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Life Cycle Assessment as an evaluation tool- A critical review on carbon footprint in dairy sector

Gokul Tamilselvan *, Nitin Tyagi

ICAR - National Dairy Research Institute, Karnal, India

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* *Corresponding author:*
Gokul Tamilselvan
Email: drgokults@gmail.com

Reviewed by:

Gopi M.
National Institute of Animal Nutrition and Physiology, Adugodi, Bengaluru - India

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Abstract

Global warming, a pressing issue affecting countries worldwide, is primarily driven by greenhouse gases emission from various sources including natural disasters and human activities, including industrial processes, agriculture, livestock farming, and the use of fossil fuels. This review specifically addresses the carbon emissions related with dairy farming for milk. While there are several methods available for assessing the dairy carbon footprint, this review concentrates on the widely accepted Life Cycle Assessment (LCA) method recommended mainly by Intergovernmental Panel on Climatic Change. LCA is favoured globally for its comprehensive coverage of the entire product life cycle. The review delves into the application of the LCA method at the farm level, detailing the stages involved in the life cycle assessment. It also provides an in-depth discussion on carbon footprint up to the farm gate level and extends its analysis to encompass the carbon footprint beyond the farm gate for milk production. A significant portion of the review is dedicated in order to elucidate the carbon footprint of dairy cattle and buffalo farming in various countries, drawing insights from diverse research studies worldwide. The focus is primarily on large ruminants, considering that a substantial portion of enteric methane emissions arises from cattle and buffaloes. The review meticulously presents total carbon footprint values for milk production, derived from the cumulative emissions associated with diverse activities involved in the production of milk. This comprehensive examination leads to understanding of the environmental impact of dairy farming and underscores the need for sustainable practices to mitigate the carbon footprint related with milk production globally.

1. Introduction

Livestock production has gained global attention because of its significant contribution to greenhouse gas (GHG) emissions and its impact on the greenhouse effect also called global warming. As per Gerber et al. (2013), livestock production leads to 14.5% of anthropogenic GHG emissions, making it a major player in climate change. Among livestock production industries, milk and beef production are the main contributors for this emissions. Dairy sector at the global level, alone contributes 4.0% of GHG emissions totally. In India, the livestock sector has a vital role in the economy, as it contributes nearly 25.8% to the total output value of the agriculture sector and 4.12% to the country's GDP in 2022-23 (DAHD 2023). Indian livestock also holds the distinction of being the highest milk producer globally, consist of 24% of world milk production with an annual output of 230.58 million tonnes in 2022-23 (DAHD 2023). While these contributions are commendable for India's economy, they also result in emissions throughout the entire life cycle of livestock products, including milk, meat, and wool. The GHG emissions from livestock production in India encompass various processes. Emissions include direct emissions from livestock, such as enteric, dung methane (CH_4), and nitrous oxide (N_2O). Indirect emissions from feed and fodder production, processing, transportation, land use changes, and processing of livestock products across the farm gate level are also included. The three main GHGs emitted during the livestock production process are carbon dioxide, methane, and nitrous oxide. These emissions have a significant environmental impact and contribute to the future challenge of climate change.

Ruminants, such as cattle and buffaloes, produce CH_4 as a byproduct obtained from fermentation process that occurs during the digestion of feed in their rumen. This methane emission is a significant contributor to anthropogenic CH_4 emissions, with buffaloes alone leading to 39% of total livestock-related CH_4 emissions (Singhal et al. 2005). Methane is a greenhouse gas (GHG), with 21 times higher global warming potential (GWP) than that of carbon dioxide (CO_2), even though relatively it has a short lifetime of 12 years compared to 120 years CO_2. Consequently, reducing CH_4 emissions can have a more immediate impact on mitigating the effects of global warming compared to reducing other GHGs (FAO 2006). One of the major contributor of GHGs is food production sector which contributes approximately 30% to global GHG emissions (Boehm et al. 2018). Within the food production sector, the livestock industry is responsible for anthropogenic GHG emissions of 12% (Batalla et al. 2015), with milk production itself estimated to contribute about 3-4% of man-made GHG emissions globally (Del Prado et al. 2013; Dalgaard et al. 2014; Yan et al. 2013). The consumption of milk and other milk products is significantly higher in developed countries and rapidly increasing in low as well as middle-income countries (Roos et al. 2016). For effective communication in the climate change impact associated with food production, the carbon footprint (CF) is commonly used as a critical metric for measuring the GHG emissions related to a product (Batalla et al. 2015; Xu and Lan 2016). The International Dairy Federation recommends calculating the CF of dairy products using the Life Cycle Assessment (LCA) methodology outlined in the ISO 14000 series (Abin et al. 2018; IDF 2015).

2. Materials and methods

Within this context, extensive research to examine the greenhouse gas (GHG) impact of milk production in key milk-producing countries has been conducted, employing a comprehensive life cycle assessment (LCA) methodology.

2.1 Life Cycle Assessment (LCA) Methodology

Life cycle assessment (LCA), also called as life cycle analysis, is a comprehensive methodology used to evaluate the environmental impacts in association with livestock and its products in all stages throughout life cycle. It provides a systematic approach for quantifying emissions of greenhouse gas (GHG) throughout the entire production chain, encompassing both direct emissions, such as methane emissions through gut and manure of cattle, and indirect emissions arising from activities like fertiliser use in fodder cultivation and energy consumption during feed as well as fodder processing (Rotz and Veith 2013).

LCA follows a standardised framework of International Organization for Standardization (ISO 2006). This methodology mainly calculates the intensity of GHG among the system, presenting emissions related to a functional unit. The ISO has developed particular international standards, called as the ISO 14040 series, that outline the four main phases of conducting an LCA, as summarised by Beauchemin and McGeough (2013) such as Goal and scope definition, Life cycle inventory analysis, Life cycle impact assessment and Life cycle interpretation. Overall, LCA serves as a robust and standardised method to evaluate the environmental footprint of livestock and their products, providing valuable insights for sustainability assessments and guiding efforts to minimise environmental impacts.

2.2 Carbon footprint - Milk

In case of carbon footprint throughout milk production, the phases of LCA involves:

a) The phase, goal and scope of a life cycle assessment (LCA) study such as various system boundaries, functional units, and farming systems considered in an LCA study, involves analysing the entire life cycle up to the retailer or focusing only on activities up to farm gate. The functional unit might be defined in different ways, such as per kilogram of milk or processed milk, per kilogram of energy-corrected milk (ECM) or fat- and protein-corrected milk (FPCM). Different types of farming systems, including conventional, organic, smallholder dairy and organised farms can also be assessed. The LCA study encompasses both direct emissions from the animal production unit, such as those resulting from gut and manure and also indirect emissions in relation with inputs like fertiliser usage for fodder production (resulting in N_2O emissions), electricity used for feed processing (resulting in CO_2 emissions), diesel used for feed transportation (resulting in CO_2 emissions), and others. The schematic diagram of system boundary given by Mech et al. (2023) is depicted in Fig. 1 for better understanding of the technical processes involved in emission of GHGs from the dairy farms.

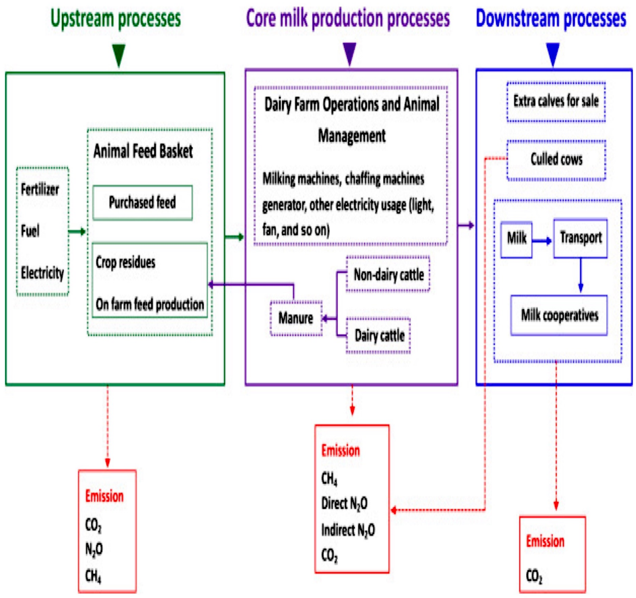

Fig. 1: System boundary for assessment of greenhouse gas emission in the dairy farms

b) The life cycle inventory analysis (LCI) phase involves collecting data on various aspects of system being studied. This includes information like the number and type of animals in particular unit, feed and fodder requirements, and other inputs and outputs. The collected data is then used to calculate the impacts on environment using relevant emission factors (EFs) or kind of default factors for all the main processes considered in the LCA study. The inventories responsible for emissions are shown in Fig. 2.

c) The impact assessment phase of an LCA study involves classifying and determining emissions with their contributions to global warming. This includes considering emissions of CO_2, CH_4, and N_2O from various sources such as cultivation, processing, and transport in feed production

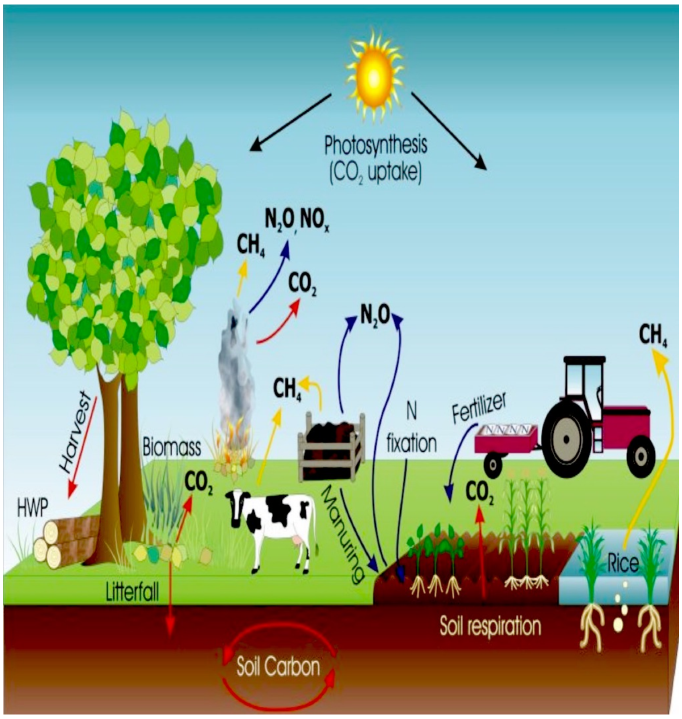

***Fig. 2**: Life cycle inventories for milk production in dairy animals*

activities, enteric fermentation, and manure management. These emissions are multiplied by their respective characterization factors to quantify their impact. The IPCC provides a set of EFs commonly used in LCA studies. The total GHG emissions are then expressed in CO_2-equivalents, taking into account their global warming potential.

d) The interpretation phase of an LCA study involves drawing and making recommendations based on the conclusions with original goals of the study. It involves analysing and understanding the results obtained from the LCA, considering the identified environmental impacts, and assessing their significance. The interpretation phase helps stakeholders and decision-makers understand the implications of the study findings and can guide them in making informed decisions and implementing appropriate measures to mitigate environmental impacts.

3. Carbon footprint in various farming systems around the world

The first LCA studies for the environmental performance examination of dairy products took place in the early 2000s (Finnegan et al. 2018), and since 2010, the number of published articles/papers on this topic for milk and its derived products has significantly increased, providing a broad range of carbon footprint values. However, the highlighted point was the scarcity of studies focusing specifically on milk production in Spain (Noya et al. 2018). Furthermore, while it is widely recognised that the farming system has a crucial role in the performance of dairy farms environmentally, there have been little comparative studies, particularly in Spain, investigating the impact of various types of farming systems for the carbon footprint of milk (Flysjo et al. 2011; Belflower et al. 2012; Rojas-Downing et al. 2017; Noya et al. 2018). While determining the overall carbon footprint of obtained dairy products, it has been reported that the greatest contribution to the total environmental impact were mainly related with products such as yogurt, cheese, and processed milk (Vasilaki et al. 2016; Finnegan et al. 2018; Hospido et al. 2003).

Casey and Holden (2006) conducted a study using life cycle assessment (LCA) methodology in Ireland in which the management practices were evaluated and greenhouse gas (GHG) emissions were calculated per unit of average milk yield. It was found that the average GHG emissions upto the level of farm-gate were approximately 1.50 kg CO_2eq/kg ECM/year and 1.3 kg CO_2eq/kg ECM/year on economic basis in low and high milk yield farms, respectively. In case of total emissions, enteric fermentation comprises 49%, fertiliser comprises 21%, dung management comprises 11%, concentrate feed comprises 13%, and electricity and diesel consumption about 5%. The study also showed that we could reduce emissions by about 14-26% by removing poor/non-lactating animals. Thomassen et al. (2008) evaluated GHG emissions with an LCA study for milk production of organic and conventional farms located in Netherlands. A detailed cradle-to-farm-gate analysis which includes on and off-farm pollution was performed. The global warming potential (GWP) per kg organic milk was found more compared to conventional milk in the study on-farm. However, the total GWP per kg of milk (including on and off-farm emissions) did not differ between the selected organic and conventional farms.

Capper et al. (2009) studied that the carbon footprint of milk was much influenced by production system. They showed that technological progress in production systems of dairy, such as the total mixed ration use and herd health management programs, led to GHG emissions reduction from 3.66 to 1.35 kg CO_2eq/kg milk between 1944 and 2007. These improvements were attributed to reduced stress and increased milk production. According to the Food and Agriculture Organization (FAO 2010), the GHG emissions at the level of farm-gate for milk production is nearly about 2.4 kg CO_2eq/kg FPCM (fat and protein corrected milk) with significant differences based on the geographical area. Emissions were 1 kg CO_2-eq/kg FPCM in North America upto 7.5 kg CO_2-eq/kg FPCM in South Africa.

In their study, Garg et al. (2016) went through a study on carbon footprint milk production in the smallholder dairy system that are multi-functional in the Anand district of Gujarat state of western India. The researchers employed a cradle-to-farm gate life cycle assessment (LCA) methodology, focusing on 60 dairy farms located in 12 geographically distinct villages within the district. The LCA method allowed the researchers to allocate CO_2, CH_4, and N_2O emissions, in terms of CO_2-equivalents (CO_2-eq), from inventories of feed, gut, and manure to fat- and protein-corrected milk (FPCM). This allocation was based on factors such as mass balance, price, and digestibility. The study found that emissions from cattle contributed 11.0%, 75.4% and 13.6% of CO_2, CH_4, and N_2O, respectively, while emissions from buffaloes contributed 8.2%, 80.5% and 11.3% of

CO_2, CH_4, and N_2O, respectively. The average carbon footprint (CF) of cow milk was quantified to be 2.3 kg CO_2-eq/kg FPCM, 1.9 kg CO_2-eq/kg FPCM, and 2.0 kg CO_2-eq/kg FPCM on the basis of mass, economic and digestibility, respectively. On the other hand, the CF of buffalo milk was found to be 3.0 kg CO_2-eq/kg FPCM, 2.5 kg CO_2-eq/kg FPCM, and 2.7 kg CO_2-eq/kg FPCM on the basis of mass, economic, and digestibility respectively. Overall, the CF in case of milk production in the dairy system of smallholders was quantified to be 2.2 kg CO_2-eq/kg FPCM. However, when considering economic operations of the smallholder system such as milk, manure, finance, and insurance, the CF minimised to 1.7 kg CO_2-eq/kg FPCM. Comparing their findings with estimates of the Food and Agriculture Organization (FAO) for southern Asia, the researchers observed that the cow and buffalo milk's Carbon footprint in the smallholder system was lower by 65% and 22%, respectively. This difference was primarily attributed to variations in GHG emission sources, managemental system of manure, digestibility of feed, and production of milk data used by FAO.

Jayasundara et al. (2019) made a research report of the carbon footprint (CF) and the financial performance of dairy farms especially for milk production in Ontario, Canada. The aim of the study was evaluation of two different measures in relation to trade-off. The researchers found that the largest contributors to the CF of milk were emissions as a result of enteric fermentation (44%) with respect to 36% from feed production and supply. With linear regression approach/model, the authors discovered that it is possible to reduce the CF related to milk production while simultaneously profitability of dairy farms might also be improved. When expressed in relation to CF of milk, nearly 60% was contributed by CH_4 in case of total CO_2 equivalents, with enteric fermentation around 44% and manure system 14%. The emissions were divided in equal manner between N_2O and CO_2 in case of CO_2 equivalents. Also, various emission components in relation with the dairy feed production and supply were combined (including N_2O emissions with respect to soil and CO_2 emissions related to crop inputs, fossil fuel use, and purchased feed), and estimated to nearly 36% of milk's total CF. It stood second in the queue as the source of greenhouse gas (GHG) emissions after enteric fermentation. The reality was that emissions from digestion of feed in rumen (enteric fermentation) and feed cultivation with purchasing accounted for almost 80% of milk's CF which highlights the importance of feed use efficiency as a key factor in reducing the intensity of milk production's GHG emissions. The study also found that emissions from manure storage system represented 18% of total milk's CF, making it the third largest source. This composed of 14% CH_4 emissions and 4% N_2O emissions. The remaining 3% of total milk's CF were attributed to emissions related to electricity and heating of fuel. Approximately 88% of total milk's CF on an average, was produced from within farm activities, while the remaining off-farm sources were 12%.

Kristensen et al. (2011) investigated the effects of GHG emissions by production systems and farming strategies in case of commercial dairy farms at the level of farm-gate using LCA. They analysed data from thirty five conventional dairy farms and thirty two organic dairy farms. The study found that more GHG emissions (1.27 kg CO_2-eq/kg ECM) were seen in organic farms compared to conventional farms (1.20 kg CO_2-eq/kg ECM). Techniques like low stocking rates in the herd with high production efficiency were regarded as promising strategy for reduction of GHG emissions per kg of milk at the level of farm-gate. Thoma et al. (2013) conducted a comprehensive study analysing the supply chain of fluid milk in United States to assess greenhouse gas (GHG) emissions from sources like fertiliser, milk packaging, through consumption to disposal. The study evaluated crop production as well as on-farm GHG emissions utilising public data and 536 farm operation surveys. Milk processing data was collected across the nation, and it included nearly 50 dairy plants, then quantification of GHG emissions from retail and consumer stages were done using various kind of informations such as primary data, design estimates, and also publicly available data. The study found that the total GHG emissions, from 2007 to 2008, were nearly 2.05 kg CO_2-eq/kg milk consumed which was based on primary data. The major and potent contributors to GHG emissions were enteric methane, feed production, and manure related emission. Gerber et al. (2013) conducted a global-scale quantification of carbon footprint based on the relationship among dairy productivity and GHG emissions using the LCA methodology. The study revealed that as productivity increases, the emissions decrease steeply from 12 kg CO_2-eq/kg FPCM (fat and protein corrected milk) to about 3 kg CO_2-eq/kg FPCM, until reaching a productivity level of around 2000 kg FPCM/cow/year. However, as productivity continues to increase to nearly 6000 kg FPCM/cow/year, the reduction in emissions becomes slower, and emissions hold in between the value of 1.6 and 1.8 kg CO_2-eq/kg FPCM. The study also found that GHG emissions per animal increases with more yields, but GHG emissions per kg FPCM decline drastically as animal annual milk productivity is higher.

Pirlo et al. (2014) conducted a study to quantify greenhouse gas (GHG) emissions related to milk production in six Buffalo farms around Italian Mediterranean region. The study employed a life cycle assessment (LCA) approach, considering various factors such as herd size, milk production, milk composition, and GHG sources. The average herd size in each farm was 360, with an average milk yield of 3563 kg fat- and protein-corrected milk (FPCM) per lactating buffalo per year, having an average of 8.24% milk fat and protein percentage of 4.57%. The GHGs considered in the study included CH_4 emission from enteric and manure sources, also N_2O from manure and fertiliser application, and CO_2 emissions through on-farm usage of fossil fuel for combustion and indirect sources such as electricity production and off-farm inputs like feeds and fertilisers. The study showed that the global warming potential (GWP) per kg FPCM to be 3.75 kg CO_2-eq in each buffalo farm. The major contributors to GHG emissions were enteric CH_4 consisting of 45% and indirect CO_2eq emissions consisting of 25%. Feed production lead to emission percentage of 34% of the total GHG emissions in relation with milk production on the farm. O'Brien et al. (2014) studied the overall GHG emissions for high-performance grass and confinement-based milk producing dairy farms using LCA method. The study found that when considering GHG emissions solely on behalf of milk production, the carbon footprint of milk in grass-based Irish farms was 5% lower (837 kg CO_2eq/t ECM) compared to UK confinement-based farms (884 kg CO_2eq/t ECM) and 7% lower in comparison to US confinement-based farms (898 kg CO_2eq/t ECM). The findings suggest that the grass-based system in Ireland resulted in lower emissions of GHG on behalf of milk production compared to the confinement-based systems in the UK and the US. The carbon footprint with respect to milk production for different countries are depicted in Table 1.

4. Conclusions

According to the various studies, it can be interpreted that the carbon footprint of milk production (functional unit) decreases with respect to increase in milk production and vice versa all over the world. The review mentions that the carbon footprint in relation to milk production exhibits variability across different countries, attributable to the diverse activities and their respective intensities within the realm of dairy farming. A more comprehensive understanding of this phenomenon can be achieved through the adoption of life cycle assessment methodology. It is discernible that the carbon related emissions emanating from dairy based sectors could be curtailed through strategic measures such as deliberate management of energy resources including electricity, diesel and by manipulating the rumen methanogenic bacteria and protozoa with the adoption of well-designed and judicious livestock feeding regimens like probiotics, essential oils, fat, ionophore antibiotics, nitrates, sulphates, phytogenic additives and other additives. Using methanogenic bacterial vaccines are also under investigation. In future, these strategies should be adopted in every farms throughout the world to get improved production efficiency with less greenhouse gas emissions.

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Table 1 Carbon footprint - milk production for different countries

Functional unit	Location	System	Carbon Footprint	Reference
1 Kg FPCM	Colombia	1313 dual purpose farms	2.9 Kg CO_2eq	(Gonzalez-Quintero et al. 2021)
1 Kg Milk	Uruguay	277 pasture-based dairy systems	3.0 Kg CO_2eq	(Darre et al. 2021)
1 Kg FPCM	Newzealand	360 dairy farms	0.78 Kg CO_2eq	(Ledgard et al. 2020)
1 Kg FPCM	Eastern Alps	75 dairy farms	1.31 Kg CO_2eq	(Berton et al. 2021)
1 Kg milk	Kenya	20 Small holder dairy farm	1.6 (0.8–2.9) kg CO_2eq Enteric-67.8%, Manure 15.1%, Feed-16.2%	(Weiler et al. 2014)
1Kg FPCM	Kenya	382 small holder dairy farms	2.5 Kg CO_2eq	(Wilkes et al. 2020)
1 Kg FPCM	China	25 Dairy farms	1.34 Kg CO_2eq	(Wang et al. 2018)
1 Kg FPCM	United States	46 Dairy farms	1.45 Kg CO_2eq	(Rotz et al. 2021)
1 Kg ECM	Australia	4 different dairy farms	0.39, 0.64, 0.54, &1.35 kg CO_2eq	(Sejian et al. 2018)
1 Kg ECM	Ireland	18 dairy farms	1.22 kg CO_2eq	(Yan et al. 2013)
1 Kg FPCM	Ireland	62 dairy farms	0.98 - 1.67 kg CO_2eq	(O'Brien et al. 2016)
1 Kg FPCM	Ireland	221 Grass-based farms	1.20 kg CO_2eq	(O'Brien et al. 2014)
1 Kg FPCM	Portugal	25 Pasture based dairy system	0.89 kg CO_2eq	(Morais et al.2018)
1 Kg FPCM	Italy	Conventional dairy farms	1.12 kg CO_2eq	(Bacenetti et al. 2016)
1 Kg FPCM	Italy	6 Buffalo farms	3.6 kg CO_2eq	(Pirlo et al. 2014)
1 Kg FPCM	Australia	139 farms	1.11 kg CO_2eq	(Gollnow et al. 2014)
1 Kg FPCM	Canada	142 dairy farms	0.441 - 1.732 kg CO_2 eq	(Jayasundara et al. 2019)
1 Kg FPCM	United States	United States 50 dairy plants	1.23 kg CO_2eq	(Thoma et al. 2013)
1 Kg FPCM	Mantova	84 dairy farms	0.82 Kg CO_2eq	(Lovarelli et al. 2019)
1 Kg FPCM	Canada	Conventional Dairy farms	0.95 Kg CO_2eq	(Mc Geough et al. 2012)

FPCM - Fat and protein corrected milk; CO_2eq - Carbon dioxide equivalents

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