materials and methods

The study was conducted on a sample of farms associated with 4 cooperatives operating in Southern Italy (3A for Sardinia, Granarolo for Puglia and Basilicata, Asso.La.C. for Calabria, Progetto Natura for Sicilia). An initial screening of the 1067 associated farms was performed. The screening was performed with a simplified survey mailed to the farms. About the 85% of the farms returned the simplified survey. In order to obtain a representative sample of adopted livestock systems, the surveyed farms were classified according to the following variables: farm localization (3 groups: hill, flat area, mountain), number of raised cows (4 groups: 0-19, 20-70, 71-149, 150-700 animals); milk production level (4 groups: <3.5, 3.5-7.0, 7.1-9.5, >9.5 t/year of milk per cow); housing type for lactating cows (3 groups: bedded-pack, cubicles, pasture); presence or absence of energy production plants from renewable resources (2 groups). About the 30% of farm from each class was selected within each cooperative.

The selected sample included 285 farms among all cooperatives (A = 83 farms; B = 88 = farms; C = 44 farms; D = 70 farms). A detailed survey was realized in order to collect farm data and the information needed for the CF estimation. The questionnaire consisted of four sections. The first section required general information (location, owned land, raised animal categories, labor, etc). The second section required information about herd consistency, and feeding and manure management adopted for each animal group. The third section required information about farm's energy utilization, equipment and tools characteristics, machines and farm operations, milking plant, irrigation, and energy production plants. The fourth section required the information related to crops cultivation and crops yield, and to farm lands management and fertilizations. The survey was administered to the farmers by specifically trained experts of the same cooperatives on the year 2012. The time interval considered for the CF estimation was equal to 12 months (October 1st, 2010 – September 30th, 2011).

The information collected with the detailed questionnaire were implemented in a file Excel® in order to perform the calculations of GHGs emissions. The IPCC (2006a) estimation method was chosen to calculate the emissions from animals, manure management, and crop cultivation. Coefficients used to calculate GHGs emissions derived from farm energy consumptions and production were estimated using published standard coefficients adaptable to the national conditions.

Within the 3 Tiers suggested by IPCC (2006a), the Tier 2 was used to calculate methane emissions from manure management and nitrous oxide emissions from crop cultivation.

The use of equations and coefficients that are not included in the IPCC Guidelines is contemplated in the IPCC Tier 3 method, in order to provide a more detailed estimation. The Tier 3 (IPCC, 2006a) was used i) to estimate methane enteric emissions by including the detail of the monthly consistency of the animal categories, and the estimation of the diet energy digestibility by using the equation of Sauvant and Giger-Riverdin (2009) and the proportion of gross energy (GE) emitted as methane (Ym) from Gerber et al., (2011); ii) to estimate N volatilization losses from manure by using the equations of Atzori et al. (2008; 2009) developed for dairy cattle farms located in Mediterranean climate conditions; iii) to estimate the GHGs emissions derived from energy utilization by performing an energetic audit during the farm information record.

The CO_2 absorption by plants and CO_2 emissions from animal respiration, manure and soils were not accounted for in this research, considering those as accounted for in the short term biogenic carbon cycle (IDF, 2010).

Following the Life Cycle Assessment (LCA) procedure (ISO, 2006), the selected system boundaries included only the emissions “from-cradle-to-farm-gate”, considering only emissions generated from the input production until the milk storage in farm facilities (i.e. transport of milk from farm to processing plant was excluded).

All the emissions produced within farm’s boundaries were classified in two different ways, i) primary and secondary emissions as defined in Rotz et al. (2010) and ii) on-farm and off-farm emissions as defined by IDF (2010). Among primary emissions were included animal enteric fermentations, manure management, crop cultivation and fuel use, whereas among secondary emissions were included those which derive from production process of fertilizers, pesticides, seeds, fossil fuels, electricity, and every kind of materials or energy’s sources used on-farm or for off-farm feed production. Among on-farm emissions all those emissions that happen within farm boundaries were considered, even if they derive from other production processes (e.g. use of fertilizers and pesticides for crop cultivation, fuel); the off-farm emissions regarded all those processes that happen outside of farm’s boundaries, but they are related with one process or with one activity realized within farm’s boundaries (e.g. emissions that derive from feed purchased in the market).

CF estimation from animals

All the animals recorded within each farm were divided into three categories: lactating cows, dry cows, and young animals; this last group was divided in three subgroups:

unweaned calves, open heifers and bred heifers. The number of replacement calves was also separately recorded.

The amount of monthly milk production of each farm was obtained from the cooperatives records and converted into fat and protein corrected milk (FPCM; milk composition equal to 4.0% of fat and 3.6% of crude protein) using the equation suggested by IDF (2010):

FPCM (kg) = milk (kg) * (0.1226 * fat % + 0.0776 * protein % + 0.2534) [1]

The production level of the herd was obtained dividing the total amount of milk sold per month by the average number of mature cows present within the herd in the same month.

Enteric CH_4 emissions were calculated on the basis of the herd energy requirements. Animal net energy (NE) requirements were estimated and converted in digestible energy (DE) using the equations summarized in Table 10.3 of IPCC (2006b).

The DE of the ration, used to convert DE into GE for each cattle category, was estimated using the equation of Sauvant and Giger-Riverdin (2009):

DE (% of GE) = 59.3 + 21.2 * concentrate of ration (%) [3]

The percentage of concentrates of ration was calculated from diet formula information reported in the survey. Corn silage was considered as forage only for the 65% of its DM content.

Diet energy digestibility (DE) was used to convert the DE in to GE.

The production of methane was calculated as

Methane (kg/d per head) = (GE intake * Ym) / 55.65 [2]

Where: Ym = % of gross energy intake converted into methane derived from the digestibility rate of feed, by applying the equation of Gerber et al. (2012): Ym (% of GE) = 9.75 – (0.05*DE %); 55.65 the energy content of methane MJ/kg CH_4).

Total enteric emissions (kg CH_4/yr) were obtained multiplying the emissions calculated monthly for an average animal category by the number of animals, and adding the results obtained for each category for the entire year of available data.

Manure CH_4 emissions were calculated as percentage of volatile solid excreted. The IPCC equations were used to obtain the daily volatile solids excretion (VS) of each animal category:

VS (kg/day per head) = [GEI * (1-DE% /100) + (UE * GEI)] * [(1-ASH)/18.45] [4]

Where: GEI = gross energy intake (Mj/d per head); UE*GEI = urinary energy expressed as (0.04*GEI for most ruminants); ASH = the ash content of manure calculated as a fraction of the dry matter (DM) feed intake (0.08 for cattle); 18.45 = conversion factor for dietary GE per kg of DM (Mj kg^{-1}).

The percentage of manure converted into methane (MCF) were obtained by regressing the values of MCF reported in the Tables 10A-4 of the IPCC (2006b), on the respective air temperatures of the same table for each manure management system considered:

MCF 1, % (liquid/slurry) = $0.1351*T^2-1.5573*T+19.494$ [5]

MCF 2, % (solid manure) = $- 0.0193*T^2 + 0.883*T- 4.8977$ [6]

MCF 3, % (pasture) = $- 0.0034*T^2+0.1852*T-0.5114$ [7]

Where T is the monthly average atmospheric temperature (in °C) recorded within the district where the farm is located obtained from historical averages of CRA-CMA, (2013).

Estimation of VS and MCF were combined in the calculation of the emission factor of manure (EF_{man}) from excretion to end of storage before land application:

$\mathbf{EF_{man}}$ = (VS*365)*[B_0*0.67*(MCF/100)] [8]

Where: B_0 = maximum methane producing capacity, m^3 CH_4 kg^{-1}, Tables 10A-4 and 10A-5 (IPCC, 2006b); 0.67 = conversion factor of m^3 CH_4 to kilograms CH_4.

Total methane manure emissions (kg CH_4/yr) were obtained multiplying the EF_{man} calculated for each animal category by the number of animals within each category, and adding than the results obtained for each animal category.

N_2O emissions from manure were estimated as a percentage of direct and indirect emissions from N excreted by animals during the reference year.

N excreted (N_{exc}) per each animal category was calculated by a nutrient balance (Mainard and Loosli, 1969):

$\mathbf{N_{exc}}$ (kg/d per head) = [DMI (kg of DM/d) * N diet (% DM)] – N in products [9]

Where: DMI intake was calculated as GE/18.45 (IPCC, 2006b); N diet was calculated based on the ration reported in the survey for each animal category, on the average protein content of each common feed from the archive of Licitra et al., (2006) and on the protein content of commercial mixes using survey values; N of animal production estimated using the NRC (2001) equations = N in milk for dairy cows; N requirements for growth for young animals; N requirements for pregnancy for pregnant cows.

The N_2O direct emissions were estimated for each animal category using this equation:

N_2O direct emissions (kg/d/head) = N_{stored} * EF_{dirN2O} * 44/28 [10]

Where: EF_{dirN2O} = IPCC (2006b) emission factors as function of manure management system that corresponded to 0.005 for liquid slurry, 0.015 for bedded-pack barns, 0.02 for pasture; 44/28 = conversion factor for N_2O-N to N_2O; N_{stored} = was calculated as remaining N in the manure subtracting the volatilized N (N_{vol}) from the excreted N (N_{exc}).

The amount of N lost by volatilization (N_{vol}) was calculated applying coefficients of nitrogen volatilization losses developed for Mediterranean conditions (Atzori et al., 2008; 2009):

N_{vol} in liquid manure management system = N_{exc}* (1.39 * T + 18.51) [11]

N_{vol} in bed-pack = N_{exc}* 036 for young animals; N_{exc}* 0.40 for dairy cows [12]

Where: T is the monthly average atmospheric temperature (in °C) recorded within the district where the farm is located obtained from historical averages of CRA-CMA, (2013).

Indirect N_2O emissions from manure derive from the N_{vol}, and they are calculated with the following IPCC (2006) equation:

N_2O indirect emissions (kg/d/head) = N_{vol} * $EF_{indirN2O}$ * 44/28 [13]

Where: $EF_{indirN2O}$ = IPCC (2006b) emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces; default value of 0.01 (IPCC, 2006c).

The GHGs emissions produced by animal enteric fermentations and manure management can be classified as primary emissions, because they are produced directly from the animals and from manure, without involving secondary products or processes. All these emissions have also to be included among the on-farm emission group, because they always start within farm's boundaries. No secondary emissions and no off-farm emissions were recorded from these sources.

CF estimation from farm energy consumptions

CO_2 emissions arising from the use of electricity, oil and gas were calculated by the analysis of the energy farm's consumptions. Energy consumptions were estimated from an energetic audit that allowed performing the estimation with a TIER 3 accuracy level of IPCC (2006).

Electric utilities consumptions were calculated on the basis of the farm equipments, machines power, and on the basis of their time of use. The operations considered are: milking procedures, milk refrigeration, manure management, ventilation and nebulization, animal brushing, water pumping, farm lighting and water heating.

Diesel's consumptions were obtained by evaluating all farm operations realized using every kind of machinery powered by diesel, such as animal feed rations preparation and distribution, manure management and agricultural tasks, and the relative time required for each operation.

Diesel's machineries consumptions per hour were estimated by applying the equation of Grisso et al. (2004):

$$\mathbf{Q}\ \text{(liters/hour)} = (0.22\ X + 0.096) \times \text{Ppto}. \qquad [14]$$

Where*:* Q = diesel consumptions; X = motor load (range, 0.4 - 0.75, different value for each operation); Ppto = machine power (kW).

Energy consumption form gas (GPL) and energy production from alternative sources (biogas and photovoltaic plants) were also considered and accounted for.

The CO_2 equivalent emissions related to each energy source were calculated by the application of the following specific coefficients:

- 0.44 kg of CO_2/kWh for electric consumptions (ISPRA, 2011);
- 3.54 kg of CO_2/kg of diesel for fuel consumptions, of which 3.15 for combustion (ISPRA, 2011) and 0,39 for fuel production (Rotz et al., 2010);
- 1.50 kg of CO_2/kg of GPL for gas consumptions (ISPRA, 2011);
- 0.38 for alternative source energy production (ISPRA, 2011).

Total energy consumptions estimated with this second step of analysis are inserted within the on-farm emission group, because only the activities realized within farm's boundaries were considered.

However, within the secondary emissions were included the CO_2 emissions attributable to fuel production (14.2% total fuel emissions), the emissions for the electricity use, because they are only referred to the production processes; secondary emissions derived from the GPL production processes are not considered within this estimation. The CO_2 amount remained after the subtraction of the secondary emissions from the total emissions deriving form energy can be considered within the primary emissions group.

CF estimation from animal feeds

The emissions from feed were estimated in two different ways either for purchased or produced feeds. An aggregation of feed types was performed from the original data, and the following classes of feed types were considered: corn silage, grass silage, grasses hay, mixed hay, alfa-alfa hay, corn meal, barley meal, soybean meal, protein meal, industrial by-products, protein supplement, concentrates, corn mash, straw, pasture, mineral and vitamin supplements, urea and amino acids supplements, fats, unified, cereal by-products, milk powder for calves. The amount of purchased and produced feeds was calculated per every type of feed used in each farm. Data were gathered from the ration information of each animal category reported in the survey.

Emissions from produced feeds where calculated per kg of DM of every crop produced on farm, considering the agronomic practices adopted. Within each farm, the average emissions, expressed in terms of CO_2eq/kg of DM of each feed type, were then multiplied for the amount of the same feed used in the formulated ration for dairy cattle feeding.

GHGs emissions related to the feed production processes included direct and indirect soil N_2O emissions activated by the application of N by organic and mineral fertilizers, emissions from crop residuals, and CO_2 emissions produced after the application of urea. Crop emissions of produced feeds were estimated considering a steady biomass C stock, with no C accumulation or depletion. Based on all these considerations, this CF estimation was realized without determining changes in the organic C stock of the soil.

Soil N_2O direct emissions from the N applied in the soil with organic and mineral fertilizers, and from crop residuals were estimated by applying the IPCC (2006c) equation:

$$\mathbf{N_2O_{direct}}\ (\text{kg } N_2O \text{ yr}^{-1}) = (F_{SN} + F_{ON} + F_{CR}) * EF_{N2Odirect} * (44/28) \qquad [15]$$

Where: N_2O_{direct} = direct emissions of N_2O from N soil application; F_{SN} = N from synthetic fertilizers (kg N_2O yr^{-1}) determined from the fertilizers N content; F_{ON} = N from organic fertilizers (kg N yr^{-1}) determined considering two N average percentages: 0.7% of N for solid manure and 0.3% of N for liquid manure (wet basis); F_{CR} = N from crops residual (kg N yr^{-1}; equation 11.6, IPCC, 2006c); $EF_{N2O\ direct}$ = emission factor for N_2O emissions from N application in the soil equal to 0.056, proposed by the Centro tematico nazionale atmosfera, clima ed emissioni in aria (2002); 44/28 = conversion factor for N_2O-N to N_2O.

Soil N_2O indirect emissions derive from the atmospheric deposition of volatilized N from soil ($N_2O_{(ADT)}$), and from leaching N ($N_2O_{(L)}$). The volatilized N can derive from mineral and organic fertilizers applied to the soil; the leaching N can derive from mineral and organic fertilizers, and residual crops applied to the soil. These two emissions were estimated by applying the following equations (IPCC, 2006c):

$\mathbf{N_2O_{(ADT)}}$ (kg N_2O yr^{-1}) = $[(F_{SN} * Frac_{GASF}) + (F_{ON} * Frac_{GASM})] * EFv * (44/28)$ [16]

Where: $N_2O_{(ADT)}$ = N_2O from atmospheric deposition of volatilized N; $Frac_{GASF}$ = fraction of F_{SN} that volatilized as NH_3 and NO_x, kg N volatilized (kg of N applied)$^{-1}$ with the IPCC (2006c) default value equal to 0.10; $Frac_{GASM}$ = fraction of F_{ON} that volatilized as NH_3 and NO_x, kg N volatilized (kg of N applied)$^{-1}$ with the IPCC (2006c) default value equal to 0.20; EFv = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces with the IPCC (2006c) default value is equal to 0.01.

$\mathbf{N_2O_{(L)}} = (F_{SN} * F_{ON} * F_{CR}) * Frac_{LEACH} * EFl * (44/28)$ [17]

Where: $Frac_{LEACH}$ = N fraction applied to the soil that may be subjected to leaching with an IPCC (2006) range between 0 and 0.30; EFl = emission factor for N_2O emissions from N soil leaching with the IPCC (2006c) default value equal to 0.0075.

CO_2 emissions from the soil application of urea for fertilizations were estimated as:

CO_2 emission (t C yr^{-1}) = M * EFu * (44/12) [18]

Where: CO_2 emission = annual C emissions urea application to the soil; M = annual amount of urea applied to the soil (t urea yr^{-1}); EFu = emission factor for C emissions that derive from urea application to the soil, t C (t urea)$^{-1}$ with the IPCC (2006c) default value equal to 0.20; 44/12 = conversion factor for CO_2-C to CO_2.

Secondary emissions from crop cultivation were represented by the CO_2 emissions that derive from the production of fertilizers, pesticides, seeds and plastics. These emissions were calculated applying the coefficients used by Rotz et al. (2010): 3.307 kg of CO_2eq/kg of N fertilizer; 1.026 kg of CO_2eq/kg of phosphatic fertilizer; 0.867 kg of CO_2eq/kg of potassic fertilizer; 22 kg of CO_2eq/kg of active ingredient within the pesticides; 0.3 kg of CO_2eq/kg of seeds; 2 kg of CO_2eq/kg of plastic.

Emissions produced from crop cultivation were considered within the on-farm emissions group, because they were estimated considering only the cultivations realized within farm's boundaries. At the same time, all those emissions were divided between primary and secondary emissions; N_2O direct emissions from N applied in the soil, indirect N_2O emissions from atmospheric deposition of volatilized N and from leaching N, and CO_2 emissions from urea soil application were considered as primary emissions, because they were produced directly from one specific process realized within the farm. CO_2 emissions derived from fertilizers, pesticides, seeds and plastics production were considered as secondary emissions because they derived from previously developed processes, realized in different places, outside of the farm.

<u>Emission from purchased feed</u> were calculated using emission coefficients based on values measured by Mogensen et al. (2012) for different imported feed commonly used in Europe (mainly concentrates) and using the average emissions measured for produced feeds in the studied farms for feeds purchased in the local market (mainly forages and silages). Only emissions for feed production, processing and transport were accounted for and were included within the off-farm emissions (Table 2.1).

GHGs emissions measured from the various emission sources were transformed into kg CO_2eq by applying the global warming potentials conversion factors of the IPCC (2007): 1 kg of CO_2 = 1 kg of CO_2eq; 1 kg of CH_4 = 25 kg of CO_2eq; 1 kg of N_2O = 298 kg of CO_2eq.

Milk is not the only product that is produced within the 285 analyzed dairy farms; calves not used for replacement and culled cows are generally sold for their meat outside of the farm. For this reason, the emission of each farm were separated among milk and meat, using product energy allocation criterion; in particular, the partitioning of the emissions was performed on the basis of the amount of energy of milk and meat produced within each farm. The equation developed by the IDF (2010) for the biological allocation between milk and meat was adopted for this experiment:

Fm = 1 – 5.7717 * R [19]

Where: Fm = fraction of total farm CF attributed to milk production; R = kg of milk/kg of meat produced; 1-5.7717 = allocation factor for milk.

Statistical analyses

Data were analyzed with MINITAB 16 with techniques of descriptive statistics, mean and standard error of the mean calculated on the 285 farms (SEM) were reported in tables. Analyses of CF means were performed among cooperatives and classes milk production level of the herd (kg of milk/yr per cow), housing type, level of on-farm feed production, and forage in ration of lactating cows. Significant level of $P < 0.05$ was tested preferring the Tuckey method of comparisons. Analyzed data included all observed values, and any outlier was excluded from the original dataset.

6.3. Results

Farm characteristics

The average size of the 285 dairy farms analyzed was equal to 44.41±2.87 ha (Table 2.2). The smallest average farm size was recorded for the Cooperative A (41.1 ha), whereas the largest one was recorded for the Cooperative C (48.6 ha). The average herd size for the 285 farms analyzed was equal to 120.8±7.72 cows. The number of mature animals raised in the sample of the Cooperative A was equal to 13855 cows, followed by the Cooperative B with 9700 cows, the Cooperative D with 5944 cows, and the Cooperative C with 4966 cows. A similar herd profile among the 4 Cooperatives was observed, on average. Considering all the 285 farms, the average percentage of young animals was equal to 39±0.5 of the total cattle present in the farm (Table 2.2). Lactating and dry cows were equal to 81±0.5% and 19±0.5% of mature cows, respectively; the highest percentage of lactating cows was showed by the Cooperative B (83%), and the lowest value was showed by the Cooperative C (74%).

The average number of calvings/cow per year was equal to 0.82±0.01 on the overall farms; the highest value was recorded for the farms of the Cooperative A (0.88), and the lowest value was recorded for the farms of the Cooperative C and D (0.74). The average milk production level for the 285 farms was equal to 6.1±0.12 tons of FPCM/year per cow; a large difference was observed between the milk production levels of the 4 Cooperatives, considering that the Cooperative A showed a milk production level equal to 7.3 tons of FPCM/year per cow, whereas the lowest value, recorded for the Cooperative C, was equal to 4.6. The average amount of milk produced per hectare for all the 285 farms was equal to 16.8±1.5 tons of FPCM/year per ha; the Cooperative A showed the highest value (26.3 tons of FPCM/year per ha), and the Cooperative C showed the lowest one (12.1 tons of FPCM/year per ha) (Table 2.2).

The percentage of purchased feeds calculated for the 4 Cooperatives was 45.5±0.9%. A high average value for the percentage of purchased concentrates (90±0.9%) was recorded in the sample; the Cooperative B showed the highest value among all the farms (98.6%), and the Cooperative A showed the lowest result (78.9%) (Table 2.2). Regarding the percentage of forages in respect to total amount of DM consumed (pasture included) the Cooperatives C and D showed the highest percentages (64.1% and 59.1% of forages in the ration DM, respectively), and the average percentage recorded for the 285 farms was equal to 57.6±0.6% (Table 2.2). The average percentage of corn silage in the lactating cow diet was equal to 11.4±1% of DM for the 4

Cooperatives; a large difference between the Cooperative A (30.2% of corn silage of ration DM) and the Cooperative B (1.4% of corn silage of ration DM) was observed. The feed utilization efficiency (kg of FPCM produced with 1 kg of ration DM) of the 4 Cooperatives was equal to 1.16±0.01 kg of FPCM per kg on average ration DM. The highest value was recorded for the farms of the Cooperative A (1.25), and the lowest for the farms of the Cooperative C (1.02; Table 2.2).

Emissions for feed production

In Table 2.3 the average of emission coefficients estimated for the feed produced of on-farm are presented. They were calculated according to the IPCC (2006c) method for each farm crop and expressed in terms of kg of CO_2eq per kg of DM produced by each farm. These values also represent the emission coefficients for feed purchased in the local market.

Carbon footprint emissions

The total amount of GHGs produced by the all 285 dairy farms was equal to 200.95 tons x 1000 of CO_2eq, for a total amount of milk produced of 141.466 tons x 1000 of FPCM (Table 2.4). The emission attributed to milk, considering the average biological allocation calculated for the 4 Cooperatives was equal to 94.6±0.05%; no significant differences were founded between the 4 allocation percentages calculated for each Cooperative.

The arithmetic mean of the CF measured in the 285 farms was equal to 1.66±0.04 kg of CO_2eq/kg of FPCM; the highest value was recorded for Cooperative C (2.19 kg of CO_2eq/kg of FPCM), followed by the Cooperative D (1.85 kg of CO_2eq/kg of FPCM), by the Cooperative B (1.45 kg of CO_2eq/kg of FPCM), and by the Cooperative A (1.41 kg of CO_2eq/kg of FPCM).

The CF expressed in terms of weighted mean, obtained by dividing the total amount GHGs emissions produced by each farm for the effective quantity of milk that each farm delivered to the cooperatives, was equal to 1.35 kg of CO_2eq/kg of FPCM. Thus, the values of CF calculated for the single cooperatives were equal to 1.29, 1.32, 1.45 and 1.56 kg of CO_2eq/kg of FPCM, for cooperatives A, B, C and D, respectively. These last results can be considered more accurate, because they can better describe the responsibility that each farm, and each Cooperative had on the general CF results; however, statistical analysis cannot be realized on weighted mean results, and only the arithmetic mean CF will be used to describe the results of this research and to compare these results to the literature.

The difference between the CF of the Cooperative D, the CF of the Cooperative C, and the CF of the Cooperative B were statistically different ($P \leq 0.05$); there were not significant differences between the CF of the Cooperative A and the CF of the Cooperative B (Table 2.4).

The frequency distribution of the 285 farms for CF classes (Figure 2.1) showed that almost 34% of the farms had 1.25 < CF <1.5 kg of CO_2eq/kg of FPCM; 23% of the farms have 1.0< CF <1.25 kg of CO_2eq/kg of FPCM; 17% of the farms have 1.50< CF <1.75 kg of CO_2eq/kg of FPCM, and the remaining farms had CF > 1.75.

Regarding the contribution of the main emission sources considered, 43% of the CF derived from enteric emissions, 20% from manure emissions, 8% from primary energy emissions, 3% from secondary energy emissions, 18% from the off-farm feed emissions, 6% from the on-farm feed primary emissions, and 2% from the on-farm feed secondary emissions (Figure 2.2). The details of contribution to CF in terms of kg of CO_2eq/kg of FPCM are reported in Table 2.4. Significant differences were observed among cooperatives for the contribution of the single emission source. In fact, enteric emissions resulted higher in Coop A and B than in Coop C and D ($P<0.05$); manure emissions of Coop C resulted much higher than in Coop D ($P<0.05$); energy emissions in Coop C and D were more than 4.5 and 2.5 times higher than values observed in Coop A and B ($P < 0.05$). Slight differences were also observed for emission related with feed produced on farm and that purchased (Table 2.4).

The CF range recorded for the 285 farms of Southern Italy was between 0.94 and 5.07 kg of CO_2eq/kg of FPCM, whereas the milk production level ranged between 1,170 and 11,100 kg of FPCM/year per cow. A large influence of the milk production level of the herd was observed in each cooperative by plotting the values of CF versus the milk production level of each farm (Figure 2.3). A nonlinear relationship was observed between these two variables that was described using a power function CF= 304,49 * MY^ $^{-0.613}$ where MY is the milk production level of a given farm expressed as kg of FPCM/year per mature cow. The observed pattern was similar for each cooperative, and the power function reached the highest r^2 when fitted on farm data of Coop A (0.80; $P < 0.001$) and the lowest on farm data of Coop C (0.58; $P < 0.001$) (Figure 2.3). Similar pattern were observed for the single components of animal emissions (enteric and manure), feed consumption emissions (produced on farm and purchased) and net emissions due to energy utilization (consumption and production) (Figure 2.4).

When the main farm characteristics of 4 classes of milk production level expressed as kg of FPCM/year per cow (low = < 4200; mid-low = 4200-6200; mid-high = 6200-8200; high = >8200) were compared, significant differences were observed (P<0.05; Table 2.5) for all variables, except for farm size and digestibility of dairy cow diets. Similarly, CF was negatively associated with milk production level and significantly different among classes (P <0.05), except for mid-high and high groups (Table 2.5). The single CF components, such as enteric fermentation and purchased feeds contribution showed large differences among classes (P< 0.05), whereas emissions from manure, energy and on farm produced feed were significantly higher in the low level of production than for other groups.

The CF from purchased feeds showed a significant difference between the 4 milk production levels (P<0.05), with a decreasing trend between the low and the high milk production levels. Feed efficiency showed a significant difference between the 4 milk production level, following a positive trend between the low and the high milk production level (Table 2.5).

On the other hand, even if the total farm CF decreased with the increase of the production level, the percentage contribution of the emission source did not show large variations for enteric methane, showing increasing trend for manure and purchased feed emissions and decreasing trend of on-farm produced feed (Figure 2.5).

Differences in farm characteristics and CF among groups of farms classified for housing types are showed in Table 2.6. Four groups were considered, three main groups such as cubicle, bed-pack and farms that included pasture were selected. Then, the bedded pack housing solution group was divided into 2 other subgroups, on the basis of the milk production levels recorded in those farms. No differences were observed for ha of land, ration digestibility of dairy cows or number of raised cows among groups. On the other hand, cubicle farms and bed-pack farms showed significantly higher (P<0.05) production level and higher feed efficiency use for milk production and lower forages percentage of ration DM than pasture and bed-pack farms with lower milk production level. The CF from enteric fermentations, energy use, and purchased feeds were higher (P<0.05) for cubicle and bed-pack with high milk production level than the other two groups. Each group was different from each other for manure emissions, that resulted bed-pack low milk > cubicles > bed-pack high milk > pasture (P<0.05) whereas no significant differences were recorded for the CF percentage of on-farm produced feeds among the 4 groups.

Differences in farm characteristics and CF among groups of farms classified for the degree of self sufficiency for consumed feed (expressed as % of on farm produced feed on the total consumed) are showed in Table 2.7. Three groups of farms were selected based on low self-sufficiency (<42% of on-farm feeds), medium self-sufficiency (42-54% of on-farm feeds), and high (>66% of on-farm feeds). Farm dimension and corn silage, as % DM in lactating cows diets, did not show significant differences among the 3 groups ($P<0.05$). The forage percentage (DM basis) and the DE% of the lactating cows diet, were positively associated with self sufficiency, being 63%, 55% and 50% in high, medium and low groups respectively ($P<0.05$; Table 2.7). The total CF and its single components of low level of self-sufficiency were only numerically different than medium level, but they were significantly different than high level and positively associate with the degree of self sufficiency ($P<0.05$; Table 2.7).

Differences in farm characteristics and CF among groups of farms classified for forage consumption are showed in Table 2.8. The farms were divided into 3 groups on the basis of the forage percentages of the ration DM, which were equal to < 55%, 55-65% and >65% of total DM, low medium and high respectively. The 3 groups differed for milk production level of the herd ($P<0.05$) that was negatively associated with both the level of forage percentage and feed efficiency. Ration DM forage percentages were negatively associated with both corn silage use and DE% of lactating cows diets ($P < 0.05$). Total CF, and emissions from enteric fermentations and energy, were positively associated with forage percentage ($P<0.05$). Otherwise, emissions from manure and from on-farm produced feeds of low and medium levels of forage percentages did not differ significantly among them but were lower than the high level of forage percentage ($P<0.05$) (Table 2.8).

2.4. Discussion

General considerations

The average CF estimated in the 285 farms, equal to 1.66 kg of CO_2 eq/kg of FPCM, was similar to the CF results obtained by several authors (e.g. Casey and Holden, 2005; Thomassen et al., 2008; Capper et al., 2009; Flysjö et al., 2011; Guerci, 2012; Guerci et al., 2013). In particular, if the CF value obtained in this experiment is compared with the CF results estimated within farms that showed a similar milk production level, the analogy between the CF results is even more evident. The average milk production level recorded within the 285 farms was included between 4.6 and 7.3 tons of FPCM/year per cow, and the CF results were included between 1.41 and 2.19 kg of CO_2 eq/kg of FPCM. Casey and Holden (2005), Thomassen et al. (2008), Capper et al. (2009), Penati et al. (2010), Rotz et al. (2010), Flysjö et al. (2011), Hegemann et al. (2011), Guerci et al. (2013), measured the CF of the dairy farms in different countries and in different dairy systems, obtaining a CF value included between 0.55 and 1.49 kg of CO_2 eq/kg of FPCM; these analyzed systems presented a milk production level included between 5.0 and 10.22 tons of FPCM/year per cow. The results obtained by the authors listed above were estimated using different functional units (e.g. ECM); in order to realize a valid comparison, all these CF results and their respective milk production levels were transformed using the FPCM formula of the IDF (2010).

The highest CF value among the estimations described before was obtained by Hegemann et al. (2011), which calculated a CF value equal to 2.06 kg of CO_2 eq/kg of FPCM with a milk production level of 5.8 tons of FPCM/year per cow. This estimation was realized on animals that presented a milk production level similar to that measured for the 285 farms of the present experiment. However, the CF value calculated by Hegemann et al. (2011) represents the average result of a large estimation realized on 38 countries, which showed different CF values. The results were included between 0.8 and 3.1 kg of CO_2 eq/kg of FPCM, for a range of milk production included between 8.2 and 0.8 tons of FPCM/year per cow. The highest CF recorded in this estimation was anyway small, compared to the low level of milk production. This difference can be explained by examining all the equations and coefficients used within this estimation. Methane enteric emissions of cows were calculated using different equations, taking into account the feed ration characteristics, milk production, and animal body weight; no differences between the different annual months were considered. Manure methane emissions were calculated by multiplying a default emission factor for the number of cows and for the number of heifers considered (21 and 10.5 kg of CH_4/year per animal, respectively); no differences were considered for the housing solutions and for the atmospheric temperatures. Only direct N_2O emissions from manure were calculated, by applying the fixed coefficient of 0.0125 kg of N_2O/kg of N excreted calculated by Cederberg and Flysjö (2004). Direct N_2O emissions from fertilizers use and indirect N_2O emissions from fertilizers production were calculated by applying the fixed coefficients calculated by Cederberg and Flysjö (2004) and Simon (1998), equal to 0.013 and 0.012 kg of N_2O/kg of N fertilizer, respectively. The difference between the CF measured by Hagemann et al. (2011), and the CF measured in the present study can be justified considering that Hagemann et al. (2011) considered a small number of variables, by applying only default coefficients, without taking into account all the differences related to the climatic conditions, feed production, animal feeding, animal and manure management.

The average CF recorded for the 285 farms is similar than the one estimated by Flysjö et al. (2011), which was equal to 1.40 kg of CO_2 eq/kg of FPCM, despite the lower milk production level recorded in the Italian farms (6.1 vs. 10.22 tons of FPCM). This difference depends by the emissions caused by the land use change factor considered by Flysjö et al. (2011), which provokes an increase in the final CF result included between 0.2 and 1.3 kg of CO_2 eq/kg of FPCM. Emissions from land use change were not considered in the present study.

The CF estimation realized by Rotz et al. (2010) showed a result equal to 0.55 kg of CO_2 eq/kg of FPCM for a milk production level of 8.5 tons of FPCM; this result was different from the one obtained in the present study, considering also that the average milk production level recorded in the 285 farms of Southern Italy was lower. However, the CF estimation of Rotz et al. (2010) can be compared with the one obtained in the present study by subtracting the CF that derive from the animal respiration, and adding the CF that derive from the crop respiration. In fact, the CF calculation of Rotz et al. (2010) was realized taking into account the same variables used for the present study, using similar equations and coefficients (except for those calculated on the basis of local measurements), but subtracting the CO_2 absorbed by plants, and considering the CO_2 from animal respiration. The total amount of CO_2eq produced by the 285 Italian farms was equal to 200.95 ton x 1000, emitted by 34443 animals; the CO_2eq emitted per cow was equal to 5836 kg. Rotz et al. (2010) calculated a total GHGs amount per cow equal to 5826 kg of CO_2eq. However, if the kg of CO_2eq absorbed by crops (8199 kg of

CO_2eq/cow) are summed to this result, and the kg of CO_2eq emitted by the animals with their respiration (6213 kg of CO_2eq/cow) are subtracted from the final result, the total amount of GHGs emissions produced per cow will be equal to 7812 kg of CO_2 eq. This value is now higher than the one obtained in the present study (5836 kg of CO_2eq/cow), and this calculation demonstrates that by applying a similar method of estimation, and considering the same emission sources, the total amount of GHGs emitted per cow for the present study is lower than the amount calculated by Rotz et al. (2010). However, the milk production level of the farms still represents the factor that affects the final CF value, because the GHGs emitted by the animals can be assigned to a larger amount of milk, which will ensure a lower CF.

The CF value obtained in the present study is close to the CF calculated by Guerci et al., (2013) in the LCA of milk production of 41 dairy farms of Northern Italy; the author obtained an average CF equal to 1.30 kg of CO_2eq/kg of FPCM. The estimation realized by Guerci et al. (2013) involved 41 intensive dairy farms that presented a high milk production level, both considering the milk production level in terms of tons/cow or tons/ha; the 41 dairy farms showed a milk production level equal to 10.3 tons of FPCM/cow per year, and equal to 30.89 tons of FPCM/ha per year. Compared to the present study, the farms of Northern Italy presented, on average, a higher feed efficiency (1.3 vs. 1.16 kg FPCM/kg DM ration). The CF estimation realized by Guerci et al. (2013) followed the Tier 2 of the IPCC (2006b) for the calculations referred to the CH_4 emissions from manure and animals, and for the calculation of the N_2O emissions from manure. Compared with the present study, no differences for the DE % of the ration were considered; besides, the MCF for the CH_4 emissions from manure were selected from the IPCC (2006b) tables, without considering different atmospheric temperatures as it was done in the present study. The N excretion rate was calculated by applying the IPCC (2006b) default values assigned on the basis of the animal category (lactating cow, heifer, calf) and on the basis of the animal weight. The N volatilized from manure was calculated by applying the IPCC (2006b) equation, whereas for the dairy farms of Southern Italy an equation developed by Atzori (2008) on the basis of the Mediterranean area climatic conditions was used. The direct and indirect N_2O emissions from soil fertilizers use were realized using the Tier 1 of the IPCC (2006b); however, Guerci et al., (2013) did not consider the application of crop residues, estimating only the N_2O emissions that derived from the use of organic and mineral fertilizers. For the present study, emission factor used for the estimation of the direct N_2O emissions from

fertilizers application was selected from national data, compared with Guerci et al. (2013) that used the coefficient proposed by the IPCC (2006b).
Comparing the total CF calculated in the present study with the one obtained by Guerci et al., (2013) an important difference can be observed; within all the emission sources, emissions from animals and manure management represented the 50.1 % in Northern Italy, whereas in the farms of Southern Italy the same emission fraction within the farm represented the 63 % (43% for enteric emissions and 20% for manure management). On the other hand, the emissions that derived from the off-farm feed production represented the 21.2% in the study of Guerci et al., (2013), and the 18% in the present study; this difference can be explained considering the different approach used for the estimation. Guerci et al. (2013) used the Simapro PhD 7.3.3 software to calculate the emissions that derived from the transportation (by trucks or ships) of the row materials used for the production of the off-farm feeds, and they also considered the energy consumptions that happened within feed plants for the production of each kind of feed. In the present study the calculation for the CF that derives from the off-farm feed production was realized multiplying the fixed emission coefficients (Table 2.1) of each kind of feed for the amount of purchased feed.

Milk production level, Carbon footprint, and farm characteristics

As explained before, the milk production level affects the CF result. Basically, a high milk production level allow to assign the total amount of GHGs produced within a farm to a large amount of milk; in this way, it could appear that the milk production level does not have an effective participation within the processes that are responsible for the GHGs emissions.
The comparison between the CF results obtained by Cederberg and Flysjö (2004), Capper et al. (2009), Rotz et al. (2010), and Flysjö et al. (2011) can explain the relation between the CF and the milk production level. These authors obtained a CF included between 0.55 and 1.27 kg of CO_2 eq/kg of FPCM; the milk production levels recorded within the farms that presented these CF values were however included between 8.0 and 10.2 tons of FPCM. This fact means that even within the same milk production level, there could exist a high variability for the CF values.
In the present study, the milk production level affected the total CF and even the different components of it. The CF from enteric fermentations showed a significant difference between the first 3 milk production levels; as the milk production level

increased, the CF from enteric fermentations decreased. Bell et al. (2010) demonstrated that animal that achieve their maximum production level produce less enteric CH_4, considering that a larger fraction of the feed energy is converted into milk production, and the amount of energy that can be excreted as N and CH_4 is reduced. As explained by Yan et al. (2010) and Wall et al. (2010), the feed efficiency can affect the CF of a farm because animals that are able to convert the energy content of the ration into a larger amount of milk will produce less enteric CH_4, and the total CF of the farm can be reduced. This last concept can be confirmed observing the feed efficiency of the 285 farms analyzed in the present study; as the milk level increased, even the amount of milk produced with 1 kg of DM ration increased, and this trend was followed even by the different CF emissions. Finally, as reported by Zehetmeier et al. (2012), the achievement of a high milk production level per cow allow to maintain a constant milk production within the farm by raising a lower amount of animals, reducing the total amount of GHGs emissions produced.

Housing type and carbon footprint

As showed in the Table 2.6, different housing solutions can affect the CF of a dairy farm. Basically, methane production occurs in animal manure if anaerobic conditions are preserved (Monteny et al., 2006); animals raised within the cubicles system produce liquid slurry manure and considering that no bedding material are used, the N_2O emissions are reduced because anaerobic condition are guaranteed (Chadwick et al., 2011). Methane emissions present a lower GWP compared to N_2O, and this is why farms that present the cubicles system presented a low CF compared to the other housing solutions. In the present study the housing solution that presented the highest CF level was the bedded pack; however, the farms that adopted this housing solution and that presented a high milk production level did not have a high CF. This different result can be explained in two different ways; first of all, a higher milk production level allows the allocation of the GHGs emissions to a larger amount of milk, causing a lower CF value. On the other hand, considering that the prevailing GHG emitted from bedded pack housing solution is represented by the nitrous oxide, because of the aerobic conditions that occur within this type of manure, and considering that animals that present high milk production levels generally have low amounts of N excretions because of their high feed efficiency, the CF will show different results. The CF calculated for the farms that adopted the cubicles and the CF calculated for the farms that adopted the bedded pack (with the higher milk production level) showed the lowest values, and the DE% of the DM ration and the feed conversion efficiency of these farms was higher compared to the other two groups, confirming that feed characteristics and the animal nutrition performances can affect the CF.

Animals raised on pasture can represent an important source of GHGs emissions, mainly because of urine deposited on the soil that can produce N_2O emissions and nitrate leaching (Monteney et al., 2006); farms that presented this system showed an high CF, but observing the different component of the total CF it can be seen that the emissions from manure recorded for this group were lower than the others, and they were lower even within the CF of this group, representing less than the 10% of the total amount. On the other hand, the enteric emissions produced by this group of animals represented more than the 45% of the total CF; this fact can be explained considering the low feed conversion efficiency of these animals and the high forage percentage of their DM ration that stimulate a high amount of methane enteric emissions.

A similar result was obtained by Guerci et al. 2012 in a comparison among the dairy farms of Germany, Denmark and Italy; among all the analyzed farms, those that presented the animals fed on pasture showed a low contribution for the total CF from manure emissions, but enteric emissions reached 83% of the total CF.

Ration characteristics and Carbon footprint

The results presented in the Table 2.8 demonstrate that the percentage of forages within the ration and the DE of the ration can strongly affect the CF of a dairy farm. By dividing the 285 farms on the basis of the percentage of forages within the rations, total CF, enteric CF, manure CF and energy CF showed a significant difference among the 3 groups; as the forage percentage increased, the DE of the DM ration and the feed conversion efficiency decreased, and the CF increased. The results of the present study confirm the result of Aguerre et al. (2011), who demonstrated that the increase of the forage percentage within the ration can partially affect the emissions from manure, but strongly influence the enteric methane emissions. In fact, the Table 2.8 shows that as the percentage of forage in the ration increased, enteric CF increased, with a significant difference among the 3 groups of farms; instead, the CF from manure had small differences as the forage percentage increased, and a significant difference was recorded only between the first 2 groups of farms and the 3rd group, which had the highest forage percentage.

Despite the differences that exist among these farms, Figure 2.2 shows that the CF decreased when the milk production level increased, following the trend that many other authors have already recorded for several dairy systems.

Those differences were in part associated with the milk production level of the herd, which was higher in Coop A than in Coop B than in Coop D than in Coop C (Table 2.3). The milk production level, causing the dilution of the emissions in the amount of produced milk, directly influences the CF value.

When the emission were expressed in terms of percentages, the differences were less evident among cooperatives and among classes of production levels, as showed by the Figure 2.5, which presented the contribution of the main 5 emission sources to total CF for the 4 production levels already examined in the Table 2.5.

This fact suggests two considerations: the milk production level can affect the CF result even considering its components separately; the distribution of the CF among animals, feeds and energy basically follows the same percentage partition, even when the milk production level changes. This last consideration is confirmed by the Figure 2.5; where the average CF obtained by 4 groups of farms (grouped on the basis of their milk production level) is represented indicating also the participation in terms of percentage of each emission source within the total CF. Different CF results were obtained for all the Cooperatives for each emission source; however, only the CF from manure, energy, and off-farm feed production showed a significant difference among all the Cooperatives ($P \leq 0.05$).

Observing the Figure 2.2, it is possible to understand why the 285 farms selected for this experiment were considered together to realize the CF estimation, despite the differences that exist between them, and that were underlined before.

Within the Figure 2.2 it is possible to find several farms that present the same production level with different CF results; on the other hand, it is also possible to find farms with the same CF result, showing different milk production levels. This is one of the reasons that clarify the selection of this farms sample. The CF estimation of the Southern Italy is not only realized to know the amount of GHGs emitted by the dairy sector of this part of Italy. Mitigation strategies have to be studied and organized in order to reduce the CF of the dairy farms, and analyzing the differences that exist within the different farms, and within the different Cooperatives, better mitigation solutions will be studied, considering that a large amount of information and characteristics will be included within them.

2.5. Conclusions

The average CF estimated in the 285 dairy cattle farms of Southern Italy was equal to 1.66 kg of CO_2eq/kg of FPCM. The milk production level of the farms, expressed in term of kg of FPCM/year per cow, represented the most important factor that affected the CF result. Farms that presented high milk production levels obtained low CF results; however, within the same milk production level, different CF results were obtained. This fact suggested that further factors have to be considered in order to develop mitigation strategies to reduce the CF.

Besides the milk production level, the GHGs emissions that derived from the off-farm feed production processes demonstrated to have an important influence on the total farm CF, especially considering the high percentages of purchased feeds that were recorded for these farms. Furthermore, the largest percentage of the purchased feeds was represented by concentrates, which are mainly produced from industrial feed plants. The estimation of the GHGs emissions that derive from the production of the concentrate feeds was realized using default coefficients from the literature, without investigating all the sources of emission that compose these emissions. Additional studies have to be realized to accurately estimate the CF that derive from the off-farm feed production, in order to obtain a wide CF estimation, and in order to develop useful mitigation strategies.

2.6. References

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2.7. Tables

Table 2.1. Emission coefficients (kg of CO_2eq/kg of DM) used to calculate emissions of purchased feeds.

	Coefficients (kg of CO_2eq/kg of DM)			
Feed type	**Coop. A**	**Coop. B**	**Coop. C**	**Coop. D**
Corn silage	0.17*	0.09*	0.14*	0.15*
Grass silage	0.25*	0.12*	0.19*	0.12*
Grass hay	0.31*	0.16*	0.21*	0.22*
Mixed hay (grass-legume)	0.23*	0.18*	0.19*	0.18*
Alfa-alfa hay	0.06*	0.07*	0.11*	0.04*
Corn meal	0.29	0.28	0.29	0.28
Barley meal	0.36	0.18	0.25	0.24
Soybean meal	0.67	0.67	0.67	0.67
Other meal high in protein	0.25	0.25	0.25	0.25
Industrial by-products	0.40	0.40	0.40	0.40
High protein commercial mix	0.70	0.70	0.70	0.70
Commercial mix	0.60	0.60	0.60	0.60
High moisture grain	0.28	0.28	0.28	0.28
Straw	0.04	0.04	0.04	0.04
Pasture	0.06	0.06	0.06	0.06
Mineral and vitamin supplements	0.25	0.25	0.25	0.25
Urea and amino acids supplements	0.25	0.25	0.25	0.25
Fats	0.80	0.80	0.80	0.80
Cereals by-products	0.40	0.40	0.40	0.40
Milk powder	2.00	2.00	2.00	2.00

*emission coefficient calculated as average values of on farm produced feed in the same cooperative.

Tale 2.2. Descriptive characteristics of the farms included in the sample. Values were separated for farms associated in different cooperatives (A, B, C, D)

Item	A	B	C	D	Total	Mean	SEM
Farms, n.°	83	88	44	70	285	285	-
Land, ha	41.15	44.83	48.67	46.73	12657.92	44.41	2.87
Total cattle, n.°	13855	9700	4966	5944	34434	120.8	7.72
Mature cows, n.°	7899	5770	3042	3610	20298	71.22	4.57
% lactating	81.75[ab]	83.90[a]	74.55[c]	79.39[b]	-	80.72	0.48
% dry	18.25[bc]	16.10[c]	25.45[a]	20.61[b]	-	19.28	0.48
Young cattle, % of mature cows	41.51[a]	39.77[ab]	33.55[c]	38.10[b]	-	38.91	0.49
Calves n/yr per cow	0.88[a]	0.85[a]	0.74[b]	0.74[b]	-	0.82	0.01
Milk yield, t FPCM/yr per ha	26.36[a]	12.22[b]	12.13[b]	14.51[b]	-	16.89	1.54
Milk yield, t FPCM/yr per cow	7.39[a]	6.47[b]	4.64[c]	5.38[c]	-	6.19	0.12
Purchased feeds, % DM	48.30	48.45	49.32	48.29	-	48.50	0.94
Purchased conc., % DM	78.90[b]	98.61[a]	84.67[b]	96.02[a]	-	90.08	0.96
Forages, % DM ration	54.16[c]	56.33[bc]	64.16[a]	58.95[b]	-	57.55	0.62
Corn silage*, % DM ration	30.22[a]	1.45[b]	5.24[b]	5.46[b]	-	11.40	0.98
kg FPCM/kg DM ration	1.25[a]	1.21[a]	1.03[b]	1.05[b]	-	1.16	0.01

*only for lactating cows.

Table 2.3. Emission coefficients (kg of CO_2eq/kg of product) for on-farm feed production. Values were separated for farms associated in the 4 cooperatives (A, B, C, D)

	Coefficients (kg of CO_2eq/kg of DM)						
Feed type	**A**	**B**	**C**	**D**	**Mean**	**Max**	**Min**
Corn silage	0.17±0.005	0.09±0.01	0.14±0.017	0.15±0.03	0.15±0.006	0.44	0.04
Grass silage	0.25±0.03	0.12±0.01	0.19±0.02	0.12±0.01	0.16±0.01	0.43	0.04
Grasses hay	0.31±0.014	0.16±0.01	0.21±0.01	0.22±0.02	0.25±0.009	0.65	0.06
Mixed hay	0.23±0.02	0.18±0.05	0.19±0.02	0.19±0.009	0.18±0.005	0.56	0.09
Alfa-Alfa hay	0.06±0.01	0.07±0.02	0.11±0.016	0.04**	0.08±0.008	0.42	0.01
Corn meal	0.29±0.06	0.28*	0.29±0.06	0.28*	0.29±0.06	0.40	0.19
Barley meal	0.36±0.07	0.18±0.01	0.25±0.02	0.24±0.02	0.22±0.01	0.57	0.03
High moisture grain	0.29±0.06	0.28*	0.29±0.06	0.28*	0.29±0.06	-	-
Straw	0.04*	0.04*	0.04*	0.04*	0.04*	-	-
Pasture	0.06*	0.06*	0.06*	0.06*	0.06*	-	-
Unifeed residuals	0.25*	0.25*	0.25*	0.25*	0.25*	-	-

* coefficients calculated from average local data
** only 1 farm presented this cultivation

Table 2.4. Carbon footprint emissions measured in the sampled farm (n = 285) associated with the 4 Cooperatives (A, B, C and D).

Item	A	B	C	D	Total	Mean	SEM
CO_2eq tot, tons x 1000	84.73	56.57	25.84	33.98	200.95	0.70	0.045
Milk collected, tons x 1000	62.95	41.29	16.99	20.27	141.466	0.49	0.036
Weighted Coop mean CF, kgCO_2eq/kg of collected FPCM	**1.29**	**1.32**	**1.45**	**1.56**	**-**	**1.35**	**-**
Arithmetic farm mean CF, kg CO_2eq/kg FPCM	**1.41^c**	**1.45^c**	**2.19^a**	**1.85^b**	**-**	**1.66**	**0.04**
CFP allocated to milk, %	95.55	96.04	95.07	93.60	-	95.65	0.17
CF components, kgCO_2eq/ kg FPCM							
Enteric,	0.64^b	0.62^b	0.83^a	0.77^a	-	0.71	0.014
Manure,	0.30^{bc}	0.32^{ab}	0.38^a	0.27^c	-	0.33	0.007
Energy,	0.11^c	0.12^c	0.52^a	0.32^b	-	0.18	0.023
Primary emissions	0.07^c	0.07^c	0.22^a	0.36^b	-	0.12	0.016
Secondary emissions	0.03^c	0.03^c	0.09^a	0.15^b	-	0.06	0.008
On-farm produced feeds,	0.14^{ab}	0.11^b	0.17^a	0.13^b	-	0.14	0.005
Primary emissions	0.10^b	0.09^b	0.13^a	0.10^{ab}	-	0.11	0.003
Secondary emissions	0.03^{ab}	0.02^c	0.04^a	0.02^{bc}	-	0.03	0.001
Purchased feeds,	0.21^c	0.28^b	0.27^b	0.35^a	-	0.30	0.005

^{a,b,c} within a row, means with a different superscript differ significantly for $P \leq 0.05$.

Table 2.5. Main farm characteristics and carbon footprint (CF) of 4 groups of farms classified on the basis of the milk production level.

Items	**Milk production level (kg FPCM/yr per cow)**					
	Low (<4200)	**Med-low (4200-6200)**	**Med-high (6200-8200)**	**High (>8200)**	**Mean**	**SEM**
Farms, n	54	75	101	55	-	-
Land, ha	40.11	41.93	49.51	44.78	44.82	2.859
Mature cows, n.°	51.36[c]	90.16[bc]	134.32[b]	206.02[a]	54.94	7.721
Dry cows, % of mature cows	0.26[a]	0.19[b]	0.16[c]	0.15[c]	0.19	0.004
Young cattle, % of mature cows	0.33[c]	0.38[b]	0.40[ab]	0.42[a]	0.38	0.004
Cow calvings/yr	0.72[c]	0.80[bc]	0.83[b]	0.91[a]	0.81	0.010
Stocking rate, cows/ha	2.03[b]	3.88[b]	3.90[b]	7.37[a]	4.21	0.377
Forages, % consumed DM	0.67[a]	0.59[b]	0.54[c]	0.51[c]	0.57	0.006
On-farm feeds,% consumed DM	0.60[a]	0.50[b]	0.49[b]	0.48[b]	0.51	0.009
Feed efficiency, kg FPCM/kg of DM	0.79[d]	1.07[c]	1.27[b]	1.39[a]	1.15	0.014
Corn silage, % of offered DM*	0.03[c]	0.04[c]	0.12[b]	0.27[a]	0.11	0.009
Energy digestibility (DE), % gross energy*	68.48	68.67	69.09	69.10	68.86	0.108
CF components, kgCO_2eq/kg FPCM						
CF total	2.59[a]	1.68[b]	1.37[c]	1.20[c]	1.65	0.040
CF enteric	1.06[a]	0.71[b]	0.59[c]	0.53[c]	0.70	0.014
CF manure	0.42[a]	0.31[b]	0.28[b]	0.28[b]	0.31	0.007
CF energy	0.52[a]	0.22[b]	0.14[b]	0.08[b]	0.23	0.023
CF produced feeds	0.22[a]	0.12[b]	0.11[b]	0.10[b]	0.13	0.005
CF purchased feeds	0.35[a]	0.30[b]	0.25[c]	0.21[d]	0.28	0.005

[a,b,c] within a row, means with a different superscript differ significantly ($P \leq 0.05$).
*only for lactating cows.

Table 2.6. Main farm characteristics and carbon footprint (CF) of 4 group of farms classified on the basis of the housing type adopted for lactating cows.

Item	**Housing type**					
	cubicle	**bedded pack** (low milk)*	**bedded pack** (high milk)**	**pasture**	**Mean**	**SEM**
Farms	88	76	76	45	-	-
Land, ha	48.6	38.6	46.9	43.9	44.82	2.859
Milk yield, tons FPCM/yr/cow	7.46[a]	4.32[b]	7.41[a]	4.72[b]	6.19	0.122
Mature cows, n.°	158.1[a]	99.5[b]	109.9[ab]	101.[8ab]	120.82	7.721
Forages, % of consumed DM	0.52[a]	0.64[b]	0.55[a]	0.62[b]	0.57	0.006
On-farm feeds,% of consumed DM	0.49	0.55	0.48	0.56	0.51	0.009
Feed efficiency, kg FPCM/kg of DM	1.29[a]	0.98[b]	1.30[a]	0.94[b]	1.15	0.014
Energy digestibility (DE)*, % gross energy	69.2[a]	68.4[b]	69.0[ab]	68.7[ab]	68.86	0.108
<u>CF components,</u> (kgCO_2eq/kgFPCM)						
CF total	1.45[b]	2.06[a]	1.34[b]	1.92[a]	1.65	0.040
CF enteric fermentation	0.61[b]	0.83[a]	0.57[b]	0.87[a]	0.70	0.014
CF manure	0.36[b]	0.40[a]	0.26[c]	0.19[d]	0.31	0.007
CF energy	0.11[b]	0.36[a]	0.15[b]	0.37[a]	0.23	0.023
CF produced feeds	0.13[b]	0.17[a]	0.10[b]	0.14[ab]	0.13	0.005
CF purchased feeds	0.24[c]	0.30[b]	025[c]	0.35[a]	0.28	0.005

[a,b,c] within a row, means with a different superscript differ significantly (P≤0.05).
* = < 6000 kg FPCM/cow/year; **= > 6000 kg FPCM/cow/year.

Table 2.7. Main farm characteristics and carbon footprint (CF) of 4 group of farms classified on the basis of the degree of self sufficiency for consumed feed.

Item	**Feed produced on farm, % consumed DM**				
	Low (<42%)	**Medium (42-54%)**	**High (>66%)**	**Mean**	**SEM**
Farms, n	59	101	125	-	-
Land, ha	47.32	43.67	44.58	44.82	2.859
Milk yield, tons FPCM/yr/cow	6.71[a]	6.55[a]	5.65[b]	6.19	0.122
Forages, % of consumed DM	0.50[c]	0.55[b]	0.63[a]	0.57	0.006
Feed efficiency, kg FPCM/kg of DM	1.26[a]	1.21[a]	1.06[b]	1.15	0.014
Corn silage, % of offered DM*	0.12	0.10	0.12	0.11	0.009
Energy digestibility (DE), % gross energy*	69.40[a]	68.98[ab]	68.53[b]	68.86	0.108
CF components, (kgCO_2eq/kg FPCM)					
CF total	1.44[b]	1.53[b]	1.86[a]	1.65	0.040
CF rumen fermentations	0.62[b]	0.66[b]	0.77[a]	0.70	0.014
CF manure	0.30[b]	0.29[b]	0.35[a]	0.31	0.007
CF energy	0.14[b]	0.17[b]	0.32[a]	0.23	0.023
CF produced feeds	0.09[b]	0.11[b]	0.17[a]	0.13	0.005
CF purchased feeds	0.25[a]	0.30[a]	0.30[b]	0.28	0.005

[a,b,c] within a row, means with a different superscript differ significantly (P≤0.05).
*only for lactating cows.

Table 2.8. Comparison of the main farm characteristics among 3 forage % of the feed ration, and effect of the forage % of the feed ration on the Carbon footprint.

	Forages,% DM ration				
items	**Low (<55%)**	**Medium (55-65%)**	**High (>65%)**	**Mean**	**SEM**
Farms, n	127	95	63	-	-
Milk yield, ton of FPCM/yr per cow	7.34[a]	5.98[b]	4.19[c]	6.19	0.122
On-farm feeds,% DM ration	0.45[c]	0.50[b]	0.66[a]	0.51	0.009
Feed efficiency, kg FPCM/kg of DM	1.30[a]	1.14[b]	0.90[c]	1.15	0.014
Corn silage, % of offered DM*	0.18[a]	0.08[b]	0.03[c]	0.11	0.009
Energy digestibility (DE), % gross energy*	69.5[a]	68.8[b]	67.6[c]	68.86	0.108
CF components, (kgCO_2eq/kg FPCM)					
CF total	1.35[c]	1.68[b]	2.24[a]	1.65	0.040
CF rumen fermentations	058[c]	0.70[b]	0.94[a]	0.70	0.014
CF manure	0.29[b]	0.32[b]	0.37[a]	0.31	0.007
CF energy	0.11[c]	0.23[b]	0.46[a]	0.23	0.023
CF on-farm crops	0.11[b]	0.12[b]	0.21[a]	0.13	0.005
CF off-farm crops	0.26[b]	0.30[a]	0.27[ab]	0.28	0.005

[a,b,c] within a row, means with a different superscript differ significantly ($P \leq 0.05$).

2.8. Figures

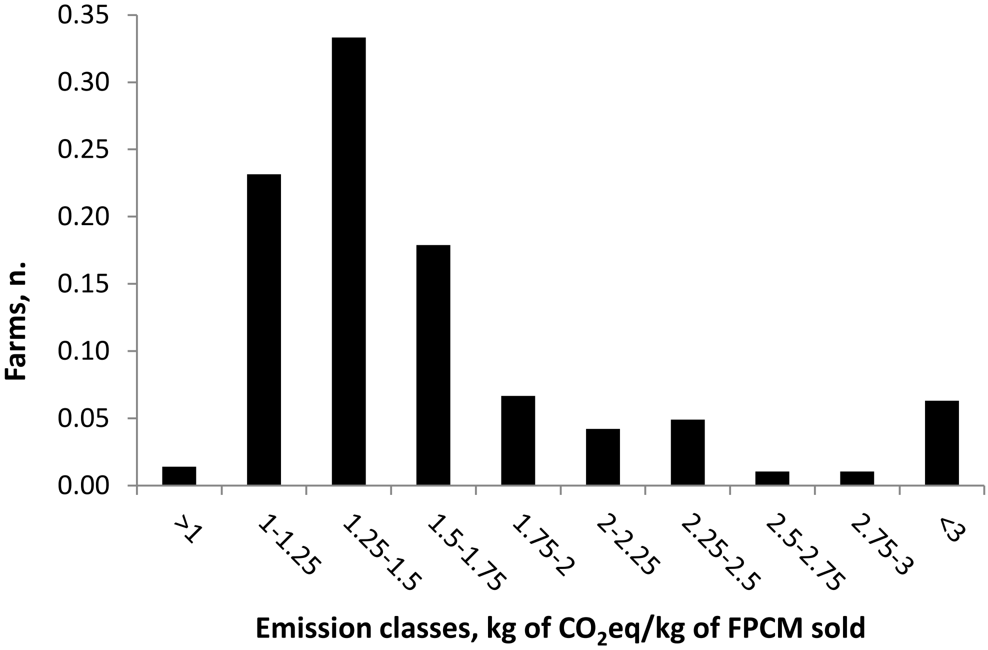

Figure 2.4. Distribution of frequency of studied farm for GHG emissions.

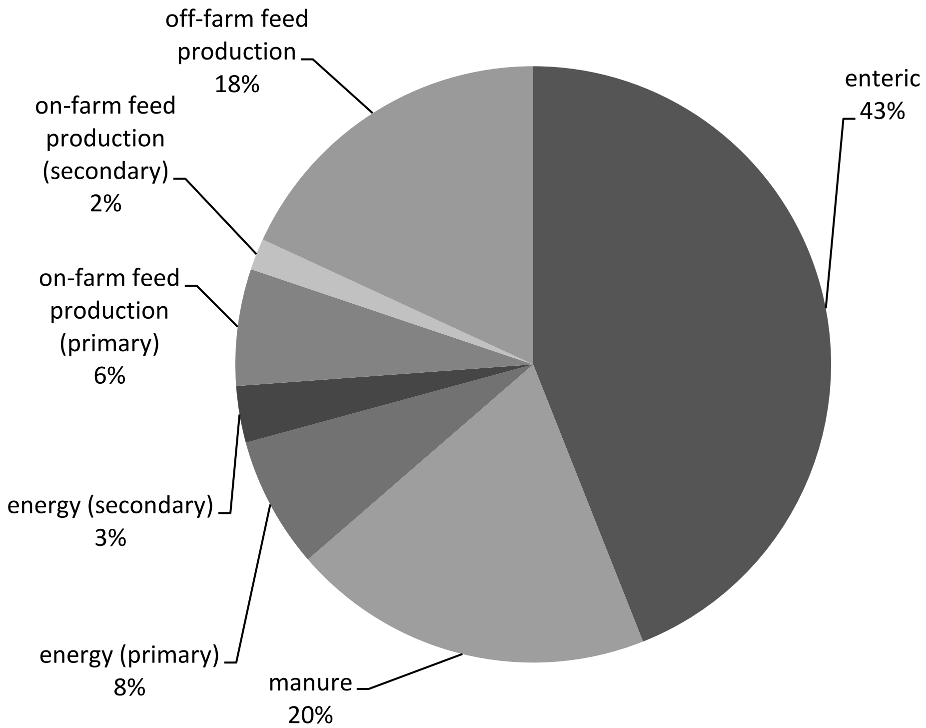

Figure 2.2. Emissions distribution by carbon footprint components (n=285).

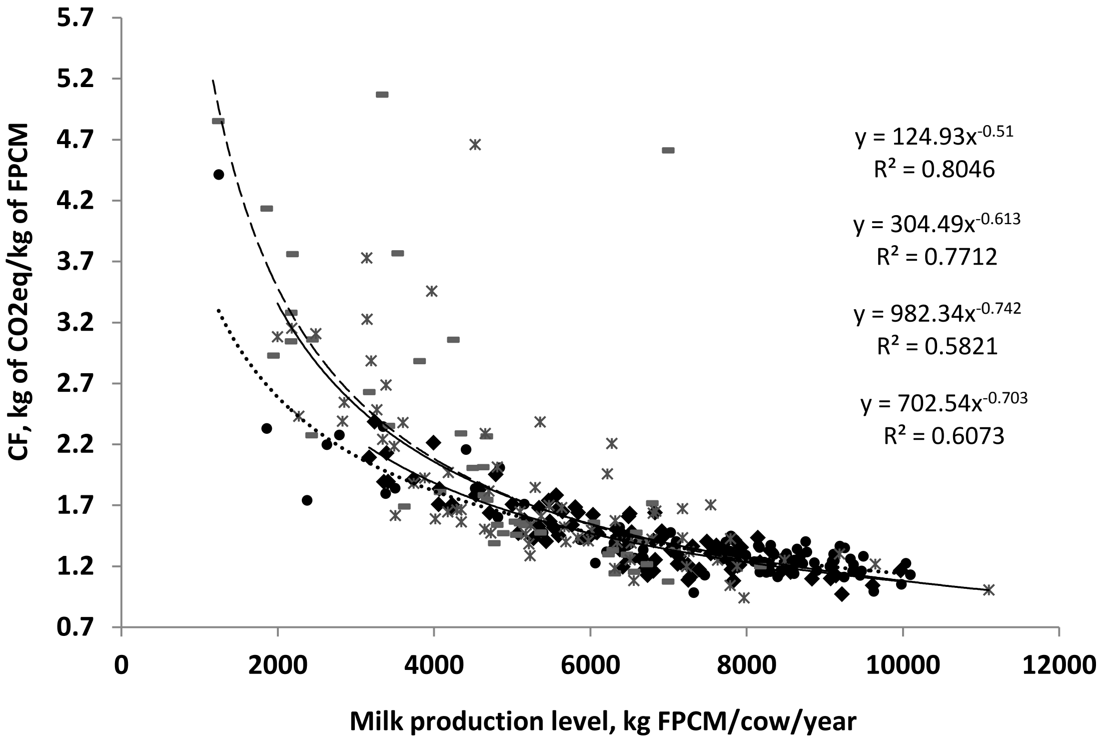

Figure 5.3. Carbon footprint and cow production level (n = 285).

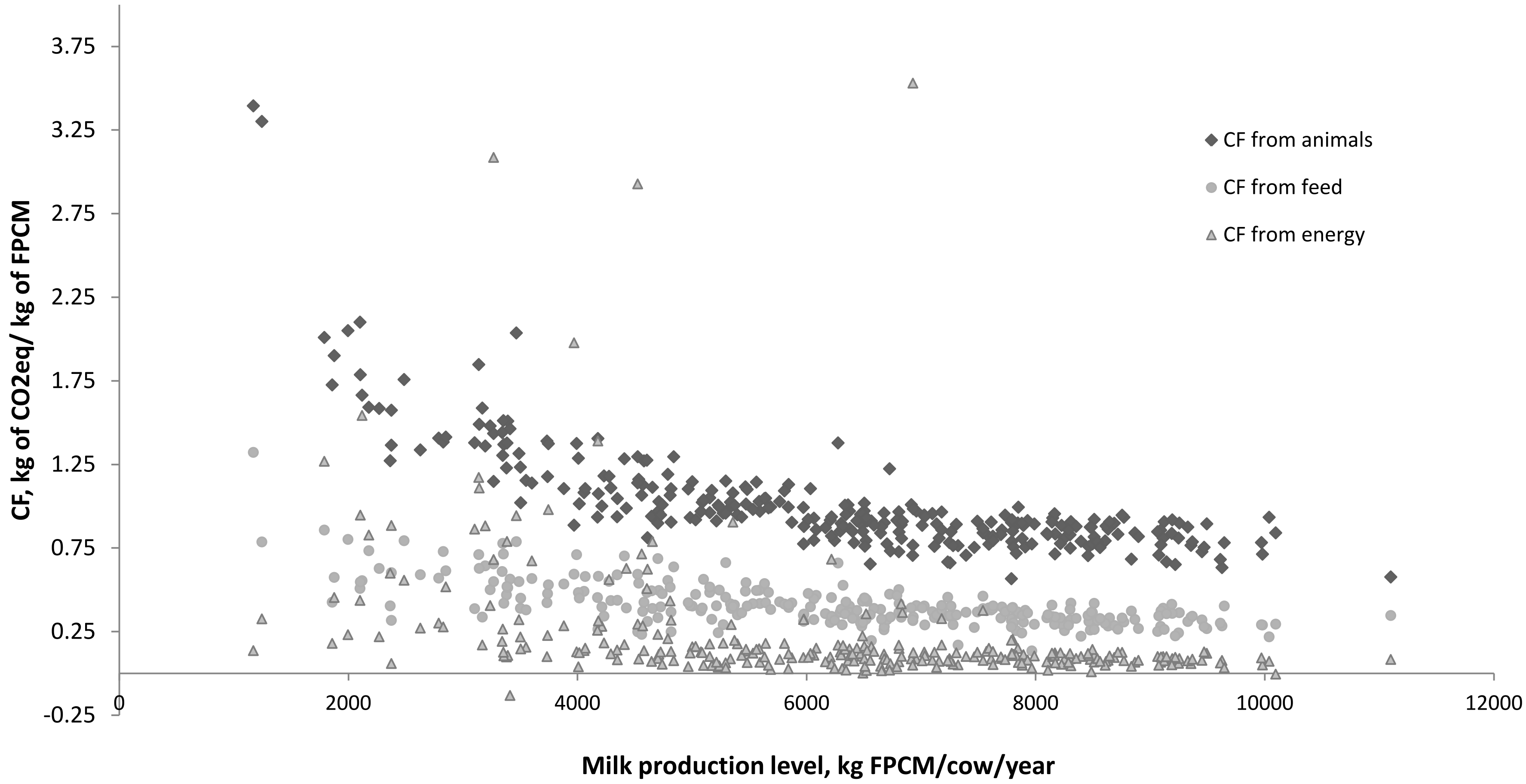

Figure 2.4. Correlation between milk production level and Carbon footprint of the 3 main emissions sources of the dairy farm.

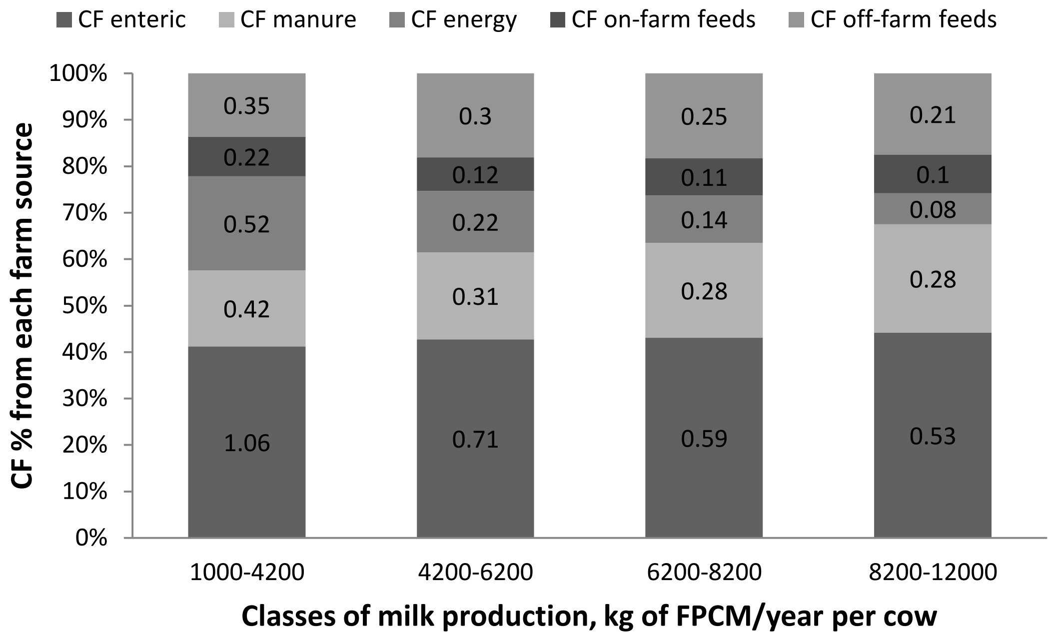

Figure 2.5. Distribution of the CF within the 5 main emission sources for 4 milk production levels.

Chapter 3

Comparison of different approaches to obtain values of methane enteric emissions to be used in carbon footprint calculations for dairy cattle farms.

3.1. Introduction

Production and elimination of methane from digestive tract is considered a physiological exigency for the ruminant (Moss et al., 2000). Methane production helps to maintain oxidative conditions of rumen anaerobic environment through reoxidation of electron carriers cofactors, such as NADH, $FADH_2$ and ferredoxin; on the other hand it represents a loss of energy for animals that removing CH_4 from their bodies by belching and flatulence can lose about the 6% of ingested energy (Johnson and Johnson, 1995). The interest into quantify, estimate and reduce methane losses is an essential factor in animal breeding, nutrition and management, because almost 2/3 of farm costs derive from feeds (Szumacher-Strabel and Cieślak, 2012). However, methane emissions can be considered at the same time an energy loss for animals and a strong environmental pollutant (Vercoe, 2007) with an effect of 25 times higher than CO_2 on the greenhouse gas pollution (GHGs) and global warming (IPCC, 2006). In addition about 50% of emissions of global methane have to be attributed to livestock activities and are mostly represented by enteric emissions of raised cattle. For that reason a large number of studies have been carried out, already many years ago (Blaxter and Wainman, 1961; Steele et al., 1992) or more recently (Aguerre et al., 2011), to understand the biological processes, to directly and indirectly estimate and quantify enteric methane production of ruminants and to understand which strategies can be more effectively applied at farm level in order to improve both the animal efficiency and the environmental performances of the milk supply chain. CH_4 enteric emissions are mainly affected by feed ration characteristics, animal production levels, animal management and genetics characteristics (Monteney et al., 2006; Aguerre et al., 2011). Hydrogen rumen production is closely connected with feed characteristics because VFA derive from feed fermentations; acetate, butyrate and propionate are produced using different feed substrates and each one of them can originates or accept different amounts of H_2 (Moss et al., 2000); dietary fats can also reduce hydrogen concentration or either indirectly increase methane emission by reducing feed digestibility (Hristov et al., 2013). Many models have been published to propose equations that allow to predict and estimate enteric methane emission of dairy cattle using different approaches. Linear and non-linear equations were developed in order to perform quickly estimations of enteric methane that might be used for nutritional purposes (e.g. to estimate the amount of energy losses caused by methane eructation (Johnson and Johnson, 1995) or with environmental purposes (e.g. to estimate the global warming potential of world herd size; Gerber et al., 2011). Direct or indirect measurements are not always feasible,

especially when estimations are referred to big areas like regions, countries or even continents; in addition, the application of direct and indirect methods would be expensive and they would require too much time to be realized. Models and set of equations used to predict methane emission are associated, positively or negatively, to various predictors, mainly dietary factors and physiological characteristic than can be obtained for many animals or farms (Storm et al., 2012). The proposed equations basically differ for the variables that take into account and the predictions made (Bhatta et al., 2007). The most simplified method is the IPCC (2006) TIER 1 which proposes a default value for lactating cows and for other cattle per world macro areas taking into account the mainly adopted livestock systems. More detailed methods or equations were developed, in order to account only for animal energy requirements or DMI (TIER 2 IPCC, 2006; Corrè 2002; Mills et al., 2003; Gerber et al., 2011) and they where further used as reference in simplified sets of equations (Pirlo e Carè, 2013; Rotz et al.,2010). Other empirical equations, based both on animal requirements and dietary information, were developed aggregating large individual databases from previous studies (Ellis et al., 2008). More specific models were developed analyzing additional effects of dietary components such as organic matter digestibility, NDF or ADF intake and content, fat content, fatty acid profil of the diet, NSC or NFC content, feeding level etc (Moe and Tyrrel, 1979; Ramin and Hutanen, 2013; Wilkerson et al., 1995; Sauvant and GigerRiverdin, 2009) and then sometimes used in whole farm models (Ellis et al., 2010). Recently a large review of the literature and the models used and proposed for methane enteric estimation in dairy cattle was reported by Hristov et al., (2013). In their report the authors also cited equations based on animal information and dietary composition elaborated by Moraes et al., (2013; cited by Hristov et al., 2013) especially developed for quantification and planning of mitigation strategies of enteric methane emissions.
The choice of the equations and coefficients to be used for the CF estimation represents a crucial point within al the estimation phases. Despite the large number of models available for the CF estimation, there is still some uncertainty about all the models that should be used for the environmental issue. Frequent doubts in CF estimations regarding the use prediction equation in whole farm models or in large inventories are: i) if different models returns different estimations in similar conditions and, ii) if the effort to gather detailed information from the area of study can be counterbalanced obtaining more accurate outputs. In fact, from a generic perspective, the use of more complex equations sets (i.e. based on dietary composition in respect to equations that only uses animal intake or animal body weight) can potentially give a better description of the variability of studied system or, at the opposite only represents a different way to obtain similar results. Starting from these considerations the aim of this work was to test few different approaches, recently suggested to estimate enteric methane emissions in dairy cattle farms or regional areas, using information reported in a regional database of Southern Italy farms and to discuss the differences in enteric methane and its effects on total farm emissions.

3.2. Material and methods

Enteric methane estimation approaches

Methane enteric estimates were performed using 8 approaches that were based on literature coefficients and equations. Selected approaches were:

1. TIER I reported in the Volume 4, Chapter 10 of IPCC (2006) guidelines;
2. TIER II reported in the Volume 4, Chapter 10 of IPCC (2006) guidelines;
3. TIER II modified: diet energy digestibility (Sauvant and Giger-Riverdin, 2009);
4. TIER II modified: energy digestibility (Sauvant and Giger-Riverdin, 2009) and fraction of gross energy intake emitted as enteric methane (Ym; Gerber et al., 2011);
5. CH_4 emission estimated with equations suggested by Hristov et al., 2013;
6. Linear equation 2d of statistical models developed for dairy, table 5 of Ellis et al., (2008);
7. Linear equation 7d of statistical models developed for dairy, table 5 of Ellis et al., (2008);
8. Non linear equation 2 of Mills et al., (2003) reported in table 3 of Ellis et al., (2008).

Complete equations and details are listed in Table 1. For each selected approach, when specific equations for different animal categories were proposed by the same reference, they were used together, alternatively the equation for lactating cows was applied to lactating and dry cows and heifers.

Dataset and emission calculations

Data used for the evaluation were obtained from a sample of farms associated with 4 cooperatives operating in Southern Italy (3A for Sardinia, Granarolo for Puglia and Basilicata, Asso.La.C. for Calabria, Progetto Natura for Sicilia). The selected sample included 285 farms among all cooperatives (A = 83 farms; B = 88 farms; C = 44 farms; D = 70 farms). A detailed survey to farmers was realized in order to collect farm data and the information needed for the CF estimation regarding i) general information (location, owned ha, raised animal categories, labor, etc), ii) herd consistency, and feeding and manure management adopted for each animal group iii) farm's energy utilization, equipment and tools characteristics, machines and farm operations, milking plant, irrigation, and energy production plants iv) crops cultivation and crops yield, and to farm lands management and fertilizations. The information collected with the detailed questionnaire were implemented in a file Excel® in order to perform the calculations of GHGs emissions.

All the animals within each farm were divided into three categories: lactating cows, dry cows, and young animals; this last group was divided in three subgroups: calves, open heifers and pregnant heifers. The number of replacement calves was also separately recorded. The amount of monthly milk production of each farm was obtained from the cooperatives records and converted into fat and protein corrected milk (FPCM; 4.0% of fat and 3.6% of crude protein) using the equation suggested by IDF (2010):

FPCM (kg) = milk (kg) × (0.1226 × fat % + 0.0776 × protein % + 0.2534).

Net energy (NE) requirements of the herd were calculated using the Tier II set of equations of IPCC, (2006), and then DMI was calculated as GE/18.45. Efficiency of energy use DE to ME was calculated equal to 0.82 (NRC, 2000). Ration digestibility in the reference database was estimated with the equation of Sauvant and Giger-Riverdin, (2009) except than for calves from birth to weaning for which an average digestibility of 85% was considered. Considering that calves were included in the default values off IPCC (2006) Tier 1, emission from calves were calculated for all the approaches using emissions obtained with approach 2; it was preferred to avoid the exclusion of calves from the dataset.

The IPCC (2006) estimation method was chosen to calculate the emissions from manure management, and crop cultivation. CO_2 emissions arising from the use of electricity, oil and gas were calculated from energy farm's consumptions estimated from an energetic audit. The emission from purchased or produced feeds where obtained separately per each type of feed used in the farm. The consumption of each feed type was obtained by combining the estimated DMI with the proportion of feeds supplied to each animal category which was gathered from the ration information reported in the survey. The CO_2eq emissions were calculated as the product of the quantity of every type of feed consumed by each animal category and a coefficient of emission (kg of CO_2 /kg of DM) of the same feed type. For produced feeds the emission coefficient was calculated from survey data on the agronomic practices adopted for each crop cultivation, using the IPCC (2006) method as reference basis. For purchased feeds in the local market (mainly hays and silages) were used the average values of emission calculated in the same database for local crops; for imported feeds coefficient measured by Mogensen et al. (2012) were used.

In this research CO_2 absorption by plants and CO_2 emissions from animal respiration, manure and soils were not accounted for, considering those as accounted for in the short term biogenic carbon cycle (IDF, 2010).

All the equations and coefficients not included in the IPCC (2006), but used to obtain emissions from manure management, feed production, purchased feeds and energy use or production were detailed in the Chapter 2 of this thesis.

Following the Life Cycle Assessment (LCA) procedure (ISO, 2006), the selected system boundaries included only the emissions "from-cradle-to-farm-gate", considering only emissions generated from the input production until the milk storage in farm facilities (i.e. transport of milk fro farm to processing plant was excluded). The criterion of biological allocation between milk and meat was used to calculate emissions attributed to milk (IDF, 2010).

For each one of the 285 farms CH_4 enteric emission of raised animals, emission related to manure management, produced and purchased feeds and energy consumption were calculated with the 8 selected approaches and the whole farm CO_2eq emissions for farm was obtained. Carbon footprint was then expressed as kg of CO_2eq emissions per kg of FPCM produced.

Sensitivity analysis

A sensitivity analysis was performed on the parameters considered by the selected equations. Independent variables of equation reported in Table 1 were changed at once in order to asses the differences estimation of enteric methane within a range of variation for each independent variable included between mean ± 2.5 × standard deviation (SD) of values observed in surveyed farms. Average, maximum and minimum enteric emissions were calculated for a lactating cow of 626 kg of BW, producing 6206 kg of FPCM in a standard lactation of 305 days.

Statistical analyses

Data were analyzed with the statistical software MINITAB 16 (2010). Before the comparison of method, 3 farms were excluded as outlier from the original dataset because surveyed farm data were not biologically consistent. On the remaining 282 farms, differences among the 8 approaches, on methane and carbon footprint estimates, were evaluated using a general linear model analysis. The approach was included as fixed factor in the model (8 levels).

The farms were divided in three groups for productive level of the herd (MYL; kg of FPCM/year per cow) from 1000 to 3999, from 4000 to 6999, and ≥ 7000 respectively. Then, a nested general linear model was used to evaluate the differences among the selected approaches (8 levels) within classes of herd milk production (3 levels). Tuckey method was preferred for comparisons. Final results were graphically shown in a boxplot of the calculated data per classes of production level in order to show the observed range of variation.

3.3. Results

Farms description

Studied farms raised a mean (±SEM) of 71 (±4.2) mature cows ranging from 8 to 820. The most part of the raised cattle were Frisona Italiana including a small part of Bruna, Pezzata Rossa and other crossbreeds. Average herd profile was described in details in Table 3.1. Considering the raised breeds, the average body weight, in the overall dataset, resulted 625 (±2.26) kg for mature cows, 438 (±1.58) for pregnant heifers and 294 (±0.8) kg for non-bred heifers (Table 3.2).

Average milk yield of the studied farms was 6206 (±124) kg of FCPM/yr per present cow. Estimated dry matter intake of lactating cows, on the basis of energy requirements, resulted in 16.7 (±0.16) kg/d, ranging from 9.9 to 24.0 kg/d; diet included, on average, 46% of concentrates, 43% of NDF and 4.4% of ether extract (EE). Lower intake and percentage of concentrates and fat, and higher values of NDF were observed for non-productive categories of cattle (Table 3.2). Energy digestibility of lactating cows was on average 69% of GE, higher than the value of 65% considered by the TIER II of (IPCC, 2006).

Results of the sensitivity analysis on the reference lactating cow showed that TIER I and TIER II have low flexibility in respect to the other methods (Table 3.3). The estimation of CH_4 emission with TIER II leaded to slightly higher value of CH_4 than TIER 1 (Table 3.3). It was probably due to the specific characteristics of the cows and diet the studied farms (i.e. BW, maintenance requirements); in addition, in TIER 1 emissions of the dry period are included in the default value, whereas only 305 days of lactation and respectiveenergy requirements for pregnancy and activity are considered for the other approaches.

Changes in CH_4 emission (kg/yr per cow) considering a variation of mean ±2.5 × SD of each independent variable used in the equation will be presented. The use of equation to estimate the DE of the diet, (approach 3, DE prediction on concentrate to forage ratio; Sauvant and Giger-Riverdin, 2009), estimated emissions 3 kg lower than TIER I and 7 kg lower than TIER II, introducing changes of the 10 % of the mean for emitted CH_4 (Table 3.3). The estimation of Ym using the approach 4 (Ym predicted using DE information; Gerber et al., 2011) resulted in a overall reduction of the average annual enteric emission, until 111 kg/yr per cow, and caused additional changes of CH_4 emission equal to 5% of the mean, in the considered range of DE.

The integration of diet composition and gross energy intake using the approach 5 (CH_4 emissions predicted using the equation of Hirstov et al., 2013) resulted in higher variability in respect to previous approaches and returned an overall value of emissions of about 98 kg/year of CH_4 per cow, lower than the previous approaches. In the considered range of variation of the correspondent independent variables, the changes of CH_4 estimates resulted equal to ±27%, ±6% and ±10% of the mean in the cases of gross energy intake (GEI), NDF % of DM and EE, respectively. Using the approach 6, (equation 2d of Ellis et al., 2008) which accounted for the only DMI of the cows, was predicted the lowest values of annual emissions per head was predicted (on average 92 kg of CH_4; Table 3.3) but introducing large variability within the two extremes of DMI considered (±33% of mean emission).

Using diet information with the approach 7 (CH_4 emissions predicted as a function of metabolizable energy intake (MEI, Mj/d) and NDF intake (kg/d), equation 7d of Ellis et al., 2008) the highest average values of emission was predicted, equal to 133 kg of CH_4 /year per cow, with changes of ±12% of mean caused by variation of MEI, and ±39% of mean caused by variation in NDF intake.

Using the only variation of MEI (approach 8, Mills et al., 2003) the average emission value was equal to 105 kg of CH_4 /year per cow with variation of 34% of the mean within the observed range of MEI.

Average annual values of methane emission per each animal category were calculated per each farm using all the 8 approaches and results were reported in Table 4.

For lactating cows mean (±SEM) value obtained including all methods was 131.6 (±0.9) kg of CH_4/yr per head ranging from 117 to 159 kg. The values of approaches 2 and 7 were the highest among others (148 and 159 kg, respectively; $p < 0.05$); intermediated values of emissions were given by the approaches 3, 4 and 8 (between 125.1 and 136,6 kg), and the lowest values of 117 kg was given by the approaches 1, 5 and 6. The differences observed between the values of sensitivity analysis and the results obtained in the sample of 282 farms are due to the fact that data of 282 farms were calculated considering 365 days of presence for the animal groups.

For dry cows mean (±SEM) value obtained including all methods was 77.1 (± 0.6) kg of CH_4/yr per head. The value from approaches 1, 7 and 5 resulted to be highest and significantly different than others ($p < 0.05$). The values obtained from approaches 2, 3, 4, 6 and 8 presented very little differences among them and ranging between 63.5 kg and 67.3 kg of approaches 2 and 4, respectively.

For pregnant heifers mean (±SEM) value obtained including all methods was 66.7 (± 0.6) kg of CH_4/yr per head. Among all, the value of approach 1 and 5 obtained, among all, the lowest values (($p < 0.05$) whereas the approach 7 obtained the highest value (($p < 0.05$). The values from approaches 2, 3, 4, 6 and 8 presented very little differences among them, ranging between 64.3 kg and 67.1 kg of approaches 2 and 4, respectively. For non-bred heifers mean (±SEM) value obtained including all methods was 57.8 (±0.9) kg of CH_4/yr per head. Among all, the value of approach 5 obtained, among all, the lowest value ($p < 0.05$), whereas the approach 7 obtained the highest value ($p < 0.05$). The values obtained from approaches 1, 2, 3, 4, 6 and 8 presented very little differences among them, ranging between 54.6 kg and 59.4 kg of approaches 2 and 6, respectively.

For calves the value of approach 1 was about 5 times higher than the sum of 365 days of emissions of an unweaned calf calculated with the approach 2. Values of 33 g of CH_4/d per head were observed using DE of 85% of GE, and Ym of 6.5% of GE.

The average value calculated per livestock unit, (total enteric emissions divided by number of mature cows) by all methods resulted equal to 199.2 (±2) kg of CH_4/yr per head. The highest value was given by the approach 7 (243 kg of CH_4/yr per head; $p < 0.05$); whereas intermediated values were given by the approaches 1, 2, 3 and 4 (between 195.4 and 209.5 kg), and lowest values were given by the approaches 5, 6 and 8 (between 177.1 and 186.6 kg).

Emissions of an average raised head considering all methods resulted equal to 90.9 (± 0.8) kg of CH_4/yr with similar differences among approaches as presented for livestock unit.

In terms of CO_2eq per kg of FPCM the differences among approaches were less noticeable (Table 3.5) because the effect of all categories and the milk production level were combined. Estimated emissions ranged from 0.64 and 0.88 kg of CO_2eq per kg of FPCM. The approach 7 resulted in highest emissions ($p < 0.05$), the approaches 1 and 2 returned intermediate emissions in respect to others ($p < 0.05$), whereas approaches 5, 6 and 8 returned the lowest values of emissions ($p < 0.05$). Approaches 3 and 4 were not statistically different from approaches 1, 2, 5 and 6.

The differences were further reduced with the inclusion of the manure and feed production management and energy use. The final value of carbon footprint allocated to milk ranged from 1.45 to 1.67 kg of FPCM. Only the approach 7 was significantly higher than others ($p < 0.05$) and not significantly different than approach 2. The proportion of enteric methane on total emissions reflected the differences among approaches already observed for enteric emissions expressed per kg of FPCM (Table 3.5).

When estimates of different approaches were analyzed within classes of production level (MYL), the results indicated that methane emissions per cow increased with MYL and emissions of methane and CO_2eq per kg of FPCM decreased with MYL (Table 3.6). It was already observed in literature by many authors (Capper et al., 2009). However, when methane emissions were expressed as kg of CH_4/year per livestock unit (mature cow and relative proportion of young cattle) they were negatively associated with classes of MYL for the approach 1 whereas positively associated with classes of MYL for all other approaches. Interestedly, within classes of MYL, the differences on estimates among approaches were still evident also when all farm emission sources were considered and when results were expressed as milk carbon footprint in CO_2eq per kg of FPCM (Table 3.6).

3.4. Discussions

Studied sample included a large number of combinations of herd profiles, farming systems, farm equipment and milk production level. Average milk yield of the studied farm (6206 ± 124 kg of FCPM/yr per cow) was very close to that one considered by the IPCC (2006) for west Europe dairy farms (6000kg of FCPM/yr per cow); it made reasonable the comparison with approach 1 (TIER 1, IPCC, 2006). Furthermore, a large number of information was available in the original database to calculate emission using different approaches including dietary composition variables. It allowed testing also the most recently developed equations for CH_4 enteric prediction, suggested by Hristov et al., (2013) in order to perform inventories at farm level pursuing objective of mitigation strategy planning.

Obtained values were in the range of emissions observed in other works respectively to equations used. Observed values of emissions are included in the range of values reported in different studies, carried out with different dietary treatments, cited by Ellis et al., (2010) that varied between 76 and 168 kg of methane/cow on annual basis. In particular the studies of Moe and Tyrrel (1977) where the DMI was at the same level of the studied farm and the proportion of corn in the diet was equal 45% of DM the emissions resulted equal to 113 kg of enteric methane on annual basis. The sensitivity analysis revealed that average emissions of a general lactating cow it could range from 91 to 133 kg of enteric methane per lactation just with the effect of the range of variation of a single variable within the developed dataset. On the other hand, the effects of considered predictors could have an effect lower than 10% (DE in approach 3 or NDF in approach 5) or higher than 30% (DMI in approach 6, NDF intake in approach 7 and MEI in approach 8; Table 3). Maximum and minimum values of emission calculated within the range of variation observed in experimental dataset (equal to mean ± 2.5 times SD of independent variables) ranged from 62 (approach 6) to 202 kg/year of methane per cow.

The approach 1 can be considered as an average reference for other approaches. The approach 2 gave significant higher results than the approach 3 and 4 because of the effect of its higher DE on GE intake. On the other hand a small and not significant effect of Ym was observed comparing the approaches 3 and 4. Looking at the values calculated for each animal category, the strictest approach (1) and the most flexible approach (5) gave similar average results for lactating cows; approach 6 was not different from them. Considering that i) approaches 2, 3 and 4 were mainly based on the effect of DE, and ii) DMI intake was based also on DE, approach 6 lead to lower significant values than approaches 2, 3 and 4. A probable estimation of DMI with other equations (i.e. NRC, 2001) and a further comparison is needed to explore that result.

In respect to the approach 1 all the approaches resulted more flexible to estimate the emission of the young categories of cattle (Table 3.4). Emissions for calves need to be discussed separately. In fact, the IPCC, 2006 judge calves as the same of other cattle in the TIER 1. Thus, their emission resulted too high in comparison to their biological characteristics. In fact, applying the approach 2 or other equations the emission of calves were heavily reduced (Table 3.4). In addition, Berends et al., (2012), testing the use of different proportion of solid feeds on dairy calves (108 kg of BW; based diet 800 kj/d from milk), found that supplying an additional amount of solid feed from 0% to 40% of total GE intake, methane emissions ranged from 2 to 36 g/d of enteric methane per head, and 0.2% and 2.2% of GE, respectively.

Estimates of enteric emission for non-bred heifers, resulted similar to TIER 1 for the approaches 2, 3, 4, 6, and 8 and lower for approach 5. On the other hand all the approaches estimated higher emission than approach 1 for pregnant heifers, indicating that the approach 5 (the only one including a special equation for young cattle), returned the most flexible method, and close results, on average to the TIER 1. Emissions of dry cows were similar to those obtained for pregnant heifers, except than in approach 1 that uses a single default value for all mature cows, and except in approach 5 that suggested a separated equations (Table 3.1) for dry cows and pregnant heifers (Table 3.4). Results reflected that the dry cows, in respect to pregnant heifers, had higher maintenance requirements and lower growth requirements, but often those groups were fed with similar diets (Table 3.2) and only specific equations can help to highlight real differences.

Values expressed per kg of FPCM little differences were observed among approaches for enteric methane, on average, and there were even not evident when included in the total carbon footprint allocated to milk. Even if a detailed exploration of the effect among farms was not executed, it is possible to state that all approaches performed with good accuracy and they can lead to similar results when used to study large areas or a large number of farm. This result was also obtained by Guerci et al., (2013) which compared a simplified approach (TIER 1 of IPCC, 2006) vs a detailed approach (modified TIER 2 method of IPCC, 2006). In their work they concluded that, the good accuracy, might justify the use of a simplified method to estimate animal emissions in large inventories, sparing time and efforts in order to obtain quickly results. A similar approach for animal emissions and a detailed approach for other emission sources was used by Fantin et al., (2012) for a LCA estimations in Italian dairy farms. The same group of Guerci et al., (2013) suggested that detailed methods can be useful for the investigation of dairy production processes and especially for the identification of the most viable mitigation strategies for specific farms and areas (Guerci et al., 2013). It was the purpose of Hristov et al., (2013) which developed a specific set of equations adapted to predict enteric methane for mitigation strategies evaluations. Estimates performed in this comparison were the most flexible The equations of Hristov et al., (2013) gave the best performance in this approach comparison in terms of flexibility moreover when results were compared within classes of productive level. In fact, the approaches 2, 3, and 4 where limited by the fact that all the variability is generated by the estimation of DE (Table 3.1). Hristov et al., (2013) reviewed the limits of equations that did not account for dietary components (i.e. fiber, carbohydrates and ether extract) explaining their limits in to explain the variability of methane emissions. The approach 6, which accounted for DMI, and the approaches 7 and 8 which accounted for dietary components, respectively were considered less flexible than approach 5 when emissions of unproductive categories were compared (Table 3.4). Specifically, approach 6 returned very similar estimations, on average, to approach 5 but have to be considered that estimation of DMI in this database was based on GE, that accounted for the larger variability in the sensitivity analysis of equation 5 (Table 3.3). A further comparison with different estimations of DMI should be performed in order to better compare the average values of approaches 6 and 5 in specific.

Looking also at the difference within MYL is possible to notice that the importance of detailed methods and approaches based on dietary information might be more important when the MYL of the farm increases. It can be explained with the fact that in farms with low MYL, unproductive categories have ha heavy impact on nutritional efficiency and on emission per kg of milk because of the low milk yield. This impact is higher than in farms with high MYL, even if intensively managed farms have a bigger percentage of young animals per cow, as observed in the Chapter 2 of this thesis. Consequently, the proportion of young and dry animals in respect to lactating cows and the dilution of maintenance requirements on high milk productions are the main factor causing differences on emissions in farms with low MYL. At the same time this differences can be detected also by using a simplified approach or by a method that account for energy requirements. On the other hand, in intensive farms, and probably even more within farms in small ranges of high production level, the differences in animal emissions are mainly caused by diet formulation, fiber quality, concentrate type and percentage and type of fat.

3.5. Conclusions

In this work, 8 approaches to estimate methane enteric emission of a large sample of dairy cattle farms located in Southern Italy were compared. Mean values of enteric emissions calculated with different approaches and the impact of these estimations on the quantification of the farm carbon footprint was evaluated. From this analysis resulted that all considered approaches behave with similar accuracy often returning the same average values on the entire dataset. However, approaches based on animal consistency, performance and requirements might be enough detailed for quantification inventories in large areas or at farm level. At the opposite, approaches based on dietary composition and with detailed equations for animal categories should be preferred to highlight differences among farms and within farm intensively managed, in order to plan effective methane mitigation strategies.

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3.7. Tables

Table 3.1. List of methods and equations tested to estimate enteric methane emissions of different animal categories.

Approach	Reference	Equation used		
		Lactating cows equation or values	Dry cows	Replacement cattle
1	**IPCC, 2006 TIER 1**	117 kg CH_4 / year per head	57 kg CH_4 / year per head	57 kg CH_4 / year per head
2	**IPCC, 2006 TIER 2**	DE = 65% of GE;Ym= 6.5% of GE	DE = 65% of GE; Ym = 6.5% of GE	DE = 65% GE; Ym = 6.5% of GE
3	**IPCC, 2006 TIER II modified DE from Sauvant (2009)**	DE 59,3 + 21,2 PCO; Ym = 0.065	DE 59,3 + 21,2 PCO; Ym = 0.066	DE 59,3 + 21,2 PCO; Ym = 0.067
4	**IPCC, 2006 TIER II modified DE from Sauvant (2009 and Ym from Gerber et al., 2011)**	DE = 59.3 + 21.2 PCO; Ym = 9.75−0.05×DE	DE = 59.3 + 21.2 PCO; Ym = 9.75−0.05×DE	DE = 59.3 + 21.2 PCO; Ym = 9.75−0.05×DE
5	Hristov **et al., 2013**	CH_4 (GE Mcal/day) = 0.37 (0.37) + 0.0392 (0.0015) GEI (Mcal/day) + 0.0189 (0.0077) NDF (% of DM) – 0.156 (0.034) EE (% of DM) + 0.0014 (0.0003) BW (kg)	CH_4 (GE Mcal/day) = 0.45 (0.13) + 0.0503 (0.0014) GEI (Mcal/day) – 0.0556 (0.015) EE (% of DM) + 0.0008 (0.0002) BW (kg)	CH_4 (GE Mcal/day) = – 0.056 (0.122) + 0.0447 (0.0028) GEI (Mcal/day) + 0.0039 (0.0018) NDF (% of DM) – 0.033 (0.019) EE (% of DM) + 0.00141 (0.00014) BW (kg)
6	**Ellis et al., 2008**	CH_4 (MJ/d) = 3.23 (± 1.12) + 0.809 (± 0.0862) × DMI (kg/d)	CH_4 (MJ/d) = 3.23 (± 1.12) + 0.809 (± 0.0862) × DMI (kg/d)	CH_4 (MJ/d) = 3.23 (± 1.12) + 0.809 (± 0.0862) × DMI (kg/d)
7	**Ellis et al., 2008**	CH_4 (MJ/d) = 1.64 (± 1.56) + 0.0396 (± 0.0170) × ME intake (MJ/d) + 1.45 (± 0.521) × NDF (kg/d)	CH_4 (MJ/d) = 1.64 (± 1.56) + 0.396 (± 0.0170) × ME intake (MJ/d) + 1.45 (± 0.521) × NDF (kg/d)	CH_4 (MJ/d) = 1.64 (± 1.56) + 0.396 (± 0.0170) × ME intake (MJ/d) + 1.45 (± 0.521) × NDF (kg/d)
8	**Mills et al., cited by Ellis et al., 2008**	Nonlinear 2: CH_4 (MJ/d) = 45.89 − (45.89 + 0) × e[−0.003 × MEI (MJ/d)]	Nonlinear 2: CH_4 (MJ/d) = 45.89 − (45.89 + 0) × e[−0.003 × MEI (MJ/d)]	Nonlinear 2: CH_4 (MJ/d) = 45.89 − (45.89 + 0) × e[−0.003 × MEI (MJ/d)]

DE = diet energy digestibility, % of gross energy; PCO = percentage of concentrate in ration; GE = gross energy; Ym = percentage of gross energy intake converted to methane; NDF = neuter detergent fiber, % of DM; EE, ether exctract, % of DM; GEI = gross energy intake; MEI = metabolizable energy intake. × = fixed values correspond to mean values of the variable used for the same equation (GEI = 308 MJ/d; NDF =42,7% of DM; EE 4.36 % of DM; MEI = 181 Mj/d; NDF intake = 10.7 kg/d).

Table 3.2. Herd chacteristics of the sampled farms.

Item	UM	Lactating cows		Dry cows		Pregnant heifers		Non-bred heifers		Calves	
		Mean	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**	**Mean**	**SEM**
Cattle heads	n	58.2	3.50	13.0	0.77	20.7	1.23	22.5	1.33	12.7	0.75
Current body weight	kg	625.9	2.26	625.9	2.26	438.2	1.58	294.1	0.79	70.0	0.04
Weight gain	kg/d			0.200	0.001	0.500	0.001	0.800	0.001	0.800	0.001
Milk yield	kg/year per cow	6206	124	-	-	-	-	-	-	-	-
Dry matter intake	kg/d	16.67	0.16	8.45	0.05	8.48	0.05	6.99	0.04	1.71	0.08
Concentrate in ration	% of DM	0.46	0.01	0.19	0.01	0.22	0.01	0.27	0.01	0.65	0.02
Neuter detergent fiber	% of DM	0.43	0.003	0.56	0.004	0.55	0.004	0.52	0.005	-	-
Ether extract	% of DM	0.044	0.001	0.020	0.001	0.021	0.001	0.022	0.001	-	-

Table 3.3. Sensitivity analysis of the effect of independent variables considered by 7 methods on the estimation of enteric methane emissions of lactating cows. The reference animal is a lactating cow of 626 kg of BW, producing 6200 kg of fat (4.0%) and protein (3.6%) corrected milk in 305 days.

Approach	Equation set modified in thisanalysis	Fixedvalues in the equation	Variables	Observed data (n = 282)			CH_4 (kg/yr per head)			
				Mean	Mean +2.5SD	Mean +2.5SD	Mean	Mean +2.5SD	Mean -2.5SD	Diff. frommean
1	IPCC (2006) TIER 1	117 kg CH_4 /head	-				117.0	117.0	117.0	0%
2	IPCC (2006) TIER 2	DE = 65% ofGE, Ym 0.065	-				121.0	121.0	121.0	0%
3	DE = 59,3 + 21,2 PCO %; Ym = 6.5% ofGE	Ym = 6.5%	DE	68.9	75.2	62.7	114.2	104.7	125.6	10%
4	DE = 59.3 + 21.2 PCO %; Ym = 9.75−0.05×DE	DE =65% ofGE	Ym	6.31	5.99	6.62	110.8	96.5	127.9	15%
5	CH_4 (GE Mcal/day) = 0.37 + 0.0392GEI (Mcal/day) +	BW,NDF, EE*	GEI	308	433	183	97.7	124.5	70.8	27%
	0.0189 NDF (% of DM) – 0.156 ×EE	BW, GEI, EE*	NDF	42.67	56.05	29.30	97.7	102.6	91.9	6%
	(% of DM) + 0.0014 ×BW (kg)	BW, NDF,GEI*	EE	4.365	7.115	1.615	97.7	87.8	107.5	10%
6	CH_4 (MJ/d) = 3.23 + 0.809 × DMI (kg/d)		DMI	16.7	23.5	9.9	91.7	121.8	61.7	33%
7	CH_4 (MJ/d) = 1.64 + 0.0396 × MEI (MJ/d)	NDF = 10.7 kg/d*	MEI	181	254	108	133.0	148.9	117.1	12%
	+ 1.45 × NDFintake (kg/d)	MEI = 181 MJ/d*	NDF intake	10.7	19.4	4.2	133.0	202.1	81.8	39%
8	CH_4 (MJ/d) = 45.89 – (45.89 + 0) × $e^{[-0.003 \times MEI (MJ/d)]}$		MEI	181	254	108	105.3	134.1	69.5	34%

DE = diet energy digestibility, % of gross energy; PCO = percentage of concentrate in ration; GE = Gross Energy; Ym = percentage of gross energy intake converted to methane; NDF = neuter detergent fiber, % of DM; EE, ether exctract, % of DM; GEI = gross energy intake; MEI = metabolizable energy intake. * = fixed values correspond to mean values of the variable used for the same equation (GEI = 308 MJ/d; NDF =42,7% of DM; EE 4.36 % of DM; MEI = 181 Mj/d; NDF intake = 10.7 kg/d).

Table 3.4. Enteric methane (kg of CH_4/year per head) estimated with 8 different methods in the studied database.

Approach	**n**	**Lactating cow***	**Dry cow**	**Pregnant heifer**	**Non-bred heifer**	**Calf**	**Livestock unit**	**Average head**
1	282	117.0 e	117.0 a	57.0 e	57.0 bc	57.0 a	201.4 bc	91.6 c
2	282	148.4b	63.5f	64.3c	54.6c	12.1 b*	209.5b	95.7b
3	282	136.6c	66.4 de	66.5 bc	55.0 c	12.1 b*	199.5c	91.0c
4	282	132.4c	67.3d	67.1 b	55.1c	12.1 b*	195.4 c	89.1 c
5	282	116.9e	76.3c	61.1 d	47.7 d	12.1 b*	177.1e	80.7 e
6	282	117.0 e	65.9 de	66.5 bc	59.4 b	12.1 b*	180.6de	82.3 de
7	282	159.0 a	96.0b	86.2 a	77.6a	12.1 b*	243.3 a	111.2 a
8	282	125.1d	64.5ef	65.1bc	55.7bc	12.1 b*	186.6d	85.1d
Mean		131.6	77.1	66.7	57.8	12.1 b*	199.2	90.9
SEM		1.2	0.6	0.6	0.9	12.1 b*	2.0	0.8

Within column, values that not show the same letter are significantly different for $p < 0.05$.The same value obtained with method 6 was applied.

Table 3.5.Emission of CO_2 equivalent estimated with different 8 method in the studied database.

Approach	**n**	**CO_2/kg of FPCM from enteric CH_4**	**CO_2/kg of FPCM from animals and feed production**	**CO_2/kg of FPCM from animals, feed and energy use**	**Carbon footprint, CO_2/kg of FPCM allocated to milk**	**CO_2 from enteric CH_4fraction of total emissions**
1	282	0.76b	1.42bc	1.63 b	1.55b	0.46b
2	282	0.74b	1.46 ab	1.67 ab	1.59ab	0.45 bc
3	282	0.71bc	1.38 bc	1.59 b	1.51b	0.46 b
4	282	0.70bc	1.37bc	1.58 b	1.50b	0.45 bc
5	282	0.64c	1.31c	1.52 b	1.45 b	0.43 d
6	282	0.65c	1.32c	1.53 b	1.46 b	0.43 d
7	282	0.88a	1.55a	1.76 a	1.67a	0.50 a
8	282	0.67c	1.34c	1.55 b	1.47b	0.44 cd
Mean		0.72	1.39	1.60	1.52	0.45
SEM		0.017	0.027	0.038	0.035	0.003

Whitin column, values that not show the same letter are significantly different for $p < 0.05$.

Table 3.6. Comparison of enteric emissions estimated with different methods and their effects on the total carbon footprint emissions in the studied database.

Class of MYL	**Approach**	**CH_4 from lactating cow**	**CH_4 from livestock unit**	**CO_2 from enteric CH_4**	**Milk Carbon footprint**
UM		**kg/year (365 d)**		**kg/kg of FPCM**	
1000-3999 (n=45)	**1**	117.0 jkl	218.3bcdef	1.45a	2.63ab
	2	111.0 klm	178.7hijkl	1.16b	2.47b
	3	105.8lmn	176.7hijkl	1.15b	2.44b
	4	103.9mn	175.3ijkl	1.14b	2.43b
	5	97.84n	167.3l	1.09b	2.39b
	6	97.65n	168.2kl	1.10 b	2.40 b
	7	137.2fg	227.0 bc	1.50 a	2.77a
	8	100.8mn	169.1jkl	1.10 b	2.40 b
4000-6999 (n=130)	**1**	117jk	200.1defg	0.72d	1.46cde
	2	142.3ef	201.4fg	0.72d	1.55cd
	3	130.7gh	191.9ghi	0.69de	1.47cd
	4	126.6hi	187.9ghij	0.68de	1.46cde
	5	113.4kl	171.8l	0.62efg	1.40 def
	6	113.7kl	175.1jkl	0.63ef	1.41def
	7	148.1de	227.3bc	0.82c	1.60 c
	8	121.6ij	181.0 hijkl	0.65def	1.43cdef
7000 (n=107)	**1**	117jk	195.6gh	0.49i	1.09h
	2	171.4b	232.3b	0.59fgh	1.26fgh
	3	156.6c	218.2bc	0.55ghi	1.17gh
	4	151.3cd	212.8cdef	0.54hi	1.15gh
	5	129.1gh	187.5ghijk	0.47i	1.09h
	6	129.1gh	192.4ghi	0.48i	1.10 h
	7	181.2a	269.4a	0.68de	1.29efg
	8	139.6f	200.6efg	0.51hi	1.12gh

3.8. Figures

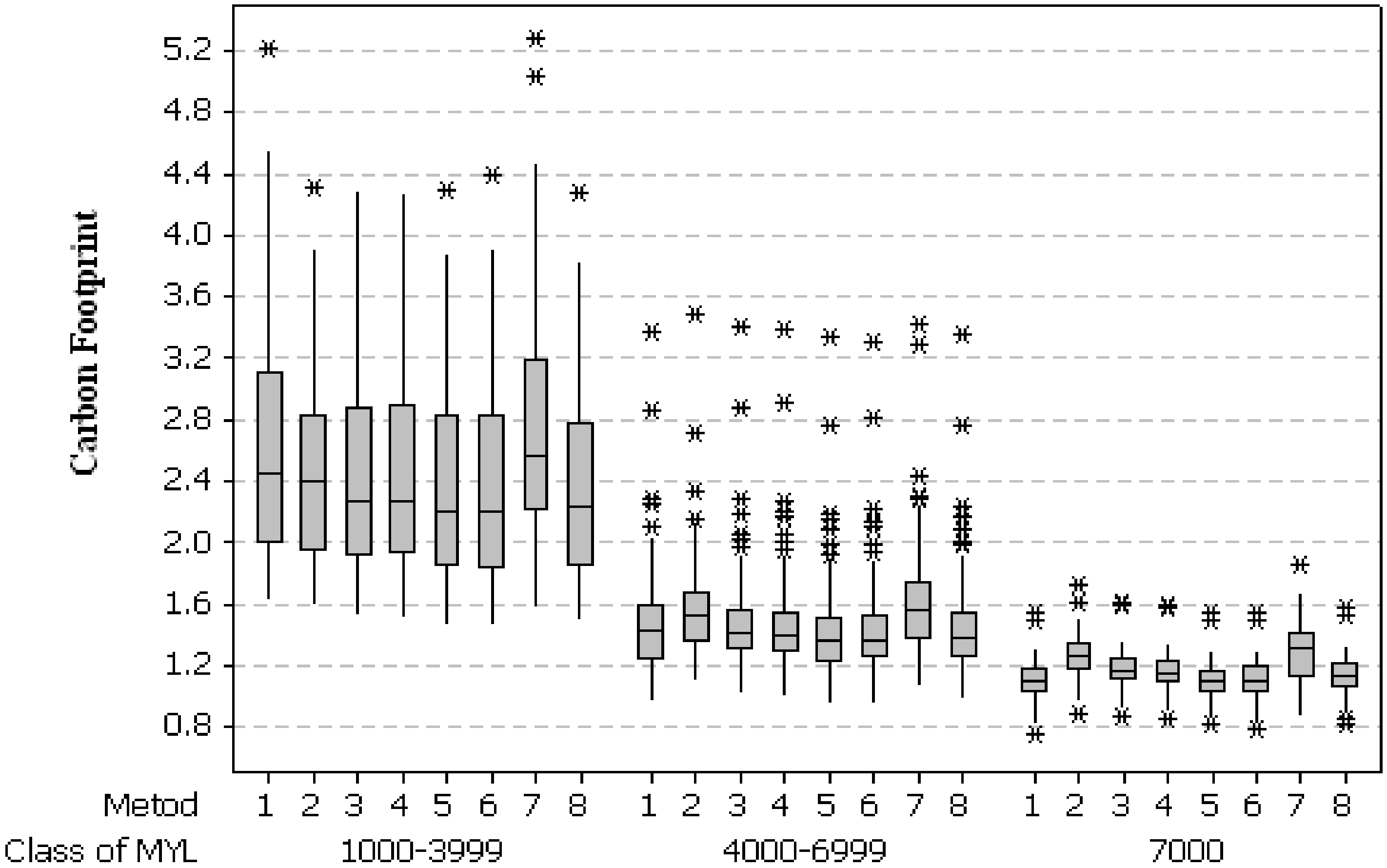

Figure 3.1. Boxplot of carbon footprint values estimated in 3 groups of farms classified on their herd production level (MYL, kg of milk/year per cow) with 8 different methods to estimate methane enteric emissions. Detailed equation set for methane estimation are reported Table 2. Carbon footprint included enteric emissions, manure emissions, on-farm and off-farm feed production emissions, and energy consumption emissions.

CHAPTER 4

Identification of production and management variables of dairy cattle farms of Southern Italy with the highest impact on their emissions of green house gases

4.1. Introduction

Several estimations of the emission of green house gases (GHG) and of the carbon footprint (CF) of the dairy farms have been published, each one realized using different equations, considering different variables, and obtaining different results. The most important variables that are generally considered in a CF estimation of a dairy farm are represented by the number of raised animals and their characteristics (breed, age, body weight), feeds characteristics, manure management (housing solutions for animals and storage solutions for manure), farm crops cultivation, energy consumptions, off-farm production of feed, fertilizers and energy.

Kristensen et al. (2011), Capper et al. (2009), Casey and Holden (2005), and Flysjo et al. (2011) realized the CF of the dairy farms in different countries using different equations and coefficients, but considering the same variables exposed above; the CF values obtained by these authors were included between 1.25 and 1.82 kg of CO_2eq/kg of FPCM. The differences of these results can be explained considering that each estimation was referred to a different farm, and different inputs obviously provide a different result. On the other hand, Guerci et al. (2013a) obtained a CF value equal to 1.30 kg of CO_2eq/kg of FPCM considering within the variables all the information related to the feed factories that produces the animal feeds. It could be reasonable to suppose that if CF estimation considers more variables, the CF result can be higher than the one obtained with few variables. This concept is not always true. The CF estimation on dairy cattle farms of Southern Italy, described in the Chapter 2 of this thesis, showed that the 2 cooperative whose farms had the highest milk production per cow had a CF around 1.4 kg of CO_2eq/kg of FPCM, as arithmetic mean. This value is similar to the one obtained by Guerci et al. (2013a), even if the estimation realized on the dairy cattle farms of Southern Italy did not consider the emissions from feed processing plants, and used a default coefficient for each purchased feed. Besides, within all the variables considered by Guerci et al. (2013a), atmospheric temperatures of the farm's area and the digestible energy of the ration were not taken into account, as instead in the estimation of dairy cattle farms of Southern Italy was done. This fact suggests that the CF value is not only affected by the number of variables considered, but it can be also affected by the relation between these variables and the GHG emissions produced within the farm.

The relation between the different variables has to be considered even because the reduction of one type of emissions within the farm can positively or negatively affect another emission source. Dijkstra et al. (2011) demonstrated that the reduction of N excretion in dairy cows realized through different feeding strategies, and improving milk production, can positively or negatively affect CH_4 emissions, depending on the adopted solution.

On the other hand, it is important to consider that the CF estimation can be realized to develop mitigation strategies for the reduction of the GHG emissions of the farms, and to improve their economic gains. It is a known fact that several variables that affect the CF of the dairy farm can also affect its profitability. Guerci et al. (2013a) demonstrated that high milk production intensity and high animal efficiency were strongly connected with the mitigation of the environmental impact; besides, high milk production levels and high animal efficiency can positively affect the profitability of the farm, considering the gain that derive from the increased amount of produced milk, and the reduction of feeding costs related to the increased feed conversion efficiency.

The aim of this work was to find among all the variables used to calculate the CF in the dairy farms of Southern Italy, those that were more correlated with it, in order to reduce the number of information needed to calculate the CF still obtaining a reliable result. Besides, the individuation of the variables that are more correlated with the CF will allow to concentrate the development of the mitigation strategies on the critical points of the dairy system that hold the larger influence on the GHG emissions.

4.2. Materials and methods

The study was conducted considering the 4 cooperatives operating in Southern Italy (3A for Sardinia, Granarolo for Puglia and Basilicata, Asso.La.C. for Calabria, Progetto Natura for Sicily) that were selected for the CF estimation calculated in the previous chapter.

All the information collected with the detailed survey realized on the 285 farms was implemented in a file of Microsoft Excel® to perform the calculations for the GHG emissions estimation. The estimation method is described in details in the Chapter 2 of this thesis.

Breafly, the he IPCC (2006) estimation method was chosen to calculate the emissions from animals, manure management, and crop cultivation. Coefficients used to calculate GHG emissions derived from farm energy consumptions and production were estimated using published standard coefficients adaptable to the national conditions.

CO_2 absorption by plants and CO_2 emissions from animal respiration, manure and soils were not accounted for in this research, considering those as accounted for in the short term biogenic carbon cycle (IDF, 2010).

Following the life cycle assessment procedure (ISO, 2006), the selected system boundaries included only the emissions "from-cradle-to-farm-gate", considering only emissions generated from the input production until the milk storage in farm facilities (i.e. transport of milk from farm to processing plant was excluded).

A selection among all the variables collected with the detailed survey was realized, in order to consider only those variables that were actually inserted in the equations for the CF calculation.

The selected variables were represented by:

- 5 variables referred to the general characteristics of the farm (e.g. farm size, farm localization, farming system, hectares of productive land, hectares of irrigated land);
- 12 variables indicating the average monthly temperature of the province in which each farm is located;
- 20 variables referred to the herd profile and its characteristics (e.g. number of lactating cows, average body weight of each group of animals);
- 32 variables referred to the ration characteristics of each group of animals (e.g. forage to concentrate ratio for the ration of each animal category of the farm);
- 5 variables referred to the energy consumptions of the farm (e.g. kg of GPL, kg of fuel consumed for feed cultivation and feeding management, kg of fuel consumed for other activities, kW of electric energy consumed, kW of energy produced from renewable sources);
- 13 variables referred to the crop cultivation activities within the farm (e.g. hectares of corn silage cultivated within each farm, kg of mineral or organic fertilizers/ha used within each farm).

The farms were then divided into 10 classes on the basis of their milk production level, in steps of 1000 kg, as reported in Figure 4.1. The CF for the farms within each class was studied to identify possible outliers. The farms that presented a CF value that exceeded the distance between the 1st and the 3rd quartile multiplied for 1.5 were considered outliers. A conservative approach was used and only 3 outliers (maximum values of CF of the classes 3000, 4000 and 6000) were excluded from the dataset in order to perform further statistical elaborations.

The new dataset was divided into two new datasets on the basis of the milk production level recorded for each farm (Figure 4.2); the 1st dataset, called low milk production (**LMP**), included 82 farms that presented a milk production level included between 1170 and 4984 kg of FPCM/year per cow; the 2nd dataset, called high milk production (**HMP**), included 200 farms that presented a milk production level included between 5002 and 11100 kg of FPCM/cow per year. This separation was realized considering that the relationship between the CF and the milk production level showed a different trend when the milk production level was lower than 5000 kg of FPCM/cow per year, by pointing out a distribution of the farms that was less affected by the milk production level. Furthermore, the separation of the dataset between the LMP farms and the HMP farms allowed to divide the dataset into 2 groups with a sufficiently high numbers of farms. About 30% of the farms were included within the low milk production level, and the 70% of the farms were included within the high milk production level group.

Data were analyzed with MINITAB (Minitab 16 Statistical Software. Minitab, Inc. State College, PA, USA) with techniques of descriptive statistics; mean and standard error of the mean (**SEM**) calculated on the 282 farms were reported in the tables. Analyses of CF means were performed among the two groups of farms, and milk production level of the herd (kg of milk/yr per cow and per hectare), herd parameters (% of lactating cows, % of dry cows, and % of replacing animals), and ration characteristics (% or forages, % of corn silage, % of purchased feeds) were also compared. Significant level of $P < 0.05$ was tested by using the Tuckey method of comparisons. A linear regression analysis was performed with R Software (R Foundation for Statistical Computing, Vienna, Austria) for the 2 datasets, in order to predict the equation that explained the CF trend on the basis of the milk production level recorded for each farm, and in order to identify those farms that presented a CF higher or lower than the mean CF calculated for each milk production level in the regression analysis.

The residues obtained from each regression analysis were plotted into 2 graphs, and those that were included within ±SD/3 were eliminated, in order to considerate only those that presented a large distance from the predicted CF.

For each one of them a linear discriminant analysis (**LDA**) was performed to determine which variables were more correlated with the CF, and which variables could determine the position of the farm in respect of the CF value predicted by the linear regression analysis. A new variable was created in order to define the position of the farms on the basis of the LDA; all the farms that presented an estimated CF value higher than the predicted one were assigned to the group 1 by the LDA; all the farms that presented an estimated CF value lower than the predicted one were assigned to the group 0 by the LDA.

A new selection among the variables was realized in order to select, on the basis of the coefficients assigned by the LDA, the variables that were more correlated with the CF calculation. A new LDA was then performed using the new selection of variables to check if even with a lower amount of variables the LDA was able to assign the farms to the group 1 or to the group 0, obtaining the same distribution realized with all the considered variables.

The selection of the variables for the 2nd discriminant analysis was realized by eliminating from each group of variables those that presented a coefficient lower than ±SD/10.

4.3. Results

Table 4.1 shows the results of the descriptive statistics realized on the two groups of farms. A significant difference was recorded for all the considered variables, except for the farm dimension ($P<0.05$).

Figure 4.3 and the Figure 4.4 show the distribution of the residues of the HMP farms and of the LMP farms, respectively. Figure 4.5 and the Figure 4.6 show the distribution of the residues after the elimination of the elements included within ±SD/3 for the HMP farms and for the LMP farms, respectively. After this first step, the HMP group was composed by 139 farms, and the LMP group presented 57 farms.

Figure 4.7 presents the distribution of the HMP farms resulting after the LDA. The farms represented with a circle (code 1) presented a CF value higher than that predicted by the regression equation yHMP of Figure 4.1; the farms represented with a square (code 0) presented a CF value lower than that predicted by the regression equation yHMP of Figure 4.1.

Figure 4.8 presents the distribution of the LMP farms resulting after the LDA. The farms represented with a circle (code 1) presented a CF value higher than that predicted by the regression equation yLMP of Figure 4.1; the farms represented with a square (code 0) presented a CF value lower than that predicted by the regression equation yLMP of Figure 4.1.

Table 4.2 presents the results of the 1st LDA, indicating the number of the farms that were correctly allocated to their own CF group (code 1 or 0) on the basis of the coefficients calculated by the LDA. Within the HMP group, 72 farms presented a CF value lower than the value predicted by the regression line of Figure 4.2, and 67 farms presented a CF value higher than the value predicted by the regression line of Figure 4.2. The principal diagonal of the LDA includes the farms assigned correctly to their own group, which were 72 for the group 0, and 65 for the group 1; the secondary diagonal includes the farms assigned to the wrong group, which were 0 for the group 0, and 2 for the group 1. Among the 139 HMP farms, only 2 farms were assigned to the wrong group, with an error equal to the 1.4%. Within the LMP group, 34 farms presented a CF value lower than the value predicted by the regression line of Figure 4.2, and 23 farms presented a CF value higher than the value predicted by the regression line of Figure 4.2. The principal diagonal includes the farms assigned correctly to their own group, which were 34 for the group 0, and 23 for the group 1; the secondary diagonal includes the farms assigned to the wrong group, which were 0 for the group 0, and 0 for the group 1. Among the 57 LMP farms, none was assigned wrongly.

Table 4.3 and the Table 4.4 show the list of the variables that were selected among those used for the 1st LDA, to perform the new LDA. Within Table 4.3, 29 variables, referred to the HMP group, are classified on the basis of the coefficients determined during the 1st LDA; within Table 4.4, 33 variables, referred to the LMP group, are classified on the basis of the coefficients determined during the 1st LDA.

Figure 4.9 shows the new distribution realized by the LDA for the HMP farms, and Figure 4.10 shows the new distribution realized by the LDA for the LMP farms. Circles and squares still represent the farms that presented a CF value higher or lower than the CF predicted by the linear regression equation of Figure 4.2, respectively.

Table 4.5 presents the results of the 2nd LDA, indicating the number of the farms that were correctly allocated to their own CF group (1 or 0) on the basis of the new coefficients calculated by the LDA. Within the HMP group, the LDA assigned 74 farms to the group 0 and 67 farms to the group 1. Only 57 of the 74 farms that are included within the group 0 were actually assigned to their own group, and the remaining 15 farms were assigned to the group 1. The same thing happened to the 67 farms of the group 1; 52 of them were correctly assigned to their own group, and the remaining 15 were assigned to the group 0.

Figure 4.9 can clarify this unexpected result ; 15 circles that were supposed to be in the group 1 are actually positioned among the squares of the group 0; on the other hand, 15 squares are positioned among the circles in the group 1. The principal diagonal includes the farms assigned correctly to their own group, which were 57 for the group 0, and 52 for the group 1; the secondary diagonal includes the farms assigned to the wrong group, which were 15 for the group 0, and 15 for the group 1. Among the 139 HMP farms, 30 farms were positioned in the wrong groups and the error percentage was equal to the 21.5%.

Within the LMP group, the principal diagonal includes the farms assigned correctly to their own group, which were 33 for the group 0, and 19 for the group 1; the secondary diagonal includes the farms assigned to the wrong group, which were 4 for the group 0, and 1 for the group 1. Among the 57 LMP farms, 5 farms were positioned in the wrong groups and the error percentage was equal to the 8.7%.

4.4. Discussions

General considerations

The comparison between the 2 groups of farms divided on the basis of the milk production level confirmed the differences that were previously underlined by the linear regression analysis (Figure 4.2). The average CF recorded in the HMP farms and in the LMP farms were different ($P<0.005$), and they were equal to 2.04 and 1.29 kg of CO_2eq/kg of FPCM, respectively. The average milk production level recorded for the HMP farms was equal to 7.26 t of FPCM/year per cow, and it was different ($P<0.005$) from the average milk production level recorded for the LMP farms, which was equal to 3.62 t of FPCM/year per cow.

The results obtained for the HMP farms are similar to those obtained by several authors that measured the CF from farms that presented the same milk production level. Thomassen et al. (2008), Kristensen et al. (2011), Guerci et al. (2013b), and Guerci et al. (2013c) obtained different CF, included between 1.11 and 1.91 kg of CO_2eq/kg of FPCM measuring the GHG emissions in farms with different characteristics, which however had an average milk production level included between 6.40 and 7.98 t of FPCM/year per cow.

The mean CF measured in the LMP was significantly higher than the average value of the HMP farms. However, mean milk production level measured within these farms was very low, especially if the CF obtained for the LMP farms is compared with the CF estimation realized by Hegemann et al. (2011) or with the CF estimation realized by Guerci et al. (2013b). Hegemann et al. (2011) obtained a CF value equal to 2.06 kg of CO_2eq/kg of FPCM with an average milk production equal to 5.81 t of FPCM/year per cow; Guerci et al. (2013b) obtained a CF value equal to 1.77 kg of CO_2eq/kg of FPCM for an average milk production level equal to 4.13 t of FPCM/year per cow.

These last considerations, referred to the farms that present a milk production level ≤5.0 t of FPCM/year per cow, confirm the preliminary observations which suggested the separation of the original dataset among high and low milk production levels. When the milk production level is lower than 5.0 t of FPCM/year per cow, the CF does not follow the same trend that is showed by the farms that presented a milk production level higher than 5.0 t of FPCM/year per cow. Within the HMP group, farms that had the same milk production level showed CF values included within a short range; this fact was confirmed above comparing the average CF of the HMP farms with the results obtained by Thomassen et al. (2008), Kristensen et al. (2011), Guerci et al. (2013b), and Guerci (2013). On the other hand, within the LMP group, farms that had the same milk production level showed CF values included within a large range, pointing out that the CF estimation can be affected by many different variables besides the milk production level.

The distribution of the residues (Figures 4.3 and 4.4) confirmed this consideration, showing the different trend followed by the CF values obtained for the HMP farms and for the LMP farms.

The significant differences in the repartition of the total CF among the various components between the HMP and the LMP farms (Table 4.1) evidenced that the various GHG sources can participate to the final CF with different percentages. The CF from enteric fermentations was significantly different (P<0.005) in terms of absolute value between LMP and HMP; however, the percentage of these emissions within the total CF remained constant for both groups. This result can be explained considering that the enteric CH_4 emissions are strongly correlated to the milk production level (Yan et al., 2010), and considering that the HMP and the LMP are divided on the basis of this variable, the proportion of the CF attributed to the enteric emissions is suppose to remain constant, because it grew following the increasing milk production level.

The CF from manure presented a significantly different value between the HMP and the LMP farms; however, the percentage of this GHG source was similar between the 2 groups, with the HMP farms that presented a percentage of CF from manure equal to the 17.12%, and the LMP farms that presented a percentage of CF from manure equal to the 21.48%.

A dramatic difference was recorded for the CF derived from the use of energy; the HMP farms had a percentage of the CF from energy use much lower (P<0.005) than that of the LMP farms (8.14% vs. 17.54% for HMP and LMP, respectively). This fact can be explained considering the low amount of purchased feeds (41.16%) recorded for the LMP farms, which suggest a high level of on-farm feed production and thus high GHG emissions from energy use. Indeed, Guerci et al. (2013a) demonstrated that the main components of the CF from energy are represented by the energy used for the production and transportation of concentrate feeds purchased off-farm, and by the energy used for the on-farm feed production. It is obvious that if the percentage of purchased feeds increases, the amount of energy used within the farm for the production of feeds will decrease. As a consequence, the percentage of the CF that derives from the off-farm feed production and transportation will increase. This is what happened in the HMP farms, where the percentage of CF from energy use showed a lower value compared with the one of the LMP farms; on the other hand, the CF from the off-farm feed production was higher, respecting the increase on the percentage of purchased feeds recorded for these farms.

Discriminant analysis

The results of the 1st LDA showed that the 87 considered variables were useful to assign correctly each farm to its CF class. Considering that only 2 of the 139 HMP farms were assigned in the wrong class and none of the 57 LMP farms was assigned incorrectly, the 1st LDA demonstrated to be reliable for 98.9% of the farms.

The selection of the variables realized in the 2nd LDA presented an interesting result. The variables selected for the HMP farms were 29, and those that were selected for the LMP farms were 33. This difference between the numbers of the selected variables can be explained considering the higher variability showed by the residues of the LMP farms, compared with the residues obtained from the HMP farms. The high variability required a higher amount of information in order to assign the farms to their own groups. The fact that the 2nd LDA, based on fewer variable than the first, caused a high error in the identification of the values of CF value higher or lower than those predicted by the regression equation of Figure 4.2, suggests that even the variable with low coefficient in the first LDA, and excluded from the second LDA, were important in determining the overall CF.

Despite this limitation, the classification of the variables selected for 2nd LDA (Tables 4.3 and 4.4) is of high value, because identified the variables with high leverage on the CF for the two classes of level of production.

The classification of the variables selected for 2nd LDA of the HMP farms (Table 4.3) presented in the first 12 positions the average atmospheric temperatures of 10 months (average temperatures of May and January were assigned to the 19th and to the 29th place), and the forage to concentrate ratio of dry cows and bred heifers. In the 13th, 14th, and 15th place there were the variables referred to the forage to concentrate ratio of the lactating cows, the nitrogen efficiency recorded for the corn grain cultivation, and the forage to concentrate ratio of the open heifers. All the variables that were positioned under the 15th place presented a coefficient lower than 2, and they were referred to the ration characteristics and to the crop cultivation; no variables concerning the energy consumptions of the farm were selected, and within the general information of the farm, the housing type and the farm localization were selected.

The farms that have a high milk production level are generally characterized by high technology levels regarding the feeding techniques and the crop cultivation, showing a sort of standardized management system that reduces the variability between these classes of farms.

The classification of the variables selected for 2nd LDA of the LMP farms (Table 4.4) presented in the first 4 positions, with very high coefficients, the dietary forage to concentrate ratio of the animal categories considered. In the first positions were those of the heifers. Then, in the 5th position there was the cultivation of corn and then various variables associated to climatic conditions or to the diet.

It appears that for the HMP farms diet quality was less important, in determining the CF, than the climatic variables. This can be due to the fact that in HMP farms the quality of the diet is generally high, while the climatic conditions can both affect CF production from manure and the production performances of the animals. In the case of LMP farms, the quality of the diet is usually much lower (higher fiber concentration), especially for replacement animals, and this can greatly affects GHG emissions directly, from enteric and manure fermentations, and indirectly, markedly varying milk production. The latter would explain the steep slope in the relationship between milk production and CF reported in Figure 4.2 for LMP farms.

4.5. Conclusions

This study explored the mechanism that cause a curvilinear relationship between milk production and CF, with marked variation of CF for small variation of milk yield until the average milk production is around 5000 kg/year per cow and limited variation of CF above this threshold.

A statistical methodology to approach this issue when large dataset are available was proposed.

The results showed that:

a) It was possible to identify the variables with the higher impact on the CF of the farms;
b) These variables were different from LMP and HMP farms, with the formers strongly affected by dietary quality, the latter by climatic conditions;
c) Many of the variables considered had a small impact. However, as a whole they were important. Indeed, when not considered in the linear discriminant analysis the markedly increased prediction errors in the CF estimation.

Based on these results, it is possible to appear that the CF of dairy cattle farms is controlled by a large number of factors. The rank in the importance of these factors, achieved in this study, need to further explored to evaluate which of the variables can be actually controlled, and at which cost, to mitigate the CF of dairy cattle farms.

4.6. References

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4.7. Tables

Table 4.1. Descriptive characteristics of the farms included in the sample. Values were separated for farms with different milk production levels (low and high).

ITEM	Milk production level (kg FPCM/cow per year)		Total	Mean	SEM
	Low (>5000)	*High* (<5000)	*All farms*		
Farms, n.°	82	200	282	282	-
Land, ha	40.91[a]	46.79[a]	12712.72	45.8	2.88
Total cattle, n.°	61.15[b]	146.55[a]	34324	121.72	4.61
Mature cows, n.°	38.66[b]	85.30[a]	20231	71.74	4.61
% lactating	75.43[b]	83.00[a]	-	80.8	0.48
% dry	17.00[b]	24.57[a]	-	19.2	0.48
% young animals	34.94[b]	40.69[a]	-	39.0	0.48
Calvings per cow n/yr	75.43[b]	84.76[a]	-	82.05	1.02
Milk yield, t FPCM/yr/ha	5.54[b]	21.54[a]	-	16.85	1.55
Milk yield, t FPCM/yr/cow	3.62[b]	7.26[a]	-	6.20	0.12
Purchased feeds, % DM	41.16[b]	51.80[a]	-	48.7	0.95
Purchased conc., % DM	94.36[a]	88.18[b]	-	89.9	0.97
Forages, % DM ration	65.57[a]	54.04[b]	-	57.3	0.62
Corn silage*, % DM ration	3.59[b]	14.64[a]	-	11.4	0.98
kg FPCM/kg DM ration	0.86[b]	1.27[a]	-	1.15	0.01
CO_2eq tot, tons x 1000	0.31[b]	0.86[a]	199.42	0.70	0.045
Milk sold, tons x 1000	0.14[b]	0.64[a]	141.15	0.50	0.036
CFP allocated to milk, %	94.0[b]	96.3[a]	-	95.6	0.17
MEAN CFP, kgCO_2eq/kgFPCM	**2.04**	**1.29**	**-**	**1.35**	**-**
Composition of CF, kgCO_2eq/ kg FPCM					
Enteric,	0.96[a](42.10%)	0.59[b](43.70%)	-	0.70	0.014
manure,	0.39[a](17.12%)	0.29[b](21.48%)	-	0.32	0.008
Energy,	0.40[a](17.54%)	0.11[b](8.14%)	-	0.20	0.016
primary emissions	0.28[a]	0.08[b]	-	0.14	0.011
secondary emissions	0.12[a]	0.03[b]	-	0.06	0.005
On-farm feed,	0.20[a](8.77%)	0.11[b](8.14%)	-	0.13	0.005
primary emissions	0.15[a]	0.09[b]	-	0.10	0.004
secondary emissions	0.05[a]	0.02[b]	-	0.03	0.002
Off-farm feed,	0.33[a](14.47%)	0.25[b](18.54%)	-	0.28	0.006
CF, kg CO_2eq/kg FPCM	**2.28[a]**	**1.35[b]**	**-**	**1.62**	**0.03**

[a,b] within a row, means with a different superscript differ significantly for $P \leq 0.05$.

Table 4.2. Results for the high milk production (HMP) and low milk production (LMP) farms of the 1st linear discriminant analysis (LDA). Allocation of the farms to the groups 1 (CF value higher than that predicted by the regression equation) and 0 (CF value lower than that predicted by the regression equation) on the basis of the LDA results.

HMP Farms (n=139), LDA with 87 variables				**LMP Farms (n=57), LDA with 87 variables**			
		Regression				**Regression**	
		0	**1**			**0**	**1**
LDA	**0**	72	2	**LDA**	**0**	34	0
	1	0	65		**1**	0	23

Table 4.3. Classification of the variables on the basis of the coefficients assigned by the first LDA realized for the high milk production (HMP) farms (n=29).

Variables selected for the 2nd LDA for the HMP farms		
name	**Unit of measure**	**Coefficient**
1- average atmospheric temperature, September	°C	14.3039
2- average atmospheric temperature, July	°C	13.8864
3- forage:concentrates ratio, dry cows	% of DMI	8.9966
4- average atmospheric temperature, June	°C	8.9493
5- forage:concentrates ratio, bred heifers	% of DMI	7.3507
6- average atmospheric temperature, December	°C	6.0873
7- average atmospheric temperature, March	°C	5.6018
8- average atmospheric temperature, October	°C	4.7088
9- average atmospheric temperature, November	°C	4.6369
10- average atmospheric temperature, August	°C	4.2862
11- average atmospheric temperature, April	°C	2.7942
12- average atmospheric temperature, February	°C	2.7895
13- forage:concentrates ratio, lactating cows	% of DMI	2.6975
14- nitrogen efficiency use, corn grain	kg DM/kg N	2.6259
15- forage:concentrates ratio, open heifers	% of DMI	2.6164
16- corn cultivation	yes/no	1.9001
17- gross energy intake, dry cows	kg DM/day	1.5732
18- forage:concentrates ratio, unweaned calves	% of DMI	1.5552
19- average atmospheric temperature, May	°C	0.8391
20- gross energy intake, bred heifers	kg DM/day	0.7526
21- housing type	cubicle/bed-pack/pasture	0.7517
22- gross energy intake, unweaned calves	kg DM/day	0.3857
23- farm localization	flatland, hill, mountain	0.3241
24- consumption of mineral fertilizers	kg N/ha	0.2284
25- gross energy intake, lactating cows	kg DM/day	0.2245
26- dry cows	n.	0.1694
27- corn silage cultivation	yes/no	0.0888
28- age at first calving	years	0.0883
29- average atmospheric temperature, January	°C	0.0681

Table 4.4. Classification of the variables on the basis of the coefficients assigned by the first linear discriminant analysis (LDA) realized for the low milk production (LMP) farms (n=33).

Variables selected for the 2nd LDA for the LMP farms		
name	**Unit of measure**	**coefficient**
1- forage:concentrates ratio, open heifers	% of DMI	11.2867
2- forage:concentrates ratio, bred heifers	% of DMI	11.0767
3- forage:concentrates ratio, dry cows	% of DMI	5.9421
4- forage:concentrates ratio, lactating cows	% of DMI	5.1571
5- corn cultivation	yes/no	2.8098
6- average atmospheric temperature, September	°C	2.2270
7- average atmospheric temperature, August	°C	1.9991
8- average atmospheric temperature, May	°C	1.5103
9- housing type	cubicle/bed-pack/pasture	1.0950
10- gross energy intake, dry cows	kg DM/day	1.0803
11- average atmospheric temperature, October	°C	1.0601
12- forage:concentrates ratio, unweaned calves	% of DMI	1.0016
13- gross energy intake, bred heifers	kg DM/day	0.7362
14- average atmospheric temperature, November	°C	0.7312
15- average atmospheric temperature, January	°C	0.7039
16- farming system	confined/mixed/pasture	0.6791
17- corn silage cultivation	ha	0.6674
18- average atmospheric temperature, February	°C	0.5722
19- average atmospheric temperature, July	°C	0.5412
20- gross energy intake, open heifers	kg DM/day	0.5304
21- average atmospheric temperature, April	°C	0.3972
22- average atmospheric temperature, June	°C	0.3701
23- dry cows	% of DMI	0.3521
24- gross energy intake, lactating cows	°C	0.2745
25- bred heifers	% of DMI	0.2720
26- on-farm feeds, unweaned calves	kg DM	0.2404
27- average atmospheric temperature, March	°C	0.1738
28- consumption of mineral fertilizers	kg N/ha	0.1728
29- irrigation service	ha	0.0747
30- surplus cows	n.	0.0674
31- beef calves	n.	0.0532
32- average atmospheric temperature, December	°C	0.0503
33- nitrogen efficiency use, corn grain	kg DM/kg N	0.0448

Table 4.5. Results for the high milk production (HMP) and low milk production (LMP) farms of the 2nd linear discriminant analysis (LDA). Allocation of the farms to the groups 1 (CF value higher than that predicted by the regression equation) and 0 (CF value lower than that predicted by the regression equation) on the basis of the LDA results.

HMP Farms (n=139), LDA with 29 variables				**LMP Farms (n=57), LDA with 33 variables**			
		Regression				**Regression**	
		0	**1**			**0**	**1**
LDA	**0**	57	15	**LDA**	**0**	33	4
	1	15	52		**1**	1	19

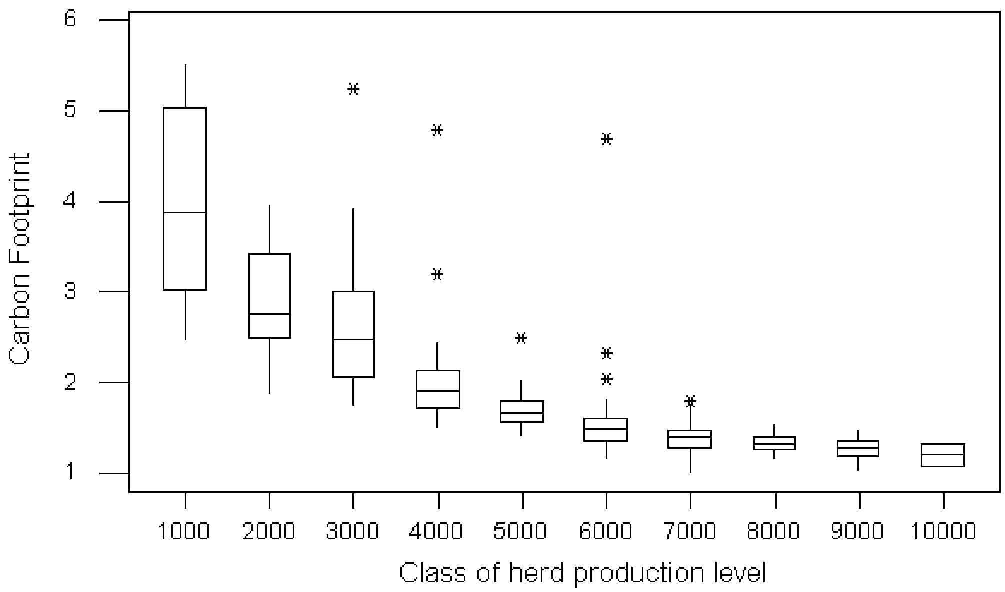

Figure 4.1. Boxplot of the original data classified for herd production level (kg of milk/year per cow). The last class included all the values > 1000 kg.

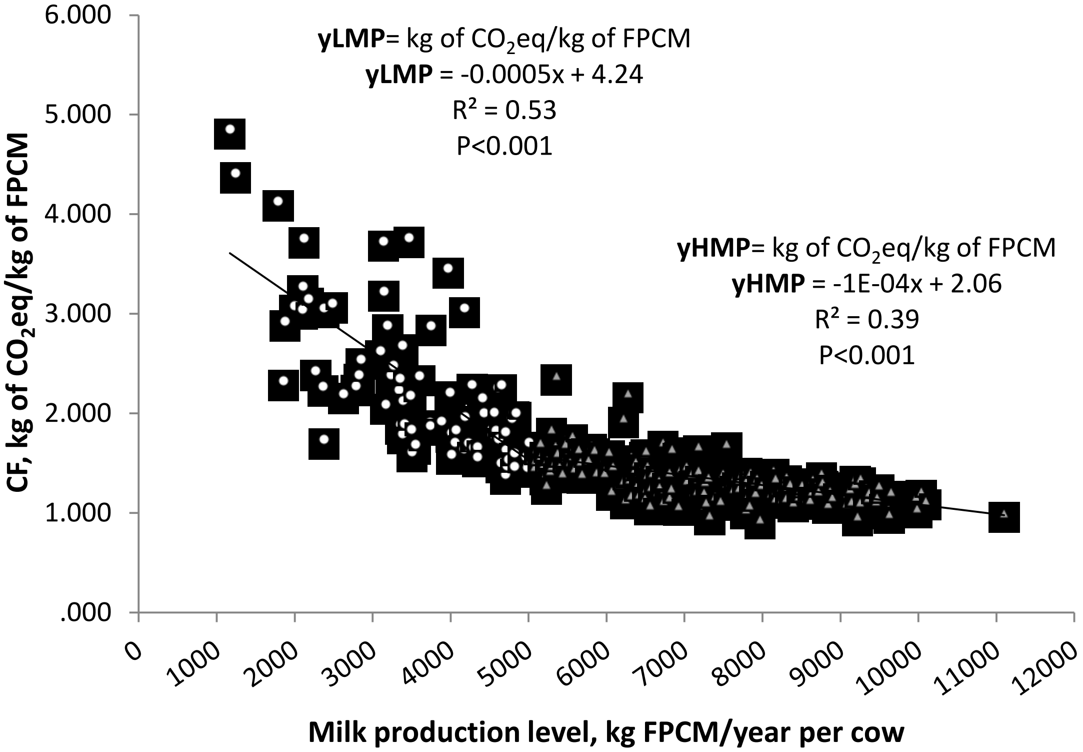

Figure 4.2. Carbon footprint (CF) and cow production level for 2 different milk production levels. With open dots are reported the farms, and the corresponding regressions between milk production and CF, with milk production below 5000 kg/y per cow, with triangles those above this threshold and the corresponding regression equation (n=82 for **yLMP**; n=200 for **yHMP**).

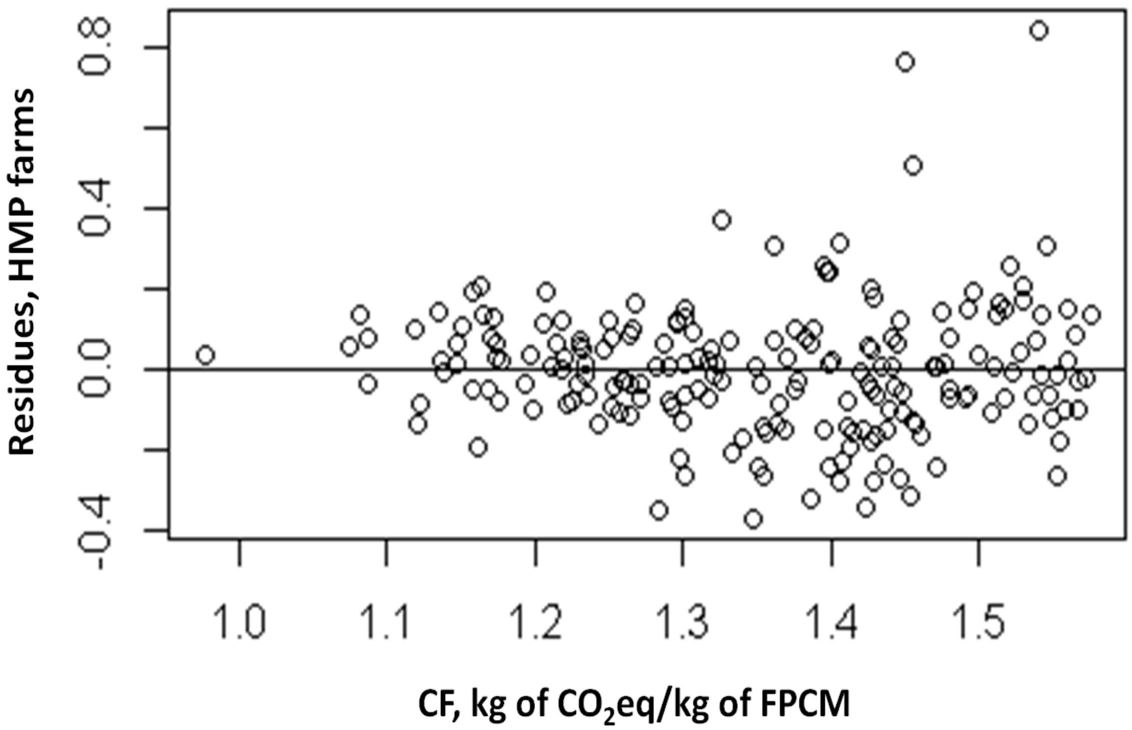

Figure 4.3. Distribution of the residues for the high production farms (HMP) farms on the basis of the CF value estimated with the linear regression analysis (n=200).

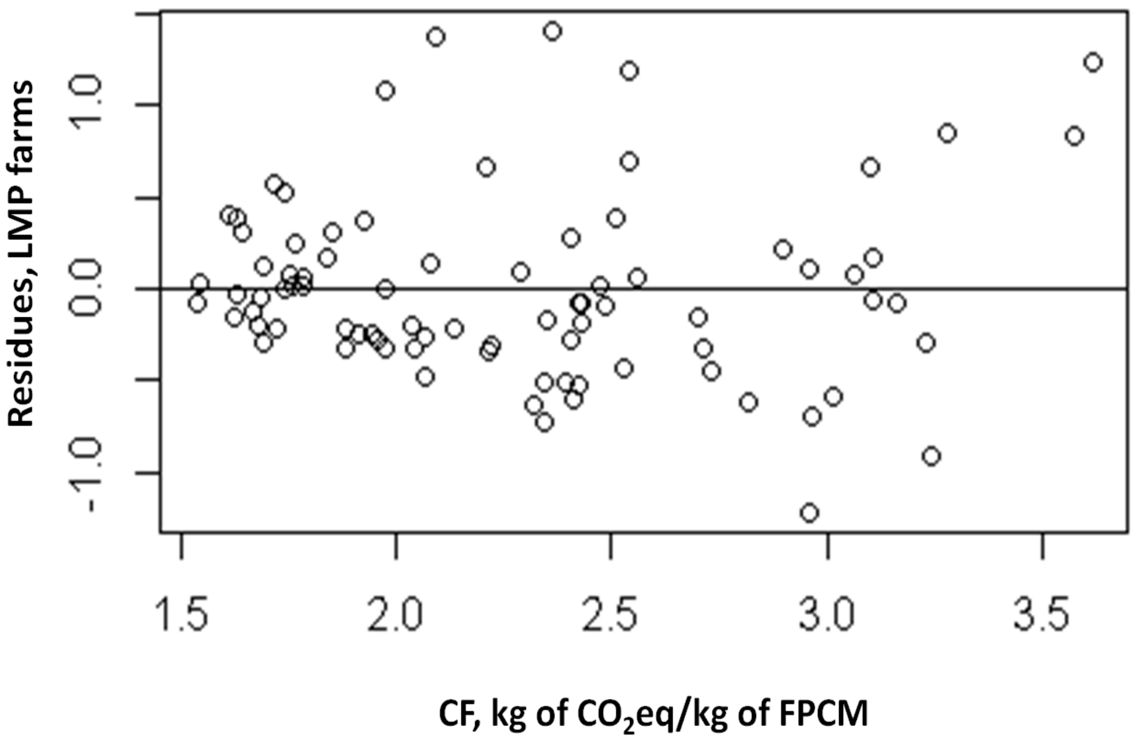

Figure 4.4. Distribution of the residues for the low production farms (LMP) on the basis of the CF value estimated with the linear regression analysis (n=82).

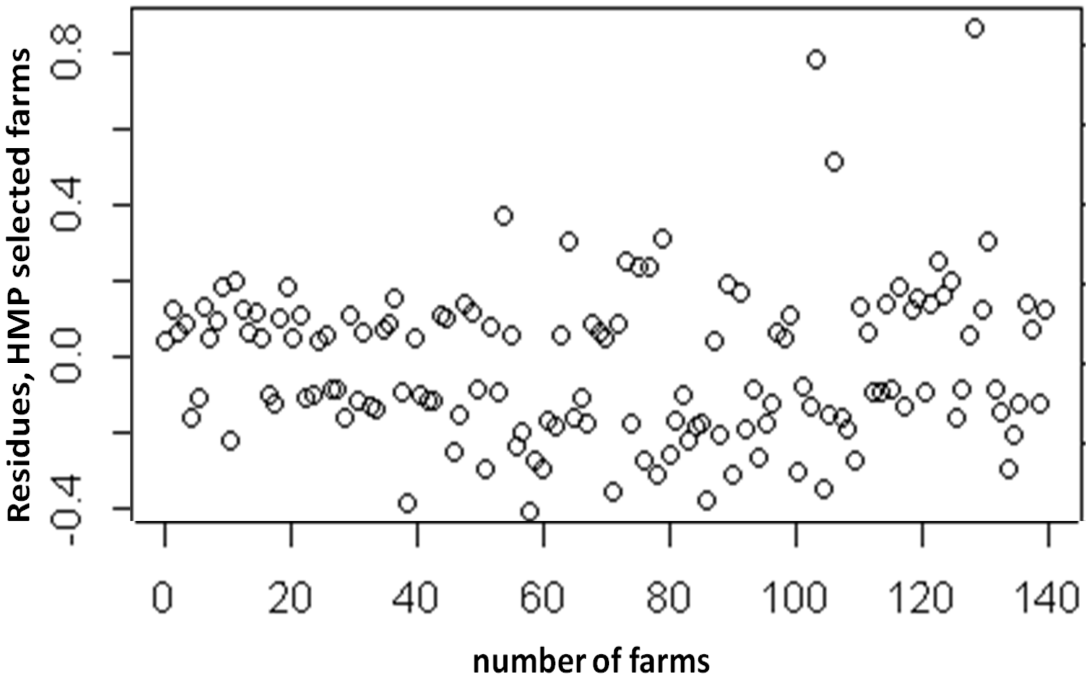

Figure 4.5. Distribution of the residues of the high production farms (HMP) after the elimination of those included within ±SD/3 (n=139).

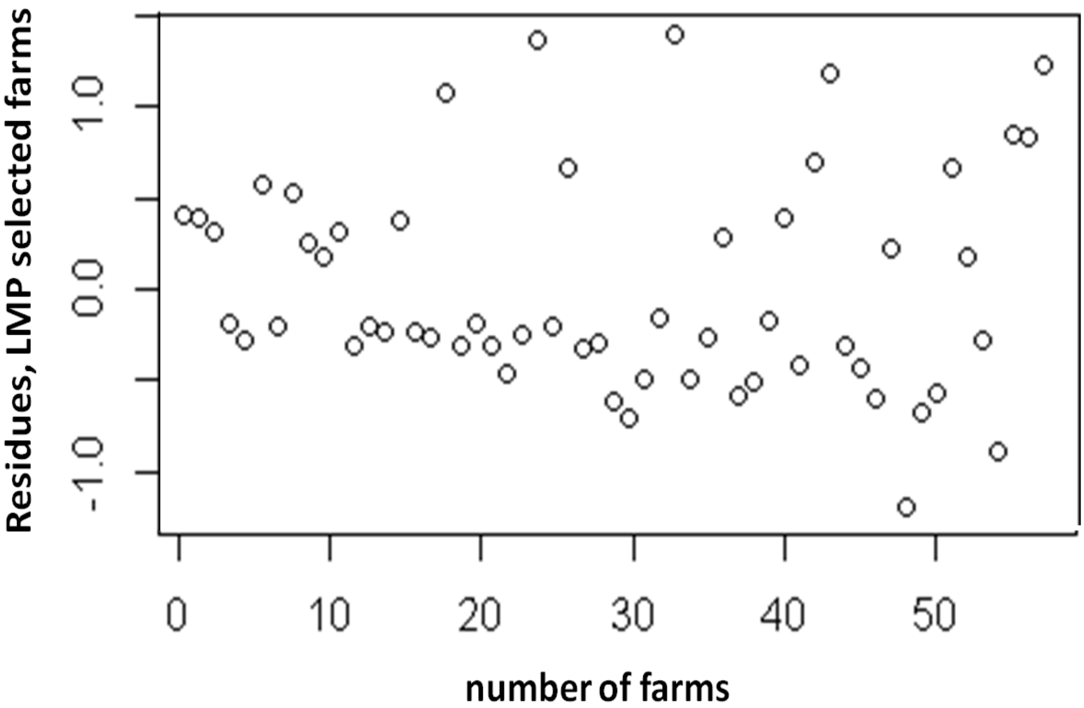

Figure 4.6. Distribution of the residues of the low production farms (LMP) after the elimination of those included within ±SD/3 (n=57).

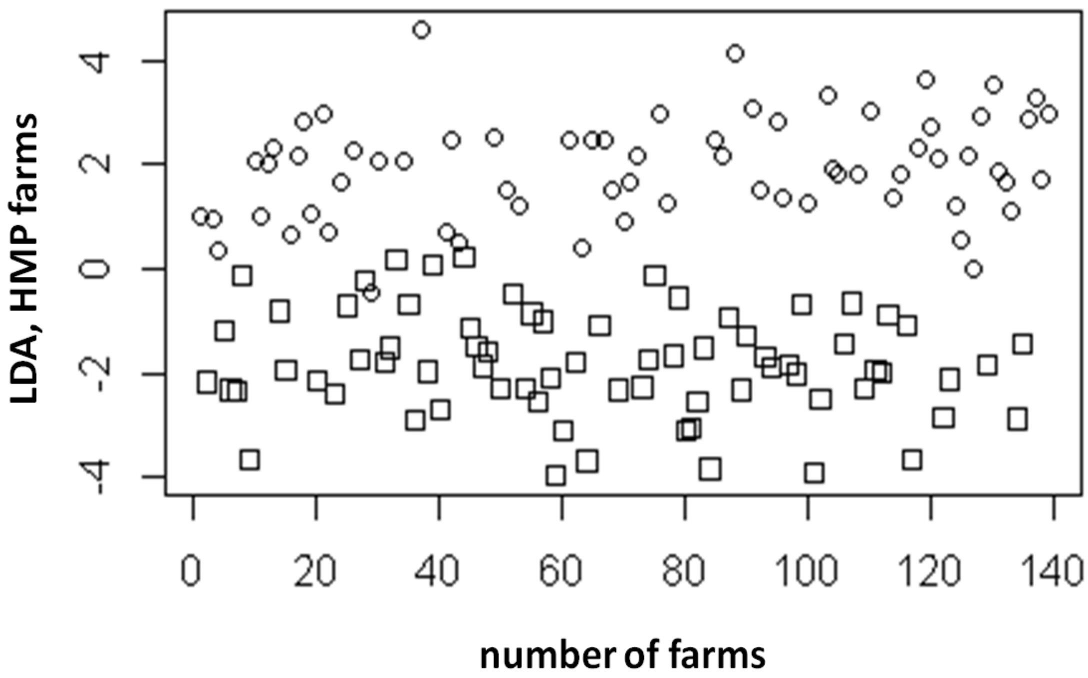

Figure 4.7. Linear discriminant analysis (LDA) graph plot for the high production farms (HPM; n=139) realized with all the selected variables (n=87). Circles and squares indicate the farms that presented a CF higher or lower, respectively, than the CF predicted by the linear regression analysis.

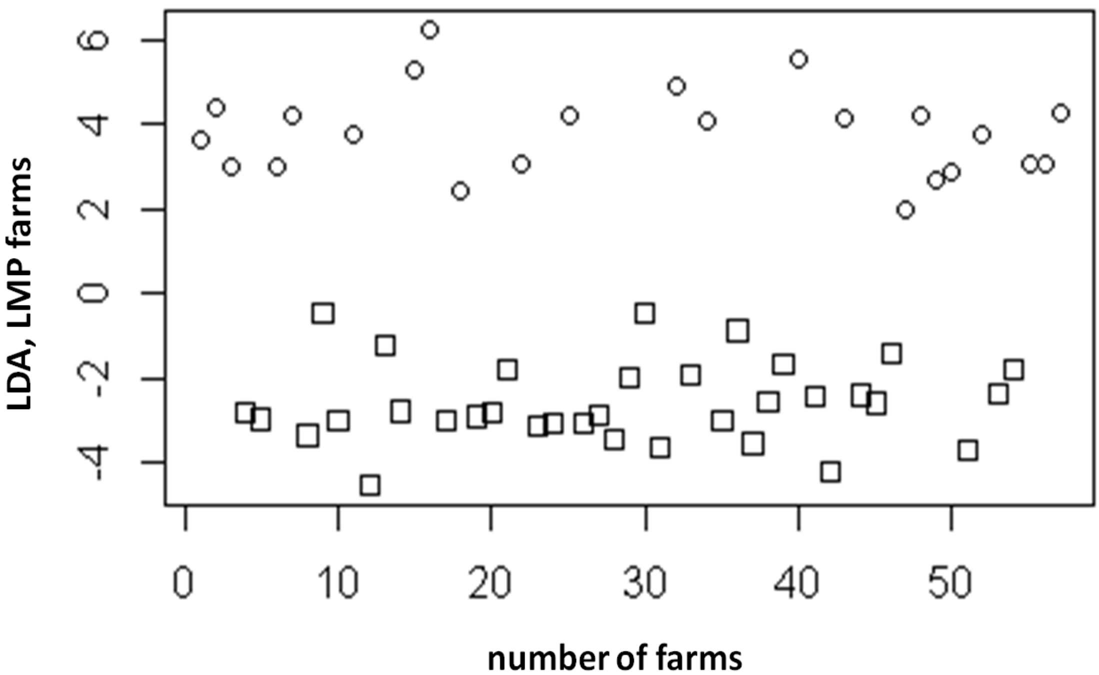

Figure 4.8. Linear discriminant analysis (LDA) graph plot for the low production farms (LPM; n=57) realized with all the selected variables (n=87). Circles and squares indicate the farms that presented a CF higher or lower, respectively, than the CF predicted by the linear regression analysis.

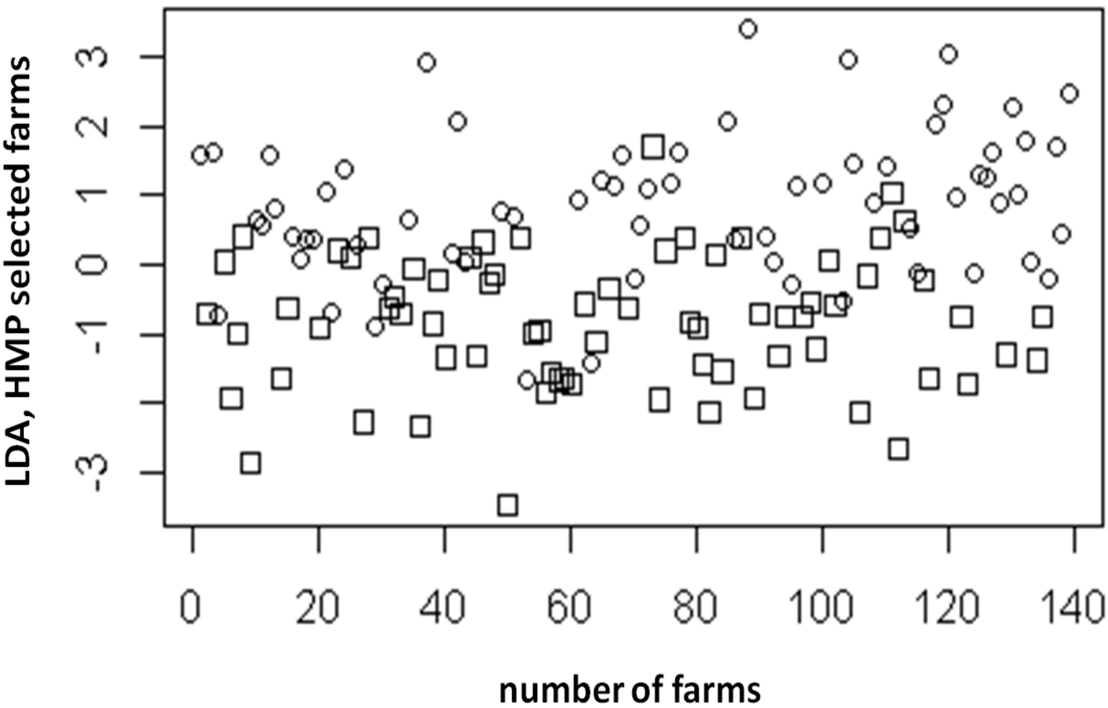

Figure 4.9. Linear discriminant analysis (LDA) graph plot for the high production farms (HPM) (n=139) realized with the variables that obtained the higher coefficients in the previous LDA (n=29). Circles and squares indicate the farms that presented a CF higher or lower, respectively, than the CF predicted by the linear regression analysis.

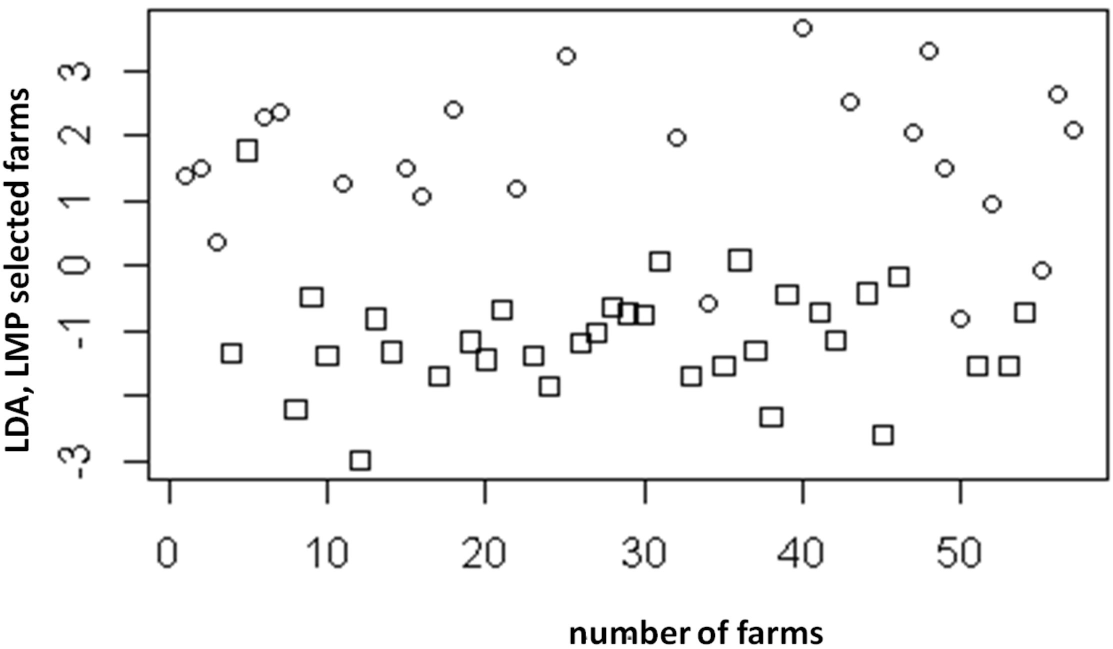

Figure 4.10. Linear discriminant analysis (LDA) graph plot for the low production farms (LPM) (n=57) realized with the variables that obtained the higher coefficients in the previous LDA (n=33). Circles and squares indicate the farms that presented a CF higher or lower, respectively, than the CF predicted by the linear regression analysis.