OVERVIEW OF GHG EMISSIONS ASSOCIATED TO RAW MILK PRODUCTION. COMPARISON OF MILK AND CHEESE CARBON FOOTPRINTS WITH SEMI-CONFINEMENT AND PASTURE SYSTEMS.

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ABSTRACT

Milk production was estimated to contribute with 3-4% of the anthropogenic GHG emissions. However, several differences can be found in the carbon footprint associated to raw milk depending on several factors, such as the geographical area, species of cow and production system. In this work, a global overview of works published on CF of raw cow milk is provided. Additionally, two different dairy systems (semi-confinement and pasture-based) have been analysed by Life Cycle Assessment (LCA) in order to determine the effect on the CF of milk produced. High quality inventory data was obtained directly from these facilities and the main factors involved in milk production were included (co-products, livestock food, water, electricity, diesel, cleaning elements, transport, manure and purines management, gas emissions to air…). In accordance with reviewed literature, it was found that the carbon footprint of milk was basically determined by the cattle feeding and cow gas emissions. The values of milk CF found in the systems under study were within the range for cow milk production worldwide (0.9-4.7 kgCO_2eq/kg$_{FPCM}$). Specifically, in the semi-confinement and the pasture-based dairy farms 1.22 and 0.99 kgCO_2eq per kg$_{FPCM}$ were obtained,

respectively. The environmental benefits obtained with the pasture grazing system are mainly due to the less use of purchased fodder but also to the allocation between milk and meat that resulted to be a determinant methodological issue in CF calculation.

Finally, data of the evaluated dairy systems have been employed to analyse the influence of raw milk production on cheese manufacturing. With this aim, CF of a small-scale cheese factory has also been obtained. The main subsystems involved were included (raw materials, water, electricity, energy, cleaning products, packaging materials, transport, wastes and gas emissions) were included in the inventory of the cheese factory. CF values were 16.6 and 14.7 kgCO_2eq per kg of cheese for milk produced in semi-confinement and pasture-based systems, respectively. The production of raw milk meant more than 60% of CO_2eq emissions associated to cheese, so the primary production is the principal hot-spot to reduce the GHG emissions derived from cheese making.

Keywords: LCA; dairy farm; raw milk production; pasture-based; semi-confinement; carbon footprint; cheese.

1. INTRODUCTION

Food production is a key contributor to greenhouse gas (GHG) emissions worldwide and it accounts for 30% of total GHG emissions (Boehm et al., 2018). Specifically, the livestock sector contributes with 12% of all anthropogenic GHG emissions (Batalla et al., 2015) and the milk production was estimated to mean 3-4% to the global man-made greenhouse gas emissions (Dalgaardet al., 2014; Del Prado et al., 2013; Yan et al., 2013).

Milk and other dairy products are consumed in large amounts in most of developed countries and consumption is rapidly increasing in other low and middle income countries (Röös et al., 2016). Between 2013 and 2014 the production of cows' milk in the EU-28 increased by almost 4%. In particular, farms across the EU-28 produced approximately 160 million tonnes of cow milk in 2014 (Eurostat, 2016). Milk production in Europe continues to intensify and it is expected to become the world's largest milk exporter (Styles et al., 2018). In terms of milk production, Spain occupies the seventh position in the European framework (6.8 million tonnes in 2014) with several areas of important dairy farming activities, many of them located in the Northwest of the country (Noya et al., 2018).

Due to the global growing concern about climate change, on May 2018 the Council of European Union formally adopted the Regulation on binding annual emission reductions by Member States from 2021 to 2030, also known as the Effort Sharing Regulation. This regulation, together with the revised ETS Directive and the LULUCF Regulation, creates a binding legal framework for the EU's efforts to reduce overall greenhouse gas emissions by at least 40% by 2030, with respect to 1990 levels (European Commission, 2018). To communicate the climate change impacts derived from food production, it is usually employed the carbon footprint (CF), a crucial indicator to communicate the GHG emissions associated to a product (Batalla et al., 2015(Xu and Lan, 2016).). According to the International Dairy Federation, the calculation of the carbon footprint of a product should be based on the LCA methodology included in the ISO 14000 series (IDF, 2015 Abín et al., 2018; Rice et al., 2018)).

The first LCA studies relating to dairy products were compiled in the early 2000s (Finnegan et al., 2018) and the number of works published on environmental performance of dairy foodstuffs increased dramatically from 2010 to date, giving a wide range of values for the CF of milk and derived products. However, Noya et al. (2018) have recently stated that few of these works have been focused on Spanish milk production. In addition, and, although it is well known that the farming system is a determinant parameter on environmental performance of dairy farms (Rojas-Downing et al., 2017), few works (and no one in Spain) has been carried out on comparing the effect of the farm system on the milk CF (Flysjö et al., 2011; Belflower et al. 2012). The CF of the milk determines the CF of the derived dairy products, since it has been reported that raw milk production was the most significant contributor to the total impact associated to dairy products such as cheese, yogurt or processed milk (Canellada et al., 2018; Finnegan et al., 2018; Hospido et al., 2003; Vasilaki et al., 2016). Consequently, this work has been carried out with three main objectives, firstly to carry out a mini-review on carbon footprint of milk worldwide, secondly, widen the knowledge of carbon footprint of milk production in Spain comparing two contrasting milk production systems and, thirdly, analyse the effect of the milk production systems on the carbon footprint of an artisanal cheese. With this aim, two dairy farms sited in the same region of Spain (Asturias) have been selected as study cases, one with a typical production system of this region (a semi-confinement system) and the other with a pasture-based system. Additionally, the data of these two dairy systems have been employed to obtain the carbon footprint of a small-scale cheese factory sited in the same region. The artisanal production of cheese has a strong traditional character worldwide and this cheese factory has been chosen as representative of traditional cheese production in southern Europe.

2. MATERIALS AND METHODS

2.1. Objectives and functional unit definition

LCA methodology was used as a tool with the aim to determine the carbon footprint of the dairy farms selected as representative of two different milk production systems (a semi-confinement system and a pasture-based system). In both cases, the functional unit was defined as 1 kg of fat and protein-corrected milk (FPCM) calculated according to the recommendations of the International Dairy Federation (IDF, 2015). Additionally, carbon footprint of a small-scale cheese factory was also calculated employing milk from the two different dairy systems with the aim to determine the effect of milk origin on cheese CF. In this case, the functional unit chosen was 1 kg of cheese.

2.2. System description and boundaries

The analysis of the dairy farms was carried out considering a “cradle to farm gate” perspective. The farms were located in North Spain (Asturias). At the moment of the study, the semi-confinement farm consisted on 72 Holstein cows (48 milk producers and 24 heifers and calves) with a yearly milk production of 365000 L. During the year of the study, 21 male calves and 7 culled cows were sold for slaughtering (a total of 5355 kg live weight per year). The farm had a total of 30.45 Ha of land for farming (4.61 Ha for maize, 9.64 Ha for grass and 16.20 for other forages). Regarding the pasture-based farm, at the moment of the study, the farm consisted on 13 heads of livestock, i.e., 11 milk producer cows (10 Holstein and 1 Jersey) and 2 calves. During the year of the study the production of milk was 40730 L, 6 male calves and 3 culled cows were sold for slaughtering (a total of 2068 kg live weight per year), whereas 2 dead calves were managed as dangerous wastes for incineration. The farm also had a total of 14 Ha of land for farming (2 Ha for maize and 12 Ha for grazing).

Additionally, to analyse the effect of the milk production system on the carbon footprint of artisanal cheese, the small-scale factory described on Canellada et al. (2018) was considered.

2.3. Inventory analysis

The study included the whole life cycle involved in the production of the raw milk, i.e., farming of maize, transport and production of raw materials (animal feed, cleaning products, bedding materials and drugs), consumption of water and energy, cow emissions (CO_2, CH_4 and NH_3) and management of manure, purines and wastewater. In the semi-confinement farm, cattle were fed fodder concentrate, alfalfa, hay, maize silage, meadow grass silage and, sporadically, cows were put out to pasture. In the pasture-based farm, cows were left to graze free on grass fields during the warm 6-7 months of the year, whereas during the cold months they were housed in a stall being fed fodder concentrate, maize and dry grass. In both systems, manure and purines were applied to the farming land and emissions derived from this activity were calculated considering that 30% of nitrogen was emitted as ammonia (Misselbrook et al., 2000).. Heifers born in the farm were employed for replacement, whereas bull calves and culled cows were sold for meat (considered as co-product). The allocation factor for the dairy farms were calculated for milk as indicated by the International Dairy Federation (IDF, 2015) and a value of 0.91 and 0.69 were obtained for semi-confinement and pasture-based systems, respectively. These allocation factors were employed to consequently correct the inventory data.

In relation to the cheese factory, a "cradle to retail store" perspective was considered. The majority raw material, i.e. milk, and also minority ingredients (salt and $CaCl_2$) were included in the analysis. Packaging materials, cleaning products, tap water, electricity and transport were taken into account. Emissions from a biomass pellet boiler employed to generate heat and the production of consumed pellets were also included in the study. The main waste originated from the cheesemaking process is whey, which was used to feed pigs bred in a nearby farm (this was considered in the system as pig fodder avoided). The rest of residues were recycled or landfilled and wastewater was treated.

In Figure 1 it is shown an overview of the subsystems considered in this work.

2.4. Carbon footprint

In all cases, the carbon footprint was performed employing the Greenhouse Gas Protocol V1.01 / CO2 eq (kg) by means of the LCA software package SimaPro v8. This method includes scopes 1 (all direct GHG emissions), 2 (indirect GHG emissions from consumption of purchased electricity, heat or steam) and also 3 (other indirect emissions, such as transport-related activities, waste disposal, etc.) (GHGP, 2017). The databases used were USLCI and EcoInvent v3.

3. RESULTS AND DISCUSSION

3.1. Overview of carbon footprint associated to raw milk production.

Table 1 summarises the main papers published from 2009 until time of writing regarding the carbon footprint of cow milk production in dairy farms worldwide. It is remarkable the great increment in the number of works related to this topic published in the last year, indeed almost 40% of the studies was published in 2018, which points out the increasing relevance of this issue (Figure 2). Additionally, more than a half of these studies have been carried out in Europe, whereas the rest of them have been conducted in Asia, Africa, North America and Oceania. It should be noted that there is a lack of this kind of studies in South America. Certainly, only a recently published work that analysed the CF of sheep production systems in Chile was found (Toro-Mujica et al., 2017), but none related to cow milk production. Despite to the fact that the different authors employed different methodologies, in general, they agree that production of cattle feed and cow emissions are the main contributors to the milk CF. On this matter, Del Prado et al. (2013) found that lower carbon footprints of milk were generally associated with lower proportion in cattle diet that could be used to feed humans (e.g. cereals). On the contrary, Noya et al. (2018) reported alfalfa as one of the main contributors to environmental burdens associated with feed production and proposed as alternative ingredients: maize silage and grass silage. Maize silage showed potential environmental benefits in comparison with alfalfa, whereas the effect of grass silage was not so clear and more detailed analysis would be needed to confirm its advantages. With this regards, Fathollahi et al. (2018) evaluated alfalfa hay and corn silage production systems as the main feedstuffs for dairy farming and concluded that alfalfa was more environmentally friendly, with lower emissions to air than corn silage. Colombini et al. (2016) compare the global warming potential (GWP) of milk production employing three forage system scenarios, based on corn, sorghum grain and sorghum forage silages and found that, although the differences were very small, the lowest value was obtained using a corn silage based diet. Additionally, the cow feed not only affects GHG emissions due to its production, but it was also pointed out that methane emission from enteric fermentation is strongly influenced by cow diet (Colombini et al., 2016; Del Prado et al., 2013; Thomassen et al., 2009).

Regarding to the system production, Flysjö et al. (2011) was not able to detect great differences in carbon footprint between pasture grazing system in New Zealand and indoor housing system with the use of concentrate feed in Swede. Soteriades et al. (2018) reported that increasing the housing period had almost no effect on CF in pasture-based dairy farming in UK. These same authors investigated the effect of replacing conventional perennial ryegrass with high-sugar grasses as a forage source and concluded that this measure allowed reductions in GWP. Belflower et al. (2012) also found similar values of CF in pasture based and confinement systems in USA. Contrarily, O´Brien et al. (2015) proposed that grass-based dairy farms would allow higher levels of milk production per hectare reducing the CF and enhancing at the same time the economic performance.

Bava et al. (2014) reported that, although it was not easy to establish a clear connection between intensive farming and environmental performances, farms with cows more efficient in converting feed to milk imply lower impacts per milk unit. In this context, Bakken et al. (2017) stated that an intensification of Norwegian dairy production, which implies higher yields per animal, would contribute to score more favourably in terms of GWP. Woldegebriel et al. (2017), who studied milk production in Ethiopia at three different scales, found that in rural farms the environmental impacts per cattle unit were lower than in large-scale farms. However, the milk yield per cow was higher in the large-scale farms, so that the impacts per kg of milk did not differ significantly between the three scales analysed. These authors also concluded that the impacts in the global warming potential category derived from the Ethiopian dairy farms were higher than those reported for the same type of farms in developing countries due to the low-quality forages and wheat bran used to feed the animals.

Some authors also identified manure management practices as one of the hot-spots for milk production. Castanheira et al. (2010) pointed out that more than 70% of CO_2eq generated from milk production were due to CH_4 emitted from enteric fermentation and manure management. The choice of manure management was one of the factors responsible for differences found for five milk production regions in USA (Thoma et al., 2013). Additionally, manure management practises were also identified as an important factor to reduce carbon footprint in Australia (Gollnow et al., 2014) and Fan et al. (2018) reported that, in China, the fully coupled mode, which recycles both solid and liquid animal manure, implies lower GHG emissions than the semicoupled mode, which only recycles solid manure to farmlands.

An important methodological issue, which is in many cases crucial for the outcome of raw milk CF, is the consideration of the coproduction of several products in the farm, such as the sale of cattle for slaughter. In fact, most works recently published on milk CF include allocation between milk and meat (Gollnow et al., 2014; IDF, 2015).

The geographical area is a parameter that also affects the environmental performance of a farm. This factor determines the climate, and therefore the possibilities for animal feeding, and also the degree of technological and legislative development. Weiss and Leip (2012) analysed the GHG fluxes from the livestock sector for all EU-27 countries and concluded that the countries with the lowest net product emissions did not necessarily use similar production systems. In Figure 3, it is shown the values of carbon footprint of raw cow milk vs. Human Development Index (HDI) (UNDP, 2018) of the country where the study was carried out. Data of Table 1 have been standardised to 1

kg_{FPCM} and CF have been recalculated according to equations reported by Lorenz et al. (2019) considering the average composition of cow milk (FAO, 2019). Only real data has been taking into account for the graph, i.e. data obtained from model farms have not been included, and, when reviewed works reported and interval of CF values, maximum and minimum values have been represented. Data are shown in three groups, depending on the allocation method employed in the cited work, since it has been reported that the choice of allocation method can substantially affect the CF value (Lorenz et al., 2019). A priori, it would be expected that, in general, CF values associated with milk production should be higher in less developed countries, due to different factors, such as, the lower technological development, the employment of low-quality forages to feed the dairy cows, the lower yield per animal and also the more permissive legislation on environmental issues. On the contrary, it is remarkable that no correlation between CF and HDI could be observed for any of the three groups of data analysed. Differences between the groups with different allocation method could not be identified either, although it is obvious that for the same system different allocation methods give different results. Additionally, it should also be noticed the high variability of CF values found for the same country, even when the same allocation method is employed. See for instance, Kenya or Spain, which showed two extreme values for carbon footprint (0.9 and 4.3 and 0.8 and 2.1 $kgCO_2eq/kg_{FPCM}$, respectively). These great differences can be attributed to different factors, such as, diet/feeding system, climate, management practises and also but not only the allocation method selected when other products are coproduced.

3.2. Comparison of carbon footprint of milk production in semi-confinement and pasture-based systems.

In order to illustrate the effect of the system employed in the farm over milk CF, data from two real farms were employed to calculate CF values. Both farms were located at the same geographical region, and, in both cases, calves were sold as co-product and allocation was considered.

As can be seen in Figure 4, results obtained with the Greenhouse Gas Protocol for the analysed farms revealed cow feeding and cow emissions to air as the factors with the highest environmental loads in carbon footprint values, which agrees with results found in literature and commented above. Specifically, food was responsible of more than 40% and 20% of CF in semi-confinement and pasture-based systems, respectively. This difference is due to the fact that in pasture-based systems cows were mainly feed by being left to graze free on grasslands, so only 206 g of food not cultivated *in situ* were needed to produce 1 kg_{FPCM}, whereas in semi-confinement system 648 g of *ex situ* food were necessary. It is well known that cow emissions (mainly originated by enteric fermentation) are associated with extensive cattle production (De Oliveira and Bourscheidt, 2017; Coates et al., 2017), so that 419 g and 505 g of emissions, which corresponds with 52% and 78% of CF, were generated to produced 1 kg_{FPCM} in semi-confinement and pasture-based systems, respectively.

According to the ISO 14067 standard, both biogenic and fossil carbon should be included in carbon footprint calculation. With this consideration, 1.25 and 1.03 $kgCO_2eq$ per kg_{FPCM} were obtained in the semi-confinement and the pasture-based dairy farms, respectively. These values were within the range found in literature for cow milk production worldwide (0.9-4.7 $kgCO_2eq/kg_{FPCM}$) and quite lower than values reported for other dairy animals (sheep, goat and buffalo) (1.9-5.2 kg CO_2eq/kg milk) (Weiss and Leip, 2012; Batalla et al., 2015; Patra, 2017).

Thus, according to the results obtained in the present work, and considering the carbon footprint as indicator of the environmental impact, pasture-based dairy farms have shown to be a greener production system than semi-confinement farms. These data are in agreement to those reported by O´Brien et al. (2015) who indicated that an increase in the length of the grazing season implies a reduction in the CF. Belflower al. (2012). Flysjö et al. (2011) also obtained lower values for pasture-based systems than for confinement systems, however the differences found were relatively small. On this matter, in a recent work, Lorenz et al. (2019) carried out a methodological approach to compare milk production systems with different management options and concluded that, at a constant milk yield, the CF was significantly lower in the pasture systems compared to the semi-confinement and confinement systems.

In terms of productivity, each cow produced 7308 kg_{FPCM} per year in semi-confinement system, value very similar to that reported by Wang et al. (2018) for the North China Plain in 2015 (7000 kg_{FPCM} per cow), whereas in pasture-based system each cow produced only 3618 kg_{FPCM} per year. It is well known that productivity of milking cows showed a strong negative correlation with the CF of milk. However, in the case here analysed the benefits derived from using a pasture-based system balanced the disadvantages derived from the lower productivity. Additionally, there was a great difference between the allocation factors for the dairy farms under study (0.91 and 0.69 for semi-confinement and pasture-based systems, respectively). This means that the amount of meat produced in the farm originated by the sold of culled cows and surplus claves is determinant regarding the value of milk carbon footprint and in our case make the scale tip in favour of the pasture-based system.

Finally, it should be remarked that, as can be seen in Figure 4, fossil carbon meant almost 50% of total CF in semi-confinement daily farm, whereas it represented approximately 25% of CF of milk from pasture-based farm. Biogenic carbon comes from biological processes and it is part of the fast domain of the global carbon cycle, on the contrary, emissions from fossil sources contribute to the atmospheric pool by releasing carbon from the geologic pool and are therefore new emissions to the atmosphere (Brenton et al., 2018). In this concern, Gunn et al. (2011) affirmed that biogenic emissions are less harmful than fossil emissions. Thus, regarding GHG emission, this is also an advantage of pasture-based system compared to semi-confinement system.

3.3. Effect of milk production system on carbon footprint of artisanal cheese factory

In Figure 5 it is shown the carbon footprint values obtained with the Greenhouse Gas Protocol in an artisanal cheese factory employing milk from semi-confinement dairy farm and milk from pasture-based dairy farm. In both cases, the production of raw milk meant more than 60% of CO_2eq emissions (62 and 67% from semi-confinement and pasture-based systems, respectively). These results prove that, as it has been reported in literature by different authors, raw milk production resulted to be the main contributor to the environmental impact derived from cheese production (González-García et al., 2013; Canellada et al., 2018; Famiglietti et al., 2019; Finnegan et al., 2018; Forleo et al., 2018; Hospido et al., 2003; Santos Jr. et al., 2017; Vasilaki et al., 2016).

Considering the fossil and the biogenic carbon, the carbon footprint values were 16.9 and 15.0 kgCO_2eq per kg of cheese for milk produced in semi-confinement and pasture-based systems, respectively. So, it is noticeable that the employment of raw milk from pasture-based system instead of from semi-confinement based system was able to reduce the carbon footprint of cheese in more than 10%. The CF values found here were within the range of CF reported in literature for cow cheeses worldwide (4.2-16.9 kgCO_2eq per kg of cheese) (Canellada et al., 2018). Additionally, it should be remarked that there are few studies that have analysed the performance of small-sized and/or artisanal cheese factories, which is the case of the facility under study in the present work (Nigri et al., 2014; Santos Jr. et a., 2017). Santos Jr. et al. (2017) found that global warming potential emissions of cheese production in a small-sized dairy industry in Brazil were 14.4 kg CO_2eq/kg of product, this value is very similar to that obtained here employing milk from pasture-based systems (14.7 kgCO_2eq per kg of cheese).

Thus, reducing the impact of milk production is the key parameter to decrease the carbon footprint of cheese manufacture and different factors are involved in this issue, not only cow feeding (as it was commented above), but also dairy system, intensification, manure management practices and even the cow breed are also important aspects to be considered with regards to the impact of milk production (Capper and Cady, 2012; Kristensen et al., 2015).

4. CONCLUSIONS

Concerning the carbon footprint of raw milk production worldwide, the reviewed literature indicated that, in all cases, the feeding of cattle and the cow emissions are the major contributors (more than 90%) to greenhouse gas emissions. Nevertheless, other factors such as management practices, intensification degree, multi-functionality, cow breed, climate, etc. also influence on milk CF. Besides, it is remarkable that the sold of surplus calves and culled cows as co-products for meat production resulted a key parameter to reduce the carbon footprint by means of the allocation of environmental loads.

The results obtained for the both dairy systems analysed in this work indicated that, in accordance with literature, the production of the food and the cow gas emissions to air were the most impacting subsystems on carbon footprint. Milk produced in pasture-based system showed a carbon footprint value 18% lower than in the case of semi-confinement system. This suggests that increasing grazing season is a good option to reduce the GHG emissions derived from milk production, although the determining factor in the cases here analysed results to be the amount of animals sold for meat. Additionally, biogenic carbon represented almost half of milk CF in semi-confinement system, whereas it represented around 75% of CF of milk from pasture-based system. Since fossil emissions are usually considered more harmful than biogenic emissions, this is also an advantage of pasture-based farm compared to semi-confinement farm.

According to data obtained from the cheese factory, milk production resulted to be the main contributor to the carbon footprint of cheese, consequently, when milk from pasture-based system was employed as raw material the cheese CF was 11% reduced in comparison to the value obtained when milk from semi-confinement system was used.

To sum up, it seems clear that the main improvement action to reduce environment impacts of raw milk production systems would be the modification of feeding practices to minimise the use of fodder concentrate produced off-farm, and at the same time increasing the co-production of by-products, such as meat, in order to share the burdens associated with milk production.

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REFERENCES

Abín, R., Laca, A., Laca, A., Díaz, M. (2018) Environmental assessment of intensive egg production: A Spanish case study. J. Clean. Prod. 179: 160-168.

Bakken, A.K., Daugstad, K., Johansen, A., Hjelkrem, A.G.R., Fystro, G., Strømman, A.H., Korsaeth, A. (2017) Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments. Agric. Sys. 158: 50-60.

Baldini, C., Bava, L., Zucali, M., Guarino, M. (2018). Milk production Life Cycle Assessment: A comparison between estimated and measured emission inventory for manure handling. Sci. Total Environ. 625: 209-219.

Baldoni, E., Coderoni, S., Esposti, R. (2018) The complex farm-level relationship between environmental performance and productivity: The case of carbon footprint of Lombardy farms. Environ. Sci. Policy 89: 73-82.

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

Batalla, I., Knudsen, M.T., Mogensen, L., del Hierro, O., Pinto, M., Hermansen, J.E. (2015) Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grass lands. J. Clean. Prod. 104: 121-129.

Battini, F., Agostini, A., Tabaglio, V., Amaducci, S. (2016) Environmental impacts of different dairy farming systems in the Po Valley. J. Clena. Prod. 112: 91-102.

Bava L., Sandrucci A., Zucali M., Guerci M., Tamburini A. (2014) How can farming intensification affect the environmental impact of milk production? J. Dairy Sci. 97: 4579-4593.

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

Boehm, R., Wilde, P.E., Ver Ploeg, M., Costello, C., Cash, S.B. (2018) A comprehensive life cycle assessment of greenhouse gas emissions from U.S. household food choices. Food Policy 79: 67-76.

Breton, C., Blanchet, P., Amor, B., Beauregard, R., Chang, W.-S. (2018) Assessing the climate change impacts of biogenic carbon in buildings: a critical review of two main dynamic approaches. Sustainability 10: 2020.

Capper, J.L., Cady, R.A. (2012) A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. J. Dairy Sci. 95: 165-176.

Canellada, F., Laca, A., Laca, A., Díaz, M. (2018) Environmental impact of cheese production: A case study of a small-scale factory in southern Europe and global overview of carbon footprint. Sci. Total Environ. 635: 167-177.

Castanheira, E.G., Dias, A.C., Arroja, L., Amaro, R. (2010) The environmental performance of milk production on a typical Portuguese dairy farm. Agric. Syst. 103: 498-507.

Chobtang, J., Ledgard, S.F., McLaren, S.J., Zonderland-Thomassen, M., Donaghy, D.J. (2016) Appraisal of environmental profiles of pasture-based milk production: a case study of dairy farms in the Waikato region, New Zealand. Int. J. Life Cycle Assess. 21: 311-325.

Coates, T.W., Flesch, T.K., McGinn, S.M., Charmley, E., Chen, D. (2017) Evaluating an eddy covariance technique to estimate point-source emissions and its potential application to grazing cattle. Agric. For. Meteorol. 234-235: 164-171.

Colombini, S., Zucali, M., Rapetti, L., Crovetto, G.M., Sandrucci, A., Bava, L. (2015) Substitution of corn silage with sorghum silages in lactating cow diets: in vivo methane emission and global warming potential of milk production. Agric. Syst. 136: 106-113.

Dalgaard, R., Schmidt, J., Flysjö, A. (2014) Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. J. Clean. Prod. 73: 146-153.

Daneshi, A., Esmaili-sari, A., Daneshi, M., Baumann, H. (2014) Greenhouse gas emissions of packaged fluid milk production in Tehran. J. Clean. Prod. 80: 150-158.

De Oliveira, G., Bourscheidt, D.S. (2017) Multi-sectorial convergence in greenhouse gas emissions. J. Environ. Manage. 196: 402-410.

Del Prado, A., Mas, K., Pardo, G., Gallejones, P. (2013) Modelling the interactions between C and N farm balances and GHG emissions from confinement dairy farms in northern Spain. Sci. Total Environ. 465: 156-165.

European Commission (2018): https://ec.europa.eu/commission/index_en (accessed 9 October 2018).

EUROSTAT (2016). Milk and milk product statistics: http://ec.europa.eu/eurostat (accessed 9 October 2018).

Famiglietti, J., Guerci, M., Proserpio, C., Ravaglia, P., Motta, M. (2019) Development and testing of the Product Environmental Footprint Milk Tool: A comprehensive LCA tool for dairy products. Sci. Total Environ. 648: 1614-1626.

Fan, X., Chang, J., Ren, Y., Wu, X., Du, Y., Xu, R., Liu, D., Chang, S.X., Meyerson, L.A., Peng, C., Ge, Y. (2018) Recoupling industrial dairy feedlots and industrial farmlands mitigates the environmental impacts of milk production in China. Environ. Sci. Technol. 52: 3917-3925.

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

FAO (Food and Agriculture Organization of the United Nations) (2019): http://www.fao.org/dairy-production-products/products/milk-composition/en/ (accessed 20 May 2019).

Fathollahi, H., Mousavi-Avval, S.H., Akram, A., Rafiee, S. (2018) Comparative energy, economic and environmental analyses of forage production systems for dairy farming. J. Clean. Prod. 182: 852-862.

Finnegan, W., Yan, M., Holden, N.M., Goggins, J. (2018) A review of environmental life cycle assessment studies examining cheese production. Int. J. Life Cycle Assess. 23: 1773-1787.

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

Forleo, M.B., Palmieri, N., Salimei, E. (2018). The eco-efficiency of the dairy Cheese Chain: An Italian case study. Ital. J. Food Sci. 30: 362-380.

Galloway, C., Conradie, B., Prozesky, H., Esler, K. (2018a) Are private and social goals aligned in pasture-based dairy production? J. Clean. Prod. 175: 402-408.

Galloway, C., Conradie, B., Prozesky, H., Esler, K. (2018b) Opportunities to improve sustainability on commercial pasture-based dairy farms by assessing environmental impact. Agric. Syst. 166: 1-9.

GHGP (2017). Greenhouse Gas Protocol: http://www.ghgprotocol.org/ (accessed 8 December 2017).

Gollnow, S., Lundie, S., Moore, A.D., McLaren, J., van Buuren, N., Stahle, P., Christie, K., Thylmann, D., Rehl, T. (2014) Carbon footprint of milk production from dairy cows in Australia. Int. Dairy J. 37: 31-38.

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

Gunn, J.S., Ganz, D.J., Keeton, W.S. (2012) Biogenic vs. geologic carbon emissions and forest biomass energy production. GCB Bioenergy 4: 239-242.

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

IDF (International Dairy Federation) (2015). Bulletin of the IDF N479/2015: A common carbon footprint approach for the dairy sector - The IDF guide to standard life cycle assessment methodology: https://store.fil-idf.org/ (accessed 3 Mayo 2018).

Kiefer, L.R., Menzel, F., Bahrs, E. (2015) Integration of ecosystem services into the carbon footprint of milk of South German dairy farms. J. Environ. Manage. 152: 11-18.

Kristensen, T., Søegaard, K., Eriksen, J., Mogensen, L. (2015) Carbon footprint of cheese produced on milk from Holstein and Jersey cows fed hay differing in herb content. J. Clean. Prod. 101: 229-237.

Legard, S.F., Wei, S., Wang, X., Falconer, S., Zhang, N., Zhang, X., Ma, L. (2019) Nitrogen and carbon footprints of dairy farm systems in China and New Zealand, as influenced by productivity, feed sources and mitigations. Agric. Water Manag. 213: 155-163.

Lorenz, H., Reinsch, T., Hess, S., Taube, F. (2019) Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. J. Clean. Prod. 211: 161-170.

Misselbrook, T.H., Van Der Weerden, T.J., Pain, B.F., Jarvis, S.C., Chambers, B.J., Smith, K.A., Phillips, V.R., Demmers, T.G.M. (2000) Ammonia emission factors for UK agriculture. Atmos. Environ. 34: 871-880.

Nigri, E.M., Barros, A.C., Rocha, S.D.F., Filho, E.R. (2014) Assessing environmental impacts using a comparative LCA of industrial and artisanal production processes: “minas cheese” case. Food Sci. Technol. 34: 522-531.

Noya, I., González-García, S., Berzosa, J., Baucells, F., Feijoo, G., Moreira, M.T. (2018) Environmental and water sustainability of milk production in Northeast Spain. Sci. Total Environ. 616-617: 1317-1329.

O’Brien, D., Hennessy, T., Moran, B., Shalloo, L. (2015). Relating the carbon footprint of milk from Irish dairy farms to economic performance. J. Dairy Sci. 98: 7394-7407.

Ortiz-Gonzalo, D., Vaast, P., Oelofse, M., de Neergaard, A., Albrecht, A., Rosenstock, T.S. (2017) Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya. Agric. Ecosyst. Environ. 248: 58-70.

Patra, A.K. (2017) Accounting methane and nitrous oxide emissions, and carbon footprints of livestock food products in different states of India. J. Clean. Prod. 162: 678-686.

Rice, P., O’Brien, D., Shalloo, L., Holden, N.M. (2018) Defining a functional unit for dairy production LCA that reflects the transaction between the farmer and the dairy processor. Int. J. Life Cycle Assess. 24: 642-653.

Rojas-Downing, M.M., Harrigan, T., Nejadhashemi, A.P. (2017) Resource use and economic impacts in the transition from small confinement to pasture-based dairies. Agric. Syst. 153: 157-171.

Röös, E., Patel, M., Spångberg, J. (2016) Producing oat drink or cow's milk on a Swedish farm - Environmental impacts considering the service of grazing, the opportunity cost of land and the demand for beef and protein. Agric. Syst. 142: 23-32.

Santos Jr., H.C.M., Maranduba, H.L., de Almeida Neto, J.A., Rodrigues, L.B. (2017) Life cycle assessment of cheese production process in a small-sized dairy industry in Brazil. Environ. Sci. Pollut. Res. 24: 3470–3482.

Schueler, M., Hansen, S., Paulsen, H.M. (2018a) Discrimination of milk carbon footprints from different dairy farms when using IPCC Tier 1 methodology for calculation of GHG emissions from managed soils. J. Clean. Prod. 77: 899-907.

Schueler, M., Paulsen, H.M., Berg, W., Prochnow, A. (2018b) Accounting for inter-annual variability of farm activity data for calculation of greenhouse gas emissions in dairy farming. Int. J. Life Cycle Assess. 23: 41-54.

Sejian, V., Prasadh, R.S., Lees, A.M., Lees, J.C., Al-Hosni, Y.A.S., Sullivan, M.L., Gaughan, J.B. (2018) Assessment of the carbon footprint of four commercial dairy production systems in Australia using an integrated farm system model. Carbon Manag. 9: 57-70.

Soteriades, A.D., Gonzalez-Mejia, A.M., Styles, D., Foskolos, A., Moorby, J.M., Gibbons, J.M. (2018) Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level. J. Clean. Prod. 202: 1241-1252.

Styles, D., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., Gibbons, J. (2018) Climate mitigation by dairy intensification depends on intensive use of spared grassland. Glob. Chang. Biol. 24: 681-693.

Tabacco, E., Comino, L., Borreani, G. (2018) Production efficiency, costs and environmental impacts of conventional and dynamic forage systems for dairy farms in Italy. Eur. J. Agron. 99: 1-12.

Thoma, G., Popp, J., Shonnard, D., Nutter, D., Matlock, M., Ulrich, R., Kellogg, W., Kim, D.S., Neiderman, Z., Kemper, N., Adom, F., East, C. (2013) Regional analysis of greenhouse gas emissions from USA dairy farms: A cradle to farm-gate assessment of the American dairy industry circa 2008. Int. Dairy J. 31: S29-S40.

Thomassen, M.A., Dolman, M.A., van Calker, K.J., de Boer, I.J.M. (2009) Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 8-9: 2278-2286.

Todde, G., Murgia, L., Caria, M., Pazzona, A. (2018a) A Comprehensive energy analysis and related carbon footprint of dairy farms, Part 1: Investigation and modeling of indirect energy requirements. Energies 11: 451.

Todde, G., Murgia, L., Caria, M., Pazzona, A. (2018b) A Comprehensive energy analysis and related carbon footprint of dairy farms, Part 2: Investigation and modeling of indirect energy requirements. Energies 11: 463.

Toro-Mujica, P., Aguilar, C., Vera, R.R., Bas, F. (2017) Carbon footprint of sheep production systems in semi-arid zone of Chile: A simulation-based approach of productive scenarios and precipitation patterns. Agric. Syst. 157: 22-38.

UNDP (United Nations Development Program) (2018): http://www.undp.org/ (accessed 3 Mayo 2018).

Vasilaki, V., Katsou, E., Ponsá, S., Colón, J. (2016) Water and carbon footprint of selected dairy products: A case study in Catalonia. J. Clean. Prod. 139: 504-516.

Veltman, K., Rotz, C.A., Chase, L., Cooper, J., Ingraham, P., Izaurralde, R.C., Jones, C.D., Gaillard, R., Larsoni, R.A., Ruark, M., Salas, W., Thoma, G., Jollieta, O. (2018) A quantitative assessment of Beneficial Management Practices to reduce carbon and reactive nitrogen footprints and phosphorus losses on dairy farms in the US Great Lakes region. Agric. Syst. 166: 10-25.

Vergé, X.P.C., Maxime, D., Dyer, J.A., Desjardins, R.L., Arcand, Y., Vanderzaag, A. (2013). Carbon footprint of Canadian dairy products: Calculations and issues. J. Dairy Sci. 96: 6091-6104.

Wang, X., Ledgard, S., Lou, J., Guo, Y., Zhao, Z., Guo, L., Liu, S., Zhang, N., Duan, X., Ma, L. (2018. Environmental impacts and resource use of milk production on the North China Plain, based on life cycle assessment. Sci. Total Environ. 625: 486-495.

Weiler, V., Udo, H.M.J., Viets, T., Crane, T.A., De Boer, I.J.M. (2014) Handling multi-functionality of livestock in a life cycle assessment: the case of smallholder dairying in Kenya. Curr. Opin. Environ. Sustain. 8: 29-38.

Weiss, F., Leip, A. (2012) Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149: 124-134.

Woldegebriel, D., Udo, H., Viets, T., van der Harst, E., Potting, J. (2017) Environmental impact of milk production across an intensification gradient in Ethiopia. Livest. Sci. 206: 28-36.

Xu, X., Lan, Y. (2016) A comparative study on carbon footprints between plant- and animal-based foods in China. J. Clean. Prod. 112: 2581-2592.

Yan, M.J., Humphreys, J., Holden, N.M. (2013) Life cycle assessment of milk production from commercial dairy farms: the influence of management tactics. J. Dairy Sci. 96: 4112-24.

Yue, Q., Xu, X., Hillier, J., Cheng, K., Pan, G. (2017) Mitigating greenhouse gas emissions in agriculture: From farm production to food consumption. J. Clean. Prod. 149: 1011-1019.

Zhao, R., Xu, Y., Wen, X., Zhang, N., Cai, J. (2018) Carbon footprint assessment for a local branded pure milk product: a lifecycle based approach. Food Sci. Technol. 38: 98-105.

FIGURE CAPTIONS

Figure 1. Overview of system boundaries considered in this work.

Figure 2. Number of studies published from 2009 until time of writing on carbon footprint of cow milk production according to references summarised in Table 1.

Figure 3. Carbon footprint (CF) of raw cow milk vs. Human Development Index (HDI). Data sources: references given in Table 1 and UNDP (2018). When reviewed works reported and interval of CF values, maximum and minimum values have been represented. The FU has been standardised to 1 kg_{FPCM} and CF has been recalculated (Lorenz et al., 2019). △: economic allocation, ○: mass allocation and □: allocation not indicated.

Figure 4. Carbon footprint of raw milk obtained from Green House Gas Protocol: A) semi-confinement dairy farm and B) pasture-based dairy farm (FU = 1 kg_{FPCM} of raw milk).

Figure 5. Carbon footprint of cheese obtained from Green House Gas Protocol: A) employing milk from semi-confinement dairy farm and B) employing milk from pasture-based dairy farm (FU = 1 kg of cheese).

Figure 1

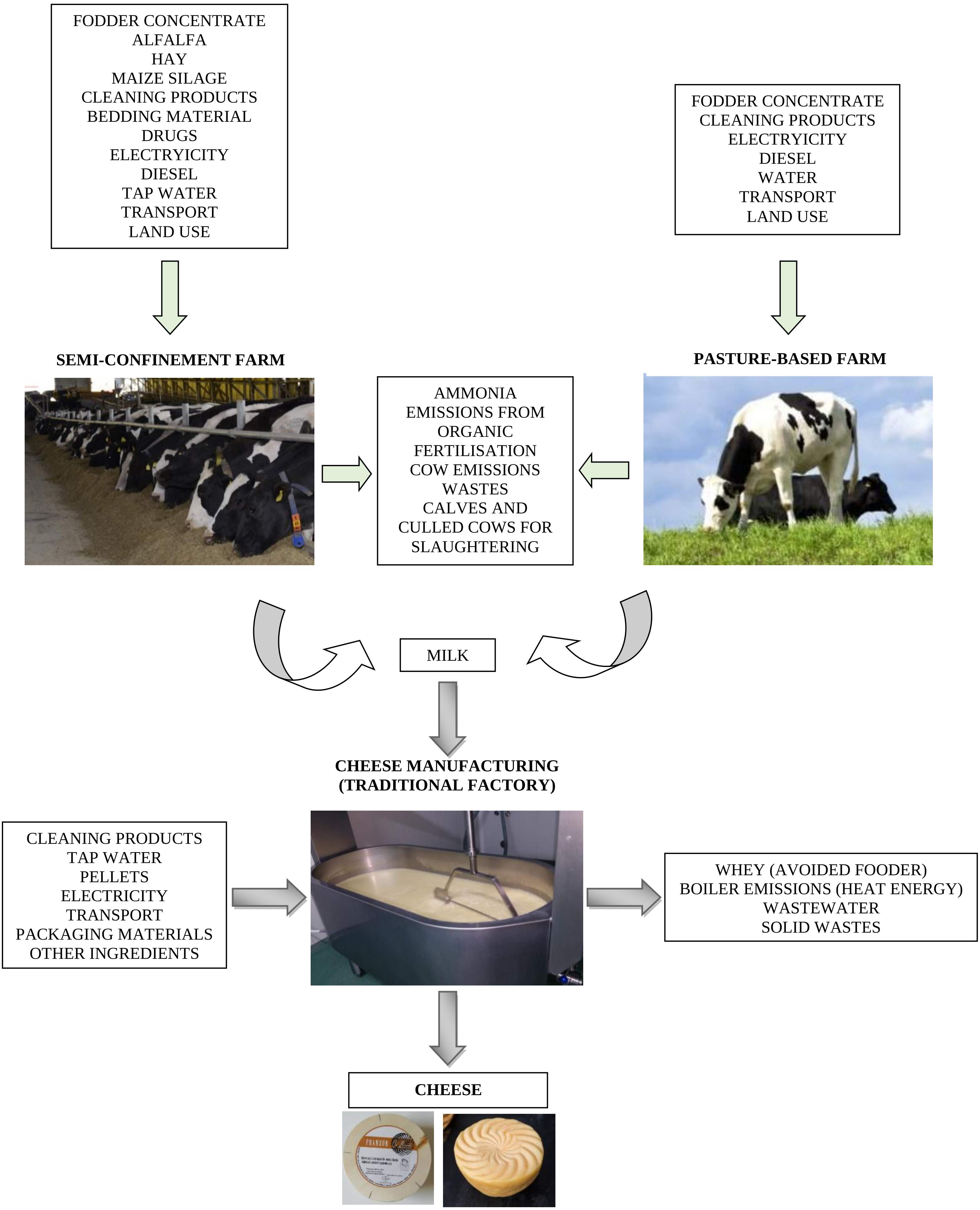
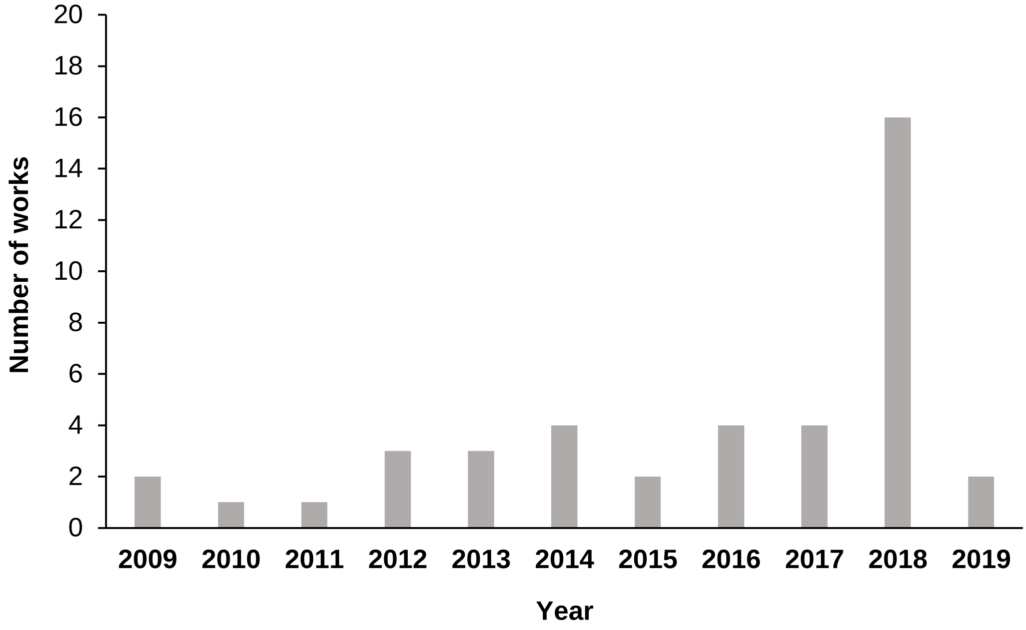
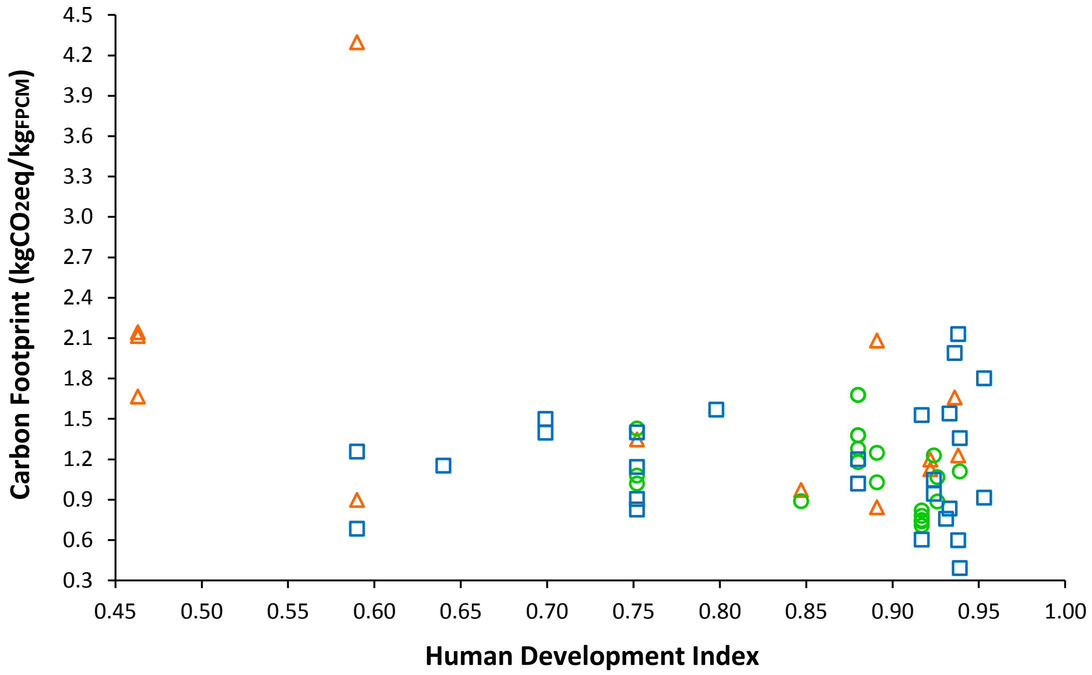

FODDER CONCENTRATE
ALFALFA
HAY
MAIZE SILAGE
CLEANING PRODUCTS
BEDDING MATERIAL
DRUGS
ELECTRYICITY
DIESEL
TAP WATER
TRANSPORT
LAND USE
FODDER CONCENTRATE
CLEANING PRODUCTS
ELECTRYICITY
DIESEL
WATER
TRANSPORT
LAND USE
SEMI-CONFINEMENT FARM
PASTURE-BASED FARM
AMMONIA
EMISSIONS FROM
ORGANIC
FERTILISATION
COW EMISSIONS
WASTES
CALVES AND
CULLED COWS FOR
SLAUGHTERING
MILK
CHEESE MANUFACTURING
(TRADITIONAL FACTORY)
CLEANING PRODUCTS
TAP WATER
PELLETS
ELECTRICITY
TRANSPORT
PACKAGING MATERIALS
OTHER INGREDIENTS
WHEY (AVOIDED FOODER)
BOILER EMISSIONS (HEAT ENERGY)
WASTEWATER
SOLID WASTES
CHEESE

Figure 2



Number of works
20
18
16
14
12
10
8
6
4
2
0
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year

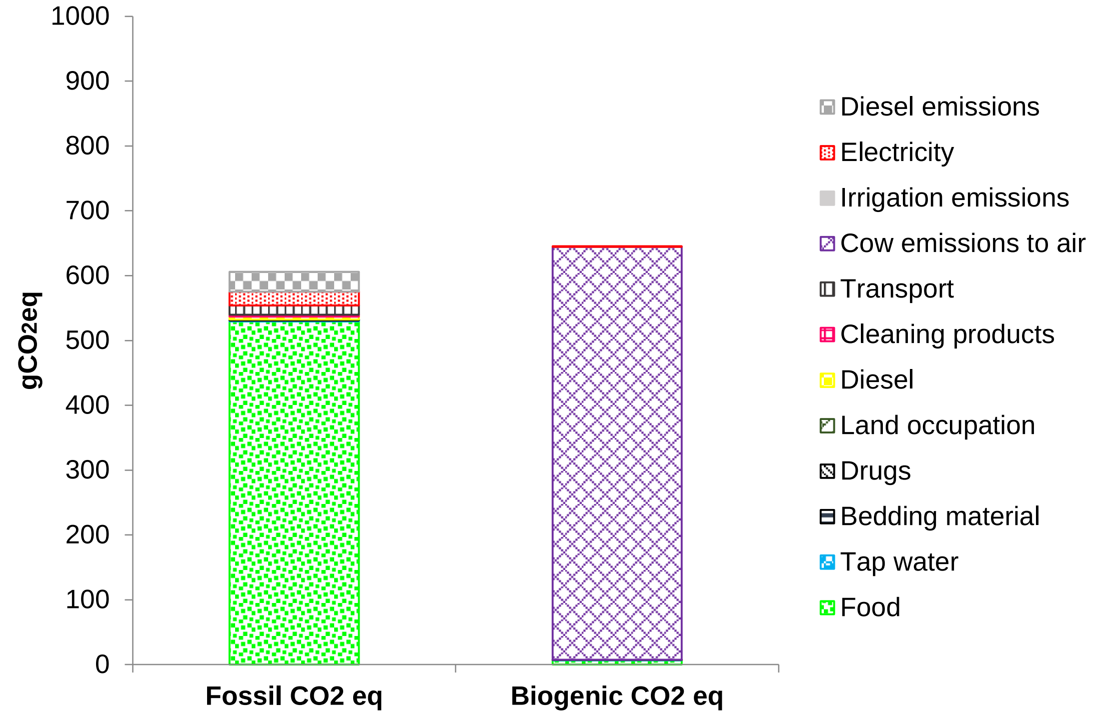
Figure 3



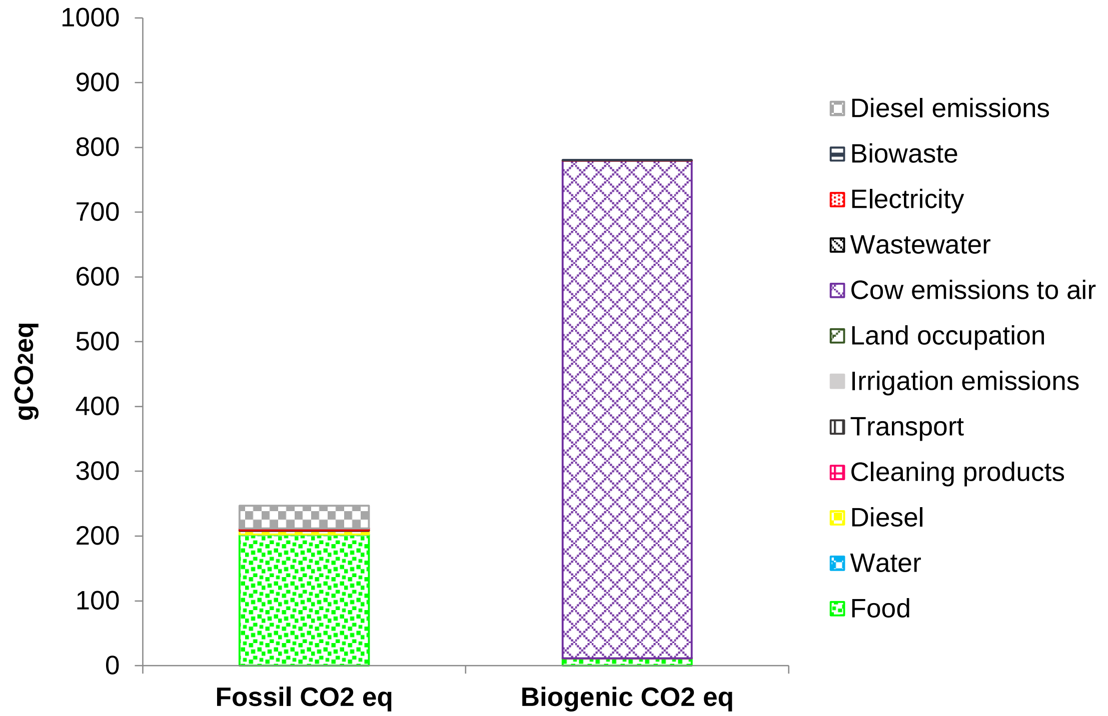
Carbon Footprint (kgCO2eq/kgFPCM)
4.5
4.2
3.9
3.6
3.3
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
Human Development Index

Figure 4

A)


1000
900
800
700
600
500
400
300
200
100
0
gCO2eq
Fossil CO2 eq
Biogenic CO2 eq
Diesel emissions
Electricity
Irrigation emissions
Cow emissions to air
Transport
Cleaning products
Diesel
Land occupation
Drugs
Bedding material
Tap water
Food

B)


1000
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200
100
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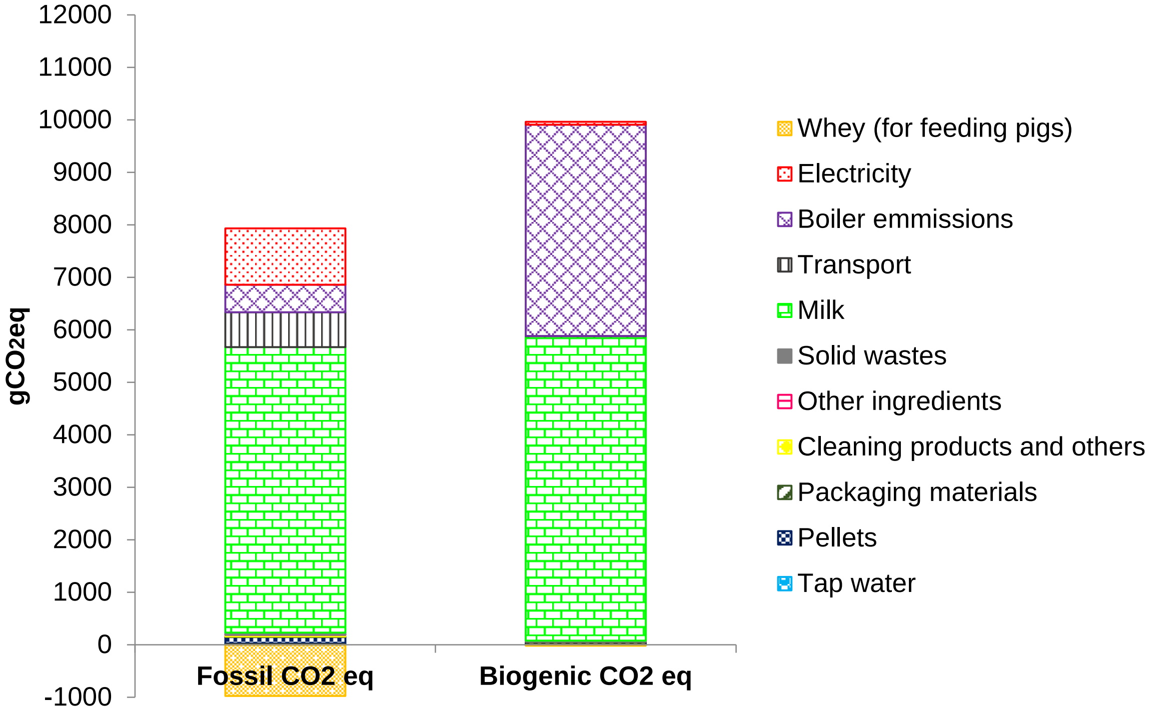
gCO2eq
Fossil CO2 eq
Biogenic CO2 eq
Diesel emissions
Biowaste
Electricity
Wastewater
Cow emissions to air
Land occupation
Irrigation emissions
Transport
Cleaning products
Diesel
Water
Food

Figure 5

A)


gCO2eq
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
Fossil CO2 eq
Biogenic CO2 eq
Whey (for feeding pigs)
Electricity
Boiler emmissions
Transport
Milk
Solid wastes
Other ingredients
Cleaning products and others
Packaging materials
Pellets
Tap water

B)

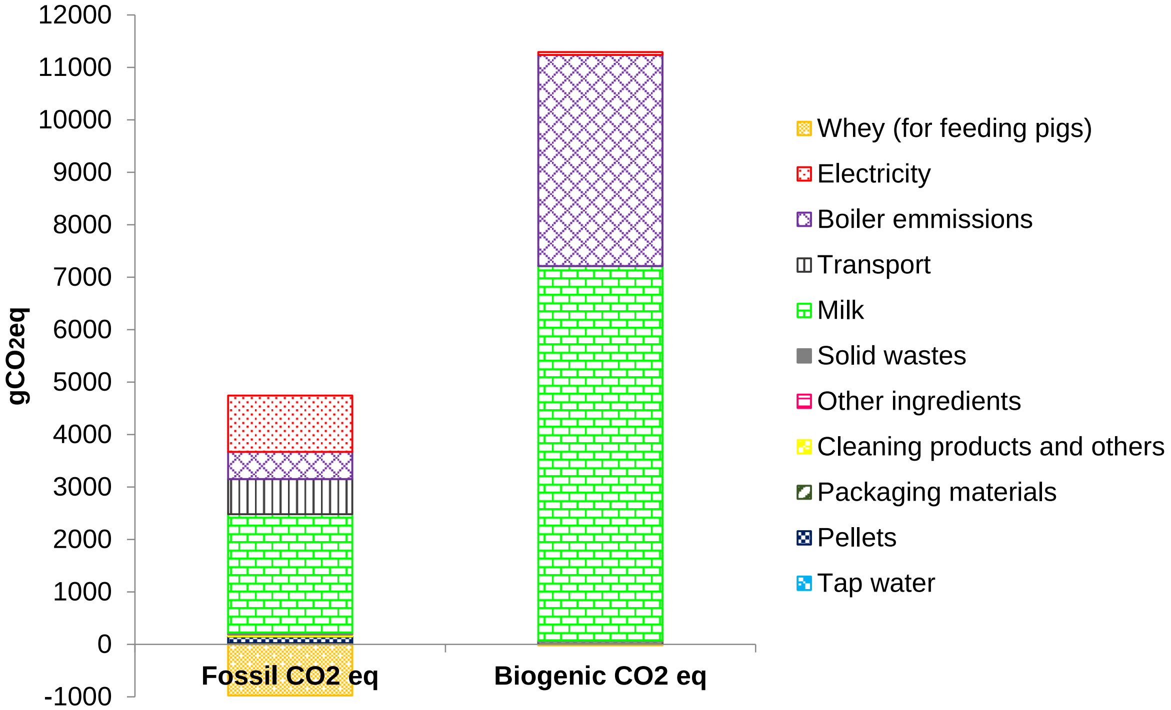

gCO2eq
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
Fossil CO2 eq
Biogenic CO2 eq
Whey (for feeding pigs)
Electricity
Boiler emmissions
Transport
Milk
Solid wastes
Other ingredients
Cleaning products and others
Packaging materials
Pellets
Tap water

Table 1

Table 1. Summary of works on carbon footprint (CF) of cow milk found in literature from 2009 until time of writing.

Reference	Country	Methodology	System boundaries	Main conclusions	CF
Basset-Mens et al. (2009)	New Zealand	- An average New Zealand system, a low input system (LI), an N-fertilised farm system (NF) and an N-fertilised and maize silage supplemented system (NFMS) were compared. - LCA	From cradle to farm gate	The ecoefficiency of the low input system was very high, whereas NF and NFMS had a similar eco-efficiency. All studied systems presented some areas for improvement.	0.93 (average value) 0.65 (LI) 0.76(NF) 0.75 (NFMS) (kg CO_2eq/kg_{FPCM})
Thomassen et al. (2009)	The Netherlands	- Economic and environmental indicators for 119 dairy farms were quantified. - LCA	From cradle to farm gate	Higher labour productivity on dairy farms was associated with lower global warming potential.	0.76 (kg CO_2eq/kg_{FPCM})
Castanheira et al. (2010)	Portugal	- Mid-sized daily farm (53.5 cows). - Economic allocation. - LCA (CF considered as global warming potential category)	From cradle to farm gate	Approximately 0.72 kg CO_2eq. per kg of milk were due to CH_4 emitted from enteric fermentation and manure management.	1.02 (kg CO_2eq/kg milk)
Flysjö et al. (2011)	New Zealand Sweden	- A cow farm with an outdoor pasture grazing system in New Zealand and an indoor housing system in Sweden. - Allocation was not conducted. - LCA	From cradle to farm gate	New Zealand milk production had a lower CF than Sweden in 89% of cases.	0.60-1.52 (New Zealand) 0.83-1.56 (Sweden) (kg CO_2eq/kg_{ECM})
Belflower et al. (2012)	USA	- Evaluation of GHG emissions and CF of two simulated dairy production systems (pasture and confinement) - Integrated Farm System Model (IFSM) / LCA	From cradle to farm gate	The CF of the two dairy production systems were quite similar.	0.58-0.88 (pasture-based) 0.56-0.87 (confinement) (kg CO_2eq/kg_{ECM})
Fantin et al. (2012)	Italy	- Production by Coop Italia of high quality (HQ) milk was environmentally compared with the registered environmental product declaration of a similar product. - LCA	From cradle to final distribution	In both cases, the farm operation stage was responsible for more than 80% of global warming potential. For global warming the difference between the two studies was only 18%.	1.3 1.1 (from cradle to farm gate) (kg CO_2eq/L_{HQ} milk)
Weiss & Leip (2012)	European Union	- Study the product-based net emissions of meat, milk and eggs. - Emissions from the total cattle herd were allocated at around 50% to milk and 50% to beef. - CAPRI model / LCA	From cradle to farm gate	Eggs and milk had a considerably lower CF per kg of product than meat. The countries with the lowest net product emissions were not necessarily characterized by similar production systems.	1.3-1.7 (kg CO_2eq/kg milk)

Del Prado et al. (2013)	Spain	- Commercial cow dairy farms. - Economic allocation. - NGAUGE model / $LAND_{DAIRY}$ model / LCA	From cradle to farm gate	Cow diet choice (source and origin) was the strongest factor explaining differences in GHG emissions from milk production.	0.84-2.07 (kg CO_2eq/kg_{ECM})
Vergé et al. (2013)	Canada	- GHG emissions from the dairy industry in five regions. - Co-product allocation. - ULICEES / $(Cafoo)^2$-milk calculator	From cradle to farm gate	The CF was lower in western provinces than in eastern provinces because of differences in climate conditions and dairy herd management.	0.93-1.12 (kg CO_2eq/L milk)
Thoma et al. (2013)	USA	- GHG emissions for five regions. - Co-product allocation. - Databases: ESDA, NASS, ERS and literature / LCA.	From cradle to farm gate	Feed represented around 30% of the GHG footprint. Regional differences were mainly determined by the feed-to milk conversion efficiency and the choice of manure management.	1.23 (average value) (kg CO_2eq/kg_{FPCM})
Yan et al. (2013)	Ireland	- Commercial cow daily farms (min. 8 -max 154 cows) - Co-product / Economic allocation. - LCA.	From cradle to farm gate	A large variation in farm tactical management was found, but the CF of milk production between farms only varied 13%. Milk output per cow was the most influential factor determining CF.	1.23 ± 0.04 (average value) (kg CO_2eq/kg_{FPCM})
Dalgaard et al. (2014)	Denmark Sweden	- Developing a tool for calculation of CF of cow milk. - Consequential/Attributional (average/allocation) - LCA (Arla model)	From cradle to farm gate	The CF of Danish and Swedish milk were similar. The major contributions to CF were enteric fermentation and the cultivation and production of feed. The result for 'Attributional' (average/allocation) was not significantly different from the result based on consequential modelling.	1.15-1.90 (kg CO_2eq/kg_{ECM})
Daneshi et al. (2014)	Iran	- CF of packaged milk was quantified. - LCA	From cradle to the milk processing gate	About 90% of the total emissions was from milk production at the farm gate. Emissions from electricity production had a considerable impact on the overall result by about 14%.	1.57 (kg CO_2eq/kg_{FPCM})
Gollnow et al. (2014)	Australia	- CF of milk from 139 farm was analysed. - Co-product allocation. - LCA	From cradle to farm gate	Allocation between milk and meat in CF significantly affected the final result. The feed conversion efficiency was the most important factor for the reduction of enteric methane emissions. Reduction potentials were also identified for manure management practices.	1.11 (average value) (kg CO_2eq/kg_{FPCM})
Weiler et al. (2014)	Kenya	- Multi-functionality of livestock in a case of smallholder milk production in the Kaptumo area (20 farmers).	From cradle to farm gate	In smallholder systems, livestock are often kept not only to produce milk or meat, but also to produce fertiliser, provide draught power and act as capital	2.0 (0.9-4.3) (food allocation) 1.6 (0.8-2.9) (economic function allocation)

		- Food / economic function / livelihood allocation. - LCA		asset. The inclusion or exclusion of multiple functions of cattle had strong impacts on the values of milk CF, and consequently on mitigation options.	1.1 (0.5-1.7) (livelihood allocation) (kg CO_2eq/kg$_{FPCM}$)
Kiefer et al. (2015)	Germany	- Different allocation methods of GHG were evaluated for 113 cow dairy farms located in grassland-based areas of southern Germany. - LCA	From cradle to farm gate	CF of dairy farms should not be examined only based on the amount of milk and meat that is produced. A broader perspective that takes into account ecosystem services in economic allocation led to a significant reduction of CF.	1.99 (no allocation) 1.53 (physical allocation) 1.66 (conventional economic allocation) (kg CO_2eq/kg$_{FPCM}$)
O'Brien et al. (2015)	Ireland	- The relationship between the CF of milk and dairy farm economic performance was analysed. - LCA and the National Farm Survey (NFS) of Ireland database.	From cradle to farm gate	Increasing the length of the grazing season and improving annual milk production per hectare and per cow reduced the CF of milk and increased farm profit.	1.20 (0.60-2.13) (kg CO_2eq/kg$_{FPCM}$)
Battini et al. (2016)	Italy	- Four typical milk production systems of the Po Valley were compared - LCA.	From cradle to farm gate	The increase in productivity may lead to a trade-off between global impacts (such as GHG emissions) and local impacts (e.g.local biodiversity and eutrophication).	1.18-1.60 (mass allocation) (kg CO_2eq/kg$_{FPCM}$)
Chobtang et al. (2016)	New Zealand	- Study pasture-based dairy farming systems in the Waikato region. - Co-product allocation. - LCA.	From cradle to farm gate	The on-farm stage (emissions associated with on-farm activities, the use of chemical fertilisers and pesticides, the use of fossil fuels and electricity and management of farm effluent and animal excreta) contributed 52-73% of the total indicator results for climate change and the contribution of enteric CH4 emissions dominated this category.	0.78-0.82 (kg CO_2eq/kg$_{FPCM}$)
Colombini et al (2016)	Italy	- Analysis of three different scenarios based on double cropping systems with different crop rotations. - Economic allocation. - LCA.	From cradle to farm gate	The lowest value of global warming potential was obtained using a corn silage based diet, but the differences among the three forage system scenarios were very small.	1.47 (corn silage) 1.51 (whole plant grain sorghum silage) 1.56 (forage sorghum silage) (kg CO_2eq/kg$_{FPCM}$)
Xu and Lan (2016)	China	- Plant-based foods and animal-based foods. - LCA	-	Animal-based foods had higher CF than plant-based food.	0.95 (kg CO_2eq/kg)
Ortiz-Gonzalo et al. (2017)	Kenya	- Study of the GHG emissions of intensive coffee-dairy farms. - Principal component analysis (PCA) and hierarchical clustering (HC) / Cool Farm Tool (CFT).	From cradle to farm gate	Most coffee-dairy farms, which produced coffee berry, maize and milk, were net sources of GHG, particularly due to the contribution of their livestock component, which is kept in in zero-grazing stalls Farms GHG emissions range between 4.5 t CO_2 eq	1.05 (0.72-1.37) (kg CO_2eq/kg)

				ha^{-1} yr^{-1} (less intensive) and 12.5 t CO_2 eq ha^{-1} yr^{-1} (more intensive).	
Patra (2017)	India	- CF values of livestock products (milk, meat and eggs). - IPCC Tier 2 (2006) guidelines	From cradle to farm gate	The wide range of CF values for milk, meat and eggs in different states of India suggested that CF could be reduced substantially changing the pattern of livestock population, improving breeding technologies and intensificating different livestock species.	1.21 (0.63-2.39) (kg CO_2eq/kg)
Woldegebriel et al. (2017)	Ethiopia	- Milk production systems with different degree of intensification (large-scale, peri-urban and rural farms) (8 farms of each type) - Economic allocation. - LCA	From cradle to farm gate	Intensification of dairy production resulted in higher environmental impacts per cattle unit. However, the impacts per kg of milk did not differ significantly. The main limitation for environmental improvement in this area is the lack of high quality forages and supplements and the management practices on the farms	1.75 (large-scale) 2.25 (peri-urban) 2.22 (rural) (kg CO_2eq/kg)
Yue et al. (2017)	China	- Quantification of CF of the major agricultural products in China. - LCA / IOA.	From cradle to farm gate	Forage feeding was the major source of emissions for livestock production. Improving agricultural management and dietary consumption changes have potential to provide considerable GHG mitigation.	1.47 (kg CO_2eq/kg)
Baldini et al. (2018)	Italy	- Comparison of estimated and measured emissions from manure handling. - Allocation factor (meat as co-product). - IPCC and EMEP/EEA equation / LCA. - Monte Carlo statistical method / LCA.	From cradle to farm gate	The IPCC and EMEP/EEA equation underestimated emissions from manure management compared to measured value. On the contrary, ammonia related impact categories showed higher values than measured value using this approach.	1.11-1.62 (estimated) 1.38-1.68 (measured) (kg CO_2eq/kg$_{FPCM}$)
Fan et al. (2018)	China	- Comparison of a semicoupled mode (recycling solid manure to farmlands) and a fully coupled mode (recycling both solid and liquid manure).	-	The fully coupled mode could reduce GHG emissions (CO_2, CH_4 and NO) by 24%, ammonia emissions by 14%, and N discharge into water by 29%, compared with the semicoupled systems.	1.20 (semicoupled) 0.75 and 0.9 (fully coupled) (kg CO_2eq/kg)
Galloway et al. (2018a)	South Africa	- Evaluation of private and social goals in pasture-based dairy production. - Woodlands Dairy's Sustainability Project database.	-	The efficient use of fertilizer and bought feed, as well as the maximum utilisation of the available land, was beneficial for the environment. Sustainability and productivity goals can be met through the same practices on pasture-based dairy farms.	1.49 (kg CO_2eq/kg$_{ECM}$)
Galloway et al. (2018b)	South Africa	- Study of the environmental impact of pasture-based dairy farms. - Woodlands Dairy's Sustainability Project	From cradle to farm gate	Farm systems which optimized milk production (applied the least amount of fertilizer and fed the least amount of purchased feeds) had the lowest	1.39 (kg CO_2eq/kg$_{ECM}$)

		database		environmental impact.	
Morais et al. (2018)	Portugal	- Calculation of the CF of a pasture-based milk production system. - Allocation of coproducts. - LCA.	From cradle to farm gate	Enteric fermentation, concentrated feed production and fertilisation are the three main sources of impact. Compared with other 84 studies, this production system has a CF lower than 80.	0.89 (kg CO_2eq/kg_{FPCM})
Rice et al. (2018)	Data from "E-Ruminant" project (Teagasc 2015).	- Create a new functional unit for raw milk at the farm gate/ processor gate (1 kg_{BPAM}). - LCA.	-	BPAM as FU included composition and hygiene properties of the milk. Environmental impacts will not be very different using BPAM or ECM as the FU, excepting when biological contamination is a serious issue. When BPAM is used as FU, high levels of biological contamination could increase CF by > 200%.	1.33-4.38 (kg CO_2eq/kg_{BPAM})
Schueler et al. (2018a)	Norway	- Use of Tier 1 approach for direct and indirect N_2O emissions and for CO_2 emissions from soil. - IPCC Tier 1 methodology / Monte Carlo simulations.	From cradle to farm gate	A significant differentiation of the milk CF between farms is possible with an IPCC Tier 1 approach.	0.91-1.79 (kg CO_2eq/kg_{ECM})
Schueler et al. (2018b)	Germany	- Study of the inter-annual variability of production data in an organic dairy farm; ~~and its~~ effect on GHG emissions. - Allocation based on energy. - Flow Analysis and Resource Management Model / LCA	From cradle to farm gate	Emissions from ruminant digestion had the highest contribution (51%) for GHG emissions. Direct emissions from soil showed the highest coefficient of variation (36%) due to simultaneous changes in fertilization, crop yield and milk yield.	0.88-1.09 (kg CO_2eq/kg_{ECM})
Sejian et al. (2018)	Australia	- Study of CF in commercial dairy production systems. - Integrated farm system model (IFSM).	-	The animal emission contribution for CF were between 39 and 60 %, whereas the manure emission contribution were between 29 and 58 %.	0.39-1.35 (kg CO_2eq/kg_{ECM})
Soteriades et al. (2018)	UK	- Investigation of the environmental footprint of high-sugar grasses as forage source in pasture-based dairy farming. - Economic allocation. - LCA	From cradle to farm gate	Replacing conventional perennial ryegrass with high-sugar grasses led to reductions in GWP, whereas increasing the housing period had almost no effect.	1.12-1.19 (kg CO_2eq/kg_{ECM})
Tabacco et al. (2018)	Italy	- Comparison of dynamic forage systems with mono-cropped corn silage system, in terms of dry matter, crude protein and metabolizable energy. - Carbon Calculator.	From cradle to farm gate	New dynamic forage system has the potential of being profitable and could enhance production efficiency and environmental quality in the more intensive forage systems.	206-273 (kg CO_2eq/t of dry matter) 1545-3330 (kg CO_2eq/t of protein)
Todde et al. (2018a)	Italy	- Analysis of direct energy requirements and related CF in conventional dairy farms.	From cradle to	The activities related to feed management and field operations required the largest part of total diesel	0.156 (kg CO_2eq/kg_{FPCM})

		- No allocation between milk and meat. - LCA.	farm gate	fuel combustion. The requirement of electricity were mainly associated to the activities linked with milk harvesting, milk refrigeration and water heating.	(global average farm emissions due to direct energy usages)
Todde et al. (2018b)	Italy	- Analysis of indirect energy inputs related to farm buildings, machinery and agricultural inputs. - No allocation between milk and meat. - LCA.	From cradle to farm gate	The indirect energy was 2.4-times greater than the direct energy consumptions. Larger farms emitted 48% less carbon dioxide than smaller farms per kg of FPCM.	0.381 (kg CO_2eq/kg$_{FPCM}$) (global average farm emissions due to indirect energy usages)
Veltmen et al. (2018)	USA	- Analysis of the efficacy of individual beneficial management practices (BMPs) to reduce the CF footprint of two model dairy farms, a 1500 cow farm and a 150 cow farm. - Allocation between milk and co-products (calves and cull cows sold) - Process-based model (IFSM).	From cradle to farm gate	The highest reductions in the CF were obtained with individual manure management interventions (4-20% reduction) followed by dietary manipulations (0-12% reduction) for both farm types. Field management BMPs had a modest effect (0-19% reduction).	0.99 (1500 cows) 1.10 (150 cows) (kg CO_2eq/kg)
Wang et al. (2018)	China	- Analysis of the environmental burdens of milk production in North China Plain. - Economic allocation. - LCA	From cradle to farm gate	Feed production and manure management were the environmental hot-spots for milk production. Improving milking cow productivity and increasing proportion of milking cows, combining various manure management systems and encouraging dairy farmers to return manure to nearby crop lands were promising measures to decrease environmental impacts.	1.34 (kg CO_2eq/kg$_{ECM}$)
Zhao et al. (2018)	China	- Measurement of CF of a local branded pure milk product. - LCA	From cradle to grave	Total CF was 1.12 kg CO_2eq/L. Raw milk production was identified as the major contributor. CF might be reduced by adjusting the proportions of the animal fodder.	0.84 (raw milk) (kg CO_2eq/L)
Famiglietti et al. (2019)	Italy	- Assessment of environmental impacts of dairy products (PDO cheeses and fresh pasteurized milk). - Biophysical allocation (raw milk and meat) and dry mass content allocation (finished dairy products and by-products). - PMT_01 tool based on Product Environmental Footprint methodology.	From cradle to distribution centre gate	The main contributor to most of the environmental impact categories was the raw milk production and the variation among the results was probably linked to the characteristics of the farms. Even if some improvements in the tool functionalities are needed, authors believe that in the future it could be easily applied on farms and dairies.	1.43 (kg CO_2eq/kg$_{FPCM}$)
Ledgard et al. (2019)	China New Zealand	- Comparison of dairy farming systems in China and New Zealand. - Milk CF was calculated from the total GHG	From cradle to farm gate	Chinese farms can improve environmental efficiency through sourcing low-impact feeds, improved manure management and integrating	China 1.43 (170 cows) 1.08 (321 cows)

		emissions considering allocation between milk and live-weight sold for meat.		manure recycling with feed crops. New Zealand farms can improve environmental efficiency through efficient use of grazed legume-based pastures rather than using crop-feeds or cow housing systems.	1.02 (1220 cows) New Zealand 0.74 (low brought-in feed) 0.71 (medium brought-in feed) 0.75 (high brought-in feed) (kg CO_2eq/kg_{FPCM})
This work	Spain	- Compare semi-confinement and pasture-based systems. - Co-product allocation (meat). - LCA (GreenHouseGas Protocol).	From cradle to farm gate	In both cases, cow feeding and cow emissions were responsible for more than 95% of the milk CF.	1.22 (semi-confinement) 0.99 (pasture-based) (kg CO_2eq/kg_{FPCM})

ECM: Energy corrected milk
FPCM: Fat and protein corrected milk
BPAM: Base price-adjusted milk