Energy Nexus 11 (2023) 100217

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

The water, land and carbon footprint of conventional and organic dairy systems in the Netherlands and Spain. A case study into the consequences of ecological indicator selection and methodological choices

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A R T I C L E I N F O

Keywords:
Ecological indicator selection
Water footprint
Land footprint
Carbon footprint
Dairy systems

A B S T R A C T

Dairy farming systems are multifunctional processes that provide milk but also beef, veal and manure. These outputs provided by dairy farms are important foods for humans but their production require natural resources like water and land, and release emissions to the water and air contributing to climate change. Many studies quantified the environmental performance of dairy farms by using a life cycle assessment (LCA) or environmental footprint calculation. This study provides a better understanding of how different methodological decisions (e.g., the choice of system boundary, GHG metric, allocation procedure for multifunctionality, and multi-environmental indicators) influence the environmental performance calculation. From a footprinting point of view, the water footprints (WFs) (i.e., green, blue and grey), land footprints (LFs) and carbon footprints (CFs) of milk, beef and veal produced in two conventional (Dutch and Spanish) and an organic Dutch dairy system are estimated. Here the system boundaries are expanded so calve systems are included. Next, the use of different indicators is discussed, e.g., green WFs and the GWP100 or GWP20. The Dutch conventional system has relatively small footprints due to high efficiency. Green, blue and grey WFs per kg of milk are 0.62, 0.09 and 0.14 m^3. The Spanish system has green, blue and grey WFs per kg of milk of 0.67, 0.15 and 0.09 m^3; the Dutch organic system of 0.84, 0.13 and 0.26 m^3. The Spanish system has the largest LF and CF, caused by feed import from countries with relatively low yields and transport greenhouse gas emissions. Dutch systems use more locally produced feed. Due to lower efficiency, the organic system has larger footprints than the Dutch conventional system. Expanding system boundaries to include calves results in an 8 to 15% CF increase. Green water dominates total WFs, an aspect excluded in LCA studies. For grey WFs, earlier studies only included nitrogen. However, if also pesticides would be included, results might be less favourable for systems relying on feed crops instead of grasslands. Also, water quality standards influence grey WFs. The study emphasizes that indicator choice influences final results. Indicators like animal welfare, biodiversity or pesticide use give different outcomes which might be more favourable for organic production.

Introduction

At present, dairy products have an important contribution to the human diet, especially in affluent countries, while demand for dairy might increase in the near future in developing countries, e.g., in China [1,2]. Dairy farm systems require natural resources, like land and freshwater, while emitting pollutants, such as greenhouse gasses, to the environment [3,4]. In 2006, the FAO has indicated that livestock, including dairy, is responsible for 37% of the anthropogenic methane emissions (with 28 times the global warming potential (GWP) of CO_2), especially from enteric fermentation by ruminants, like dairy cows, that also emit most of the anthropogenic nitrous oxide (with 296 times the GWP of CO_2), mainly from manure. To produce livestock feed, agriculture uses 70% of available agricultural land, including 33% of the croplands, and 8% of human blue water use. Moreover, it is an important cause of water pollution [2]. In the past decades, the dairy sector made huge efforts to improve its environmental sustainability by reducing its contribution to climate change and other environmental impacts. However, this sector

Abbreviations: CF, carbon footprint; CH4, methane; CO_2, carbon dioxide; CO_{2e}, carbon dioxide equivalent; ES conv, spanish conventional system; FP, footprint; FPCM, fat and protein corrected milk; GWP100, 100 year global warming potential; GWP20, 20 year global warming potential; ha, hectare; Kg, kilogram; Km, kilometre; L, litre; LCA, life cycle analysis; LF, land footprint; m^2, square metre; m^3, cubic metre; MJ, Megajoule; N, nitrogen; N_2O, nitrous oxide.

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https://doi.org/10.1016/j.nexus.2023.100217
Received 20 March 2023; Received in revised form 30 May 2023; Accepted 22 June 2023
Available online 24 June 2023

is facing external challenges that compromise these efforts. For instance, global milk consumer demand has increased continuously. As a result, the GHG emissions from this sector have increased by 18% from 2005 to 2015, and without the efforts taken by the dairy sector, the GHG emissions would have increased by 38% [5]). At the dairy farm, the major source of GHG emissions is methane (CH_4) from enteric fermentation, which is responsible for nearly 59% of the GHGs released at the farm. On-farm feed production contributes to two other important GHG emissions: nitrous oxide (N_2O) by 20% and carbon dioxide (CO_2) by roughly 9%. In addition, manure management, which includes manure storage and processing, accounts for 4% of the total N_2O emissions released at dairy farms and 5% of the total CH_4 emissions. To a lesser extent, dairy farm operations (e.g., milking, lighting, heating, cooling and machinery) and land use change contribute to a lesser extent to the total GHG emissions, being 2% and 1%, respectively [5]).

Many studies have quantified these resource needs and emissions, for example, using a life cycle assessment (LCA) or environmental footprint calculation. The first studies applying an LCA approach for agricultural products started in the end of the 20th century [6] and guidelines for the assessment have been developed, e.g., by Guinée et al. [7]. Since then, many studies on dairy farm systems used this approach. For example, Hospido et al. [8] introduced a simplified LCA for milk production in Spain. Many LCA studies on dairy systems have followed since. De Vries & de Boer [9], for example, gave a review of 16 LCA studies of dairy production systems, indicating a focus on land and energy use, including climate change, but missing topics like water consumption, eutrophication and acidification. The review of Baldini et al. [10] of 44 milk LCA studies published after 2009 has shown that, although guidelines on LCA's exist, many LCA studies are still lacking harmonization and generate results that are difficult to compare. Between 2009 and 2017, most attention went to global warming, eutrophication and acidification, while impacts like water use are often lacking an in-depth analysis. To support comparable environmental analyses related to the dairy sector, the International Dairy Federation (IDF) provides guidelines for the calculation of, for example, water and carbon footprints based on protocols of the International organization of standardization (ISO) [11,12].

The second method to quantify needs of natural resources and pollutant emissions is the use of footprints belonging to the footprint family, for example, the ecological footprint, green, blue and grey water footprint (WF) or carbon footprint (CF) [13]. The ecological footprint aimed to connect human consumption to land use, including the land areas needed to take up carbon dioxide emissions, indicating the huge pressure on available land [14], followed by the WF [15]. The first CF analyses appeared in 2007 [13]. For example, the study of Giurco & Petrie [16], who made a material flow analysis for copper production aiming to decrease CO_2 emissions, used the terminology CF. From then on, especially the number of CF studies increased, dominating the footprint studies [13], also indicating the increased importance of global warming on the policy agenda's.

LCA and footprint communities apply different definitions of terminology and system boundaries. For example, the term "water footprint" is defined as "volume of freshwater used to produce goods and services" in the water footprint community [17], but as "metric(s) that quantify the potential environmental impacts related to water" in the LCA community [18]. This difference reflects the conflictive opinions on whether the water footprint (WF) should be a volumetric or impact-orientated indicator [19]. Other differences include the quantification of green water from precipitation and grey water as an indicator of water needs to dilute polluted water. In general, footprint studies can contribute to a better understanding of consequences of human consumption on planetary boundaries, while LCA studies especially focus on environmental impacts. Basically, LCA and footprint studies both aim to achieve more sustainable production and consumption along the value chains of products and services and perform the same quantitative assessment for supply chains. This makes it possible to use each other's quantitative input results.

Nonetheless, the different methodological decisions made when analysing the environmental burden of the dairy sector have a substantial consequence for the environmental indicator results [10]. For instance, the selected greenhouse gas (GHG) metric has an important role. Focusing on the production stage, methane (CH_4) is the predominant GHG in the total CF, and unlike carbon dioxide (CO_2) and nitrogen oxide (N_2O), it is a short-lived gas. When a 100-year Global Warming Potential (GWP100) is employed, it is treated as a long-lived gas. In this case, the characterization factor for CH_4 is relatively low at 34 kg CO_2-eq/kg, but when a 20-year GWP is used, the characterization factor is 86 kg CO_2-eq/kg [20]. As this has lately been a matter of controversy, the GWP* has been developed as an alternate application of the GWP to capture the disparate effects of the various time-period climate pollutants [21]. In addition, another methodological decision that has a consequence for the environmental indicators is the chosen allocation procedure. Most studies follow an attributional approach in which the environmental burden of raw milk is attributed to the functional unit (e.g., De Boer et al. [22]; (Fantin et al. [23]). However, dairy systems are multifunctional systems where milk, beef and veal production are inherently interconnected. When the assessment focuses only on milk production, it neglects the environmental burdens outside the dairy farm boundaries (i.e., beef and veal from dairy cows and calves). To deal with this multifunctionality, several authors have used a system expansion approach (e.g., Cederberg & Stadig [24]; Mazzetto et al. [25]). Finally, another point of discussion is the selection of only one environmental indicator to assess environmental sustainability, such as the CF that focuses only on climate change, leaving aside other environmental problems and leading to different conclusions. For instance, when different production systems are compared, the application of several environmental indicators is relevant as it allows a trade-off analysis amongst indicators, providing accurate suggestions on the different production systems analysed [26]. Examples of studies that used three indicators showing differences and trade-offs between livestock production systems are Ibidhi et al. [27] who compared the land, water and carbon footprint of different production systems of sheep and chicken meat in Tunisia, and Guzmán et al. [28] who did the same for Tilapia production systems in Mexico.

This study aims to provide a better understanding of how different methodological decisions (e.g., the choice of system boundary, GHG metric, allocation procedure for multifunctionality, and multi-environmental indicators) influence the environmental performance of a dairy production system. It analyses the environmental consequence of one kg of fat-protein corrected milk (FPCM), one kg of dairy cow meat (beef), and one kg of calf meat (veal) produced in two different production systems (i.e., conventional and organic) using three environmental indicators, the green, blue and grey water footprints (WFs), the land footprint (LF) and carbon footprint (CF). The study analysed three different dairy systems as case studies: (i) conventional dairy production systems in the Netherlands; (ii) conventional dairy production systems in Galicia in Spain; and (iii) organic dairy production systems in the Netherlands. The two research questions are: (i) "What are the land, water and carbon footprints of milk, beef and veal from a conventional dairy system in The Netherlands and Spain, and from an organic dairy system in The Netherlands?" and (ii) "What are the consequences of changing the system boundaries and methodological choices in a dairy footprint study?"

The study uses the Netherlands and Galicia in Spain as case study areas, because they are highly productive dairy areas for which information is available. The focus of this study is to describe the environmental footprints of a complete dairy system that not only consists of a dairy farm and all its animals (i.e. lactating cows, dry cows, calves), but also the calve farms where calves are raised for veal. We emphasize that the industrial processes to convert raw milk, and the slaughtering of cows and calves, that also have environmental impacts fall outside the system boundary. For example, it is possible to improve the environmental impact of cheese production [29]. Next, it discusses the use of different indicators and allocation methods generating different outcomes that influence the results.

System analysis

Dairy systems

In general, a dairy system produces raw milk, beef and veal. It includes different bovine groups: adult dairy cows, juvenile dairy cows and calves. An adult dairy cow is a female cow producing milk, calves are young male or female cows that do not produce any milk. Female calves grow up to become dairy cows after the juvenile stage. To produce milk, dairy cows have to give birth every year. The cow generally gives birth to its first calf at two years of age, followed by four years of milk production [30]. This means that the average dairy cow reaches an age of six years before it produces beef. Normally, dairy cows produce milk throughout most of the year, i.e. for an average period of 305 days, although some cows produce milk year-round [30].

Artificial insemination initiates the pregnancy of a dairy cow. Therefore, the gender of the calf is determined beforehand [31]. The farmer choses a male-to-female ratio in such a way that dairy cows are replaced after four years of producing milk. Moreover, there is the profitability of selling the male calves that are worth more than females, because they produce more meat, especially when dairy cows are crossbred with beef bulls [32]. When born, calves stay on farm for a minimum of two weeks by law. Then, most male calves leave to calve raising farms, while female calves remain.

Dairy farms in the Netherlands

Dairy systems are often located in countries or regions with favourable weather conditions for grasslands, such as in the Netherlands or in the North of Spain, since these locations have a rainy climate. The main two dairy farm types in the Netherlands are the conventional and organic system. A conventional farm focuses on productivity and efficiency, the main goal is high milk production at low costs. Dairy cows sometimes stay indoors, sometimes go out for grazing. Around a third of the cows stays indoors year-round. If the cows have outdoor pastures, they generally have access in spring, summer and autumn [30]. Organic dairy systems have to adhere to guidelines with a focus on animal welfare and low pollution performance from chemical herbicides, pesticides and chemical fertilizer [33]. The costs are higher, but this is offset by a higher milk price. Dutch organic milk needs an official label, complying to requirements set by the SKAL Foundation [33].

Dairy farms in Spain

Although The Netherlands and Spain are different countries, the characteristics of the areas where dairy farms are located are similar. Most of the Spanish dairy farms are located in the Northwestern region of Spain, i.e. Galicia, which has a similar climate to The Netherlands. E.g., rainfall and temperatures are comparable [34]. In Spain, conventional dairy systems dominate and organic milk production is relatively low [35].

Dairy cow feed

Dairy cow feed consists of roughage and concentrates and is carefully managed based on the nutrients cows require in a specific stage of their life. Roughage includes mostly grass and maize, while the concentrates consist of feed ingredients high in nutrients, such as soybeans [36]. Feed requirements differ amongst bovine groups and depend on the nutrient requirements of the animals, depending on their weight and age [37]. Table I in the supporting information (SI) gives the feed inputs of the conventional Dutch and Spanish system, and the organic Dutch system.

Environmental footprints

The environment footprints relevant for the dairy sector are the green, blue and grey water footprint (WF), land footprint (LF) and carbon footprint (CF).

Green, blue and grey water footprint

The WF of a product is defined as the volume of freshwater used to produce the product, measured over the full supply chain [17]. The WF includes a blue, green and grey component. The blue WF refers to consumed surface and groundwater (known as "blue water"), while the green WF refers to consumed rainwater ("green water") defined as precipitation on land that does not run off or recharge groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (although not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth). The grey WF is determined by the amount of pollutants released in the different processes in the production chain. These pollutants need to be diluted to a level that is safe for release in the environment and meets accepted water quality standards. The grey WF is defined as the volume of water needed to dilute polluted water to accepted water quality standards [17]. A WF is always calculated for one or multiple products. Therefore, to determine the WF, an allocation to the product is necessary.

Dairy systems generate green and blue WFs, because water is needed for the production of feed (crops and grass) as well as for drinking purposes. This includes the direct WF, which is the water usage on the farm, and the indirect WF, which describes the water used in processes off-farm. In addition, there is an emission of pollutants causing grey WFs.

Land footprint

The LF of a product refers to the amount of land needed to produce the product [14]. It also includes a direct and indirect component. The direct LF is the land area for on-farm feed production, while the indirect LF refers to the land for the production of feed off-farm. Similar to the WF, allocation of the LF to the products is necessary.

Carbon footprint

The CF is the output of greenhouse gas emissions, expressed as CO_2e, of a product [13]. The CF of dairy includes the CF of: (i) feed ingredients related to agricultural energy use; (ii) N_2O emissions from fertilizers and manure; (iii) manure storage; (iv) on-farm electricity use; (v) enteric fermentation and (vi) transport. Methane emissions can be presented via different indicators for its global warming potential (GWP), namely the 100-year potential (GWP100) and the 20-year potential (GWP20) [38]. Again, it is important to apply an allocation step to the CF data.

Methods and data

The calculations of the WF, LF and CF of a conventional and an organic dairy system in the Netherlands and for a conventional dairy system in Galicia (Spain) is done in two clusters of calculation steps, the cluster of the dairy and the calves system. The dairy system consists of adult dairy cows, dry cows, female calves and male calves until the age of two weeks. The calves system consists of the male calves that have left the dairy farm at the age of two weeks, and produces veal or beef. Fig. 2 shows a diagram of the two clusters of calculation steps. The first cluster including Step 1 to 6 calculates the footprints of the dairy system, the second cluster including Step 7 to 11 the footprints of the calves system. The SI gives the detailed method and data including calculations and data sources per step. The first cluster describes the calculation steps for the WF, LF and CF of the three dairy systems, the second cluster the calculation steps for the calves system. Each system shows differences

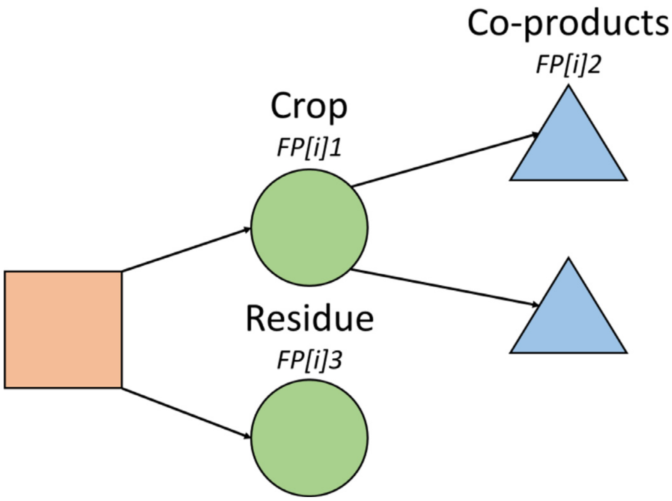

Fig. 1. A visual representation of the crop (FP[i]1), co-products (FP[i]2) and crop residue (FP[i]3). After harvest, a crop and a crop residue are separated. The crop can further be processed into different co-products.
FP[i] includes three different types: FP[i]1, the footprint of a crop, FP[i]2, the footprint of a co-product of a crop, and FP[i]3, the footprint of a crop residue.

of feed composition and volumes, composition of cows and output volumes. Data on WFs, LFs and CFs of crops are available from different sources. However, this study argues that also crop residues and crop co-products have a footprint. Therefore, the study re-allocated the footprints available for crops over crops, residues, and by-products (Fig. 1) adopting the allocation method from Hoekstra et al. [17], using product and value fractions.

Results

Land footprints

Fig. 3a-c shows the on-farm and off-farm land footprint (LF) per kg FPCM (3a), beef (3b) and veal (3c) for the Dutch and Spanish conventional and the Dutch organic dairy system. On-farm refers to crops grown on the farm grounds, while off-farm refers to imported feed ingredients.

Fig. 3a-c shows that the Spanish system has the largest total LF of milk, beef and veal, and that most LFs are related to off-farm sources. The Spanish LF per kg milk is 0.81 m^2 on-farm, and 1.52 m^2 off-farm. In the Dutch systems, the off-farm LF is relatively small. Per kg of milk, the conventional system has an on-farm LF of 0.95 m^2 and an off-farm LF of 0.35 m^2, while the organic system has a relatively large on-farm LF of 1.24 m^2, and 0.68 m^2 off-farm. Differences between on-farm and off-farm LFs for Spain and the Netherlands can be explained by the fact that Spanish dairy systems have larger feed imports, e.g., from Thailand, Indonesia, and Brazil. Spanish dairy feed also contains more concentrates than Dutch feed, which are not produced locally. Dutch systems use more locally grown feed, i.e., roughages and less concentrates. The organic system has a relatively large LF, because it has a smaller milk, beef and veal production. In the Spanish system, the production of veal is smaller, which results in a larger LF per unit of product. Table IX of the SI shows all LF data.

Water footprints

Fig. 4a-c gives the green, blue and grey WFs for the Dutch and Spanish conventional and the Dutch organic dairy system for milk (4a), beef (4b) and veal (4c).

The conventional Dutch and Spanish systems show similar total WFs for milk and beef, with a slightly larger grey WF in the Dutch system and a slightly larger blue WF in the Spanish one. However, the green and grey WFs of milk and beef of the organic system are larger, because of lower efficiency. The blue WF is also small, because there is not much irrigation in the Netherlands. The total WF of the organic Dutch system is 1.23 m^3 per kg of FPCM, 43% larger than the total WF of the Dutch conventional system of 0.86 m^3. Blue and green WFs are larger due to lower efficiency of the organic system. For veal, the Spanish system shows a relatively large total WF, similar to the WF of the organic system, because it has a relatively small amount of calves, and thus smaller

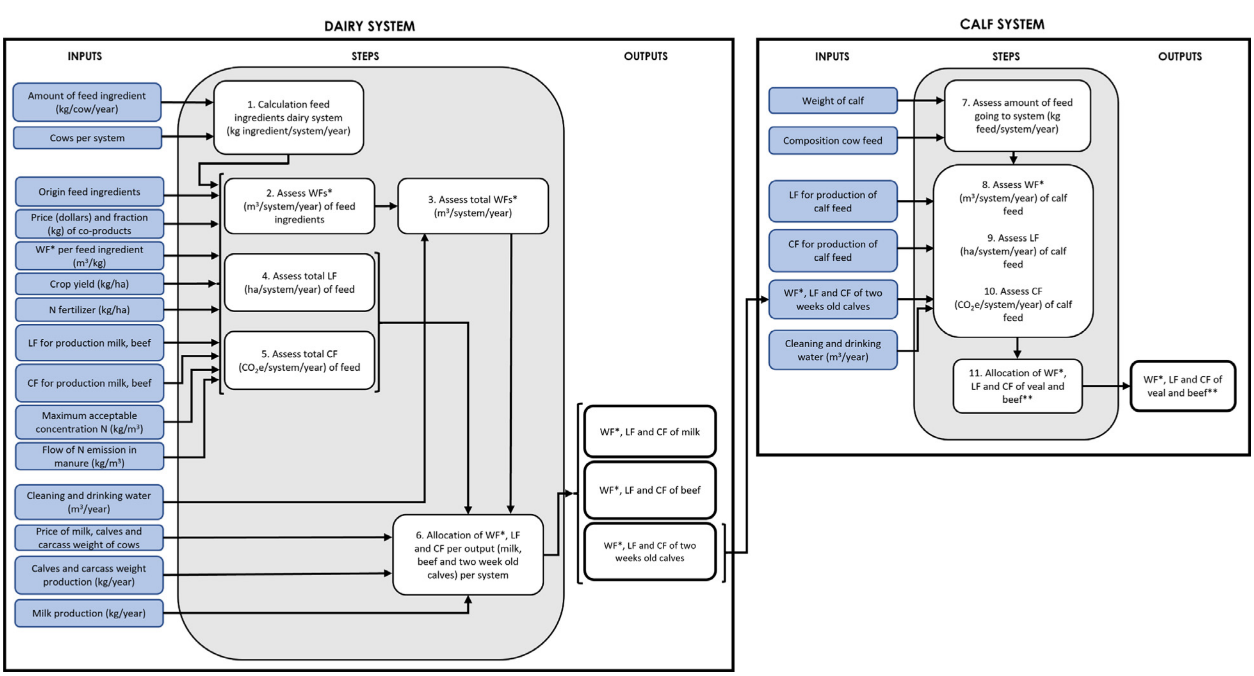

Fig. 2. Overview of inputs, outputs and calculation steps of the footprint assessment of the dairy system and the calf system. *WF (water footprints) includes green, blue and grey WFs.
**Veal and beef originating from calves that left the farm at two weeks old.
Abbreviations: WF (Water Footprint), LF (Land Footprint), CF (Carbon Footprint), N (Nitrogen).

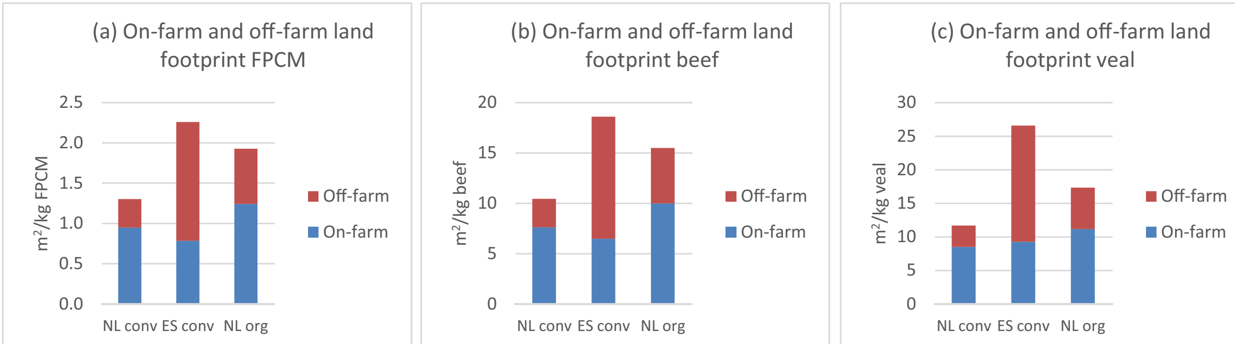

Fig. 3. a-c. On and off-farm land footprint per kg fat and protein corrected milk (FPCM) (3a), beef (3b) and veal (3c) for the Dutch and Spanish conventional and the Dutch organic dairy system. On-farm refers to crops grown on the farm grounds, while off-farm means that feed ingredients are imported. NL conv is the Dutch conventional system, ES conv the Spanish conventional system, and NL org the Dutch organic system.

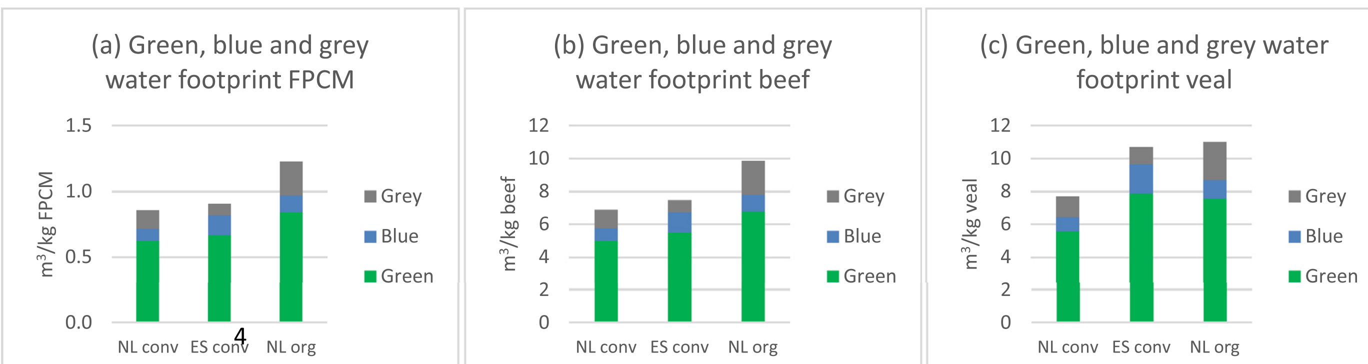

Fig. 4. The green, blue and grey water footprints per kg fat and protein corrected milk (FPCM)(4a), beef (4b) and veal (4c) for the Dutch and Spanish conventional and the Dutch organic dairy system. NL conv is the Dutch conventional system, ES conv is the Spanish conventional system, and NL org is the Dutch organic system.

veal production, increasing WFs. Tables Va-c and Table VIII of the SI give the data.

Carbon footprints

Fig. 5 shows the carbon footprints (CFs) for the Dutch and Spanish conventional and the Dutch organic dairy system based on two different calculation methods for methane, the GWP100 (100-year global warming potential) and GWP20 (20-year global warming potential).

The selection of the CF assessment method has a large effect on the CFs. When using the GWP20 method instead of GWP100, CFs more than double. For example, Fig. 5 shows that CFs of the Dutch conventional system increase from 701,000 to 1624,000 kg CO_2e./year. The Dutch systems have a relatively large increase, because methane contribution is relatively large, while the Spanish system has more non-methane emissions. Fig. 6 shows the annual CFs of the three dairy systems with two different system boundaries, with and without the calve system.

Fig. 6 shows that expanding the system boundary to include the calve system increases the CF. In the Dutch conventional and organic system, the increase is 12 and 15%, respectively. In the Spanish system, 8%. This means that excluding calve systems underestimates CFs of milk and beef.

Fig. 7a-c shows the contribution of on-farm electricity use, feed production and transport, fertilizer application, manure storage, and enteric fermentation to the CF per kg FPCM (7a), beef (7b) and veal (7c) based on the GWP100 indicator for the Dutch and Spanish conventional and the Dutch organic dairy system.

The CF of the Dutch conventional system is 0.76 kg CO_2e, of the Spanish conventional system 0.94 kg CO_2e, and of the Dutch organic system 0.95 kg CO_2e per kg of FPCM. CFs of beef and veal show similar trends. Fig. 7a-c shows that CFs of on-farm electricity and fertilizer use are relatively small. The largest contributor is enteric fermentation. In the Netherlands, it contributes 71% in the conventional and 73% in organic systems to total emissions, followed by a contribution of 10% by manure storage. In Spain, feed production and transport contribute more than in the Netherlands, because Spain imports more feed, while Dutch systems have more local feed supply. Table X, XI and XIV of the SI show all results.

Discussion

Methodological choices

To determine the environmental consequences of milk, beef and veal production in dairy systems, this study applied footprint analysis using WFs, LFs and CFs as indicators, it expanded the system boundary to include the calve system, and adopted an allocation method from the WF concept. This footprint study also used data from LCA studies. Footprint analyses and LCA studies share the quantification stage in their assessments [19], making it possible to apply each other's data. However, the assessment encountered the importance of the system boundary and indicator selection, data uncertainties and limitations, and had to make several assumptions discussed below.

System boundary

Dairy production systems are complex with several product outputs. The choice of system boundary influences results significantly, because the output of a dairy system not only includes milk, but also beef, veal and manure that have footprints too. While most earlier studies focused on milk, this study expanded the system boundary and assessed the footprints of all outputs. This study took into account that male calves leave the farm at two weeks old, and included the calve system into the system boundaries, giving a complete overview of the

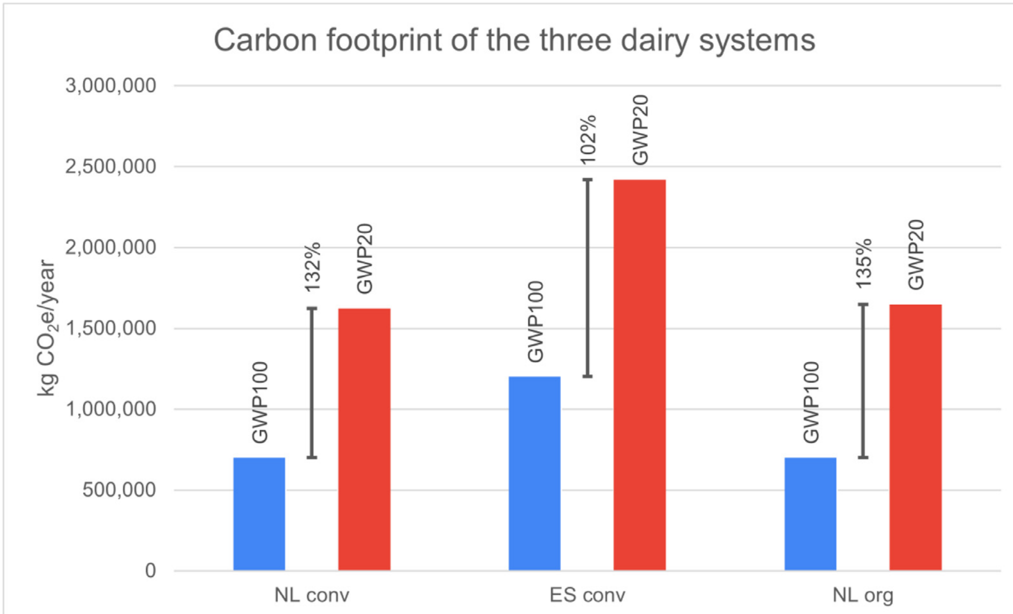

Fig. 5. Carbon footprints for the Dutch and Spanish conventional and the Dutch organic dairy system based on the GWP100 (100-year global warming potential) and GWP20 (20-year global warming potential) methods. NL conv is the Dutch conventional system, ES conv the Spanish conventional system, and NL org the Dutch organic system.

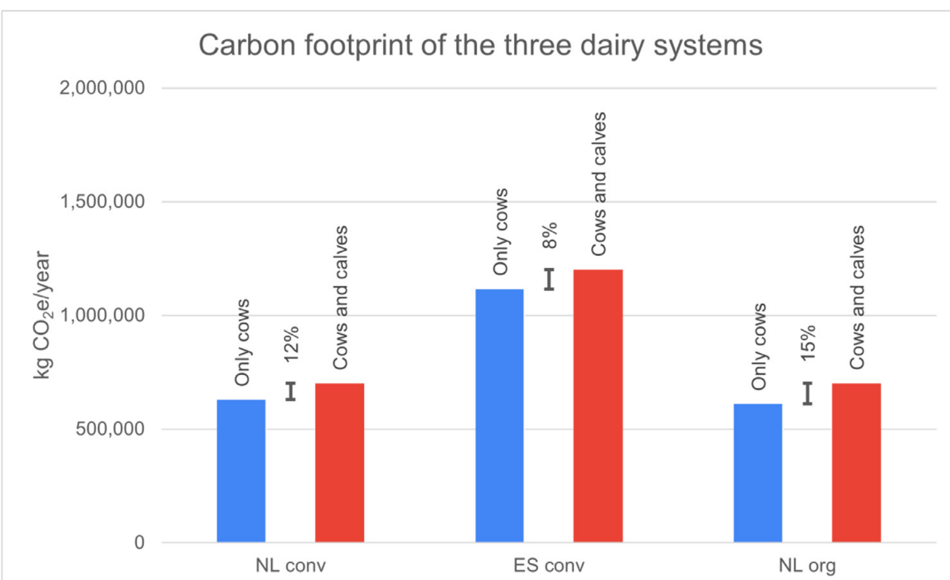

Fig. 6. Annual carbon footprints (CFs) for the Dutch and Spanish conventional and the Dutch organic dairy system with two system boundaries with and without calves leaving the farm at two weeks of age. NL conv is the Dutch conventional system, ES conv the Spanish conventional system, and NL org the Dutch organic system.

footprints of dairy production based on all output products. We showed that the expansion of the system boundary increases annual CFs by 8 to 15%. However, it is important to avoid "double counting" of emissions. For example, emissions included within expanded system boundaries might already be accounted for elsewhere. Calves that left the dairy farm move to a different system, the meat industry. This means that the footprints of calves might be double counted if a footprint study of the meat industry is carried out. Additionally, the expansion of the system boundaries makes it hard to compare studies. In order to compare results with earlier studies, the calf system must be excluded again.

Choice of indicator

This study highlights that results depend on methodological choices, such as choice of indicator. For water, we included the green and blue WFs to quantify consumed volumes. Green water is related to precipitation and included in WF analyses, but excluded in LCA studies. For example, the proposed LCA assessments of Hospido et al. [8] and of the International Dairy Federation (IDF) [11,12] only take irrigation water into account. This means that the relatively large green WFs of grazing systems are not shown in terms of water consumption, but as large land use. For water pollution we adopted nitrogen pollution from fertilizer and manure as an indicator from Mekonnen & Hoekstra [39]. That study made assessments based on 10% nitrogen losses and water quality standards of 10 mg NO_3_N per litre of water. However, other countries use other guidelines concerning water pollution. For example, in China, the standard for nitrogen (N) in surface water is 2 mg/l, which comes down to 9 mg NO_3_N/l (State Environmental Protection Administration of China and General Administration of Quality Supervision, Inspection and Quarantine of China, 2002) causing larger grey WFs. Moreover, if also other pollutants are taken into account, e.g., pesticides or herbicides, systems applying relatively many chemicals might have relatively

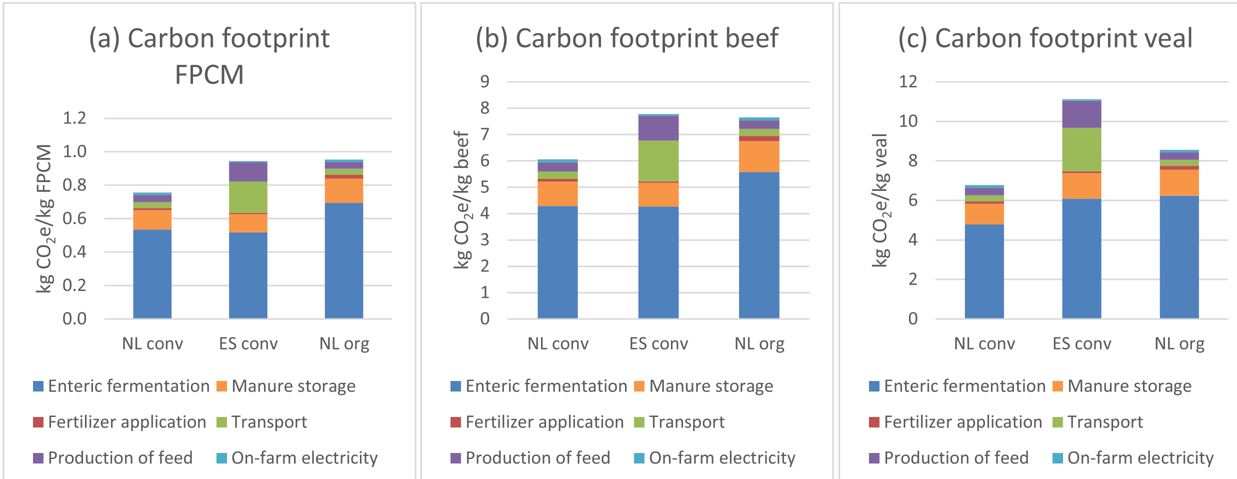

Fig. 7. a-c. Contribution on-farm electricity use, feed production and transport, fertilizer application, manure storage, and enteric fermentation to the CF per kg fat and protein-corrected milk (FPCM) (7a), beef (7b) and veal (7c) based on the GWP100 indicator for the Dutch and Spanish conventional and the Dutch organic dairy system. NL conv is the Dutch conventional system, ES conv is the Spanish conventional system, and NL org is the Dutch organic system.

large grey WFs. In addition, other water quality indicators, like biological oxygen demand might give other results.

For land, we expressed footprints in terms of square meters of land, not considering land quality aspects. If a distinction had made between the use of high quality croplands and low quality grasslands, also other results would come out.

For the CFs, the choice of indicator makes a huge difference for the outcomes. For example, the metric choice for calculating the Global Warming Potential (GWP) of methane, a gas with a high global warming potential stronger than carbon dioxide. Methane is a short-lived gas, and stays shorter in the atmosphere than carbon dioxide, so that the effect of methane is strong on a relatively short timescale. Therefore, the 100-year global warming potential (GWP100) of methane is much smaller than its 20 year-potential (GWP20) [20]. Probably, the GWP20 is a more accurate metric, but most studies use the GWP100 since it is widely accepted as the standard. To resolve this, scientists introduced the GWP*, intending to improve its accuracy [21]. Therefore, this study included both the GWP20 and GWP100 metric indicating a CF doubling for the GWP20, showing the unfavourable contribution of dairy to global warming.

The study also showed that the Dutch organic dairy system has higher footprints than the Dutch conventional system, mainly because the organic system has a lower efficiency of milk, beef and veal production. Since it allocated footprints to the output products, the footprints are larger when the output is smaller. However, if other factors besides WFs, LFs and CFs, such as biodiversity, animal welfare, limited pesticide and artificial fertilizer use, and more healthy products, were used, the study would generate different outcomes. The footprints therefore do not show the complete perspective.

Allocation

This study allocated the footprints to milk, beef and veal via an economic allocation, based on their prices and total output adopted from Hoekstra et al. [17]. However, prices fluctuate depending on prices on the global market. It is possible to allocate based on other factors, like nutritional energy, protein content, or dry mass. Different allocation methods also generate different outcomes.

Assumptions and uncertainties

The study had to make several assumptions. For example, no data were available on calf feed composition, since feed companies treat this information as a business secret. Therefore, the study assumed that calves receive the same feed as adult dairy cows but in a smaller quantity, based on their nutritional energy requirements.

Based on information from [30], the study assumed that dairy cows are kept for six years and cows produce milk for four years. However, some farmers might choose to keep their cows longer. This results in a smaller total milk yield, because when dairy cows get older and produce more calves, milk production declines. Peak production is after the fourth lactation, then it declines [40]. Moreover, female calves born from a relatively old cow tend to be smaller and produce less milk [41]. Lastly, beef production is smaller when cows are kept longer.

The study adopted data on the WF of crops from Mekonnen & Hoekstra [39] that cover the period 1996–2005. This database is not recent, since these data are not easy to calculate. Therefore, the study used data for the same time period, to match the WF data. For example, data on crop yields and weight and number of bovines slaughtered. The footprints, therefore, give an indication for the period 1996–2005. Over time, yields have improved, and animal weights might have changed. The results might change by using data that are more recent.

Comparison with other studies

Our WFs are in line with results from Mekonnen & Hoekstra [42], also because we applied the same data for crops and allocation method, so that differences originate from feed input and product output. That study gives green, blue and grey WFs for Dutch milk of 0.516, 0.044 and 0.026 m^3/kg milk, and 0.976, 0.154 and 0.181 m^3/kg milk for Spain. Our WFs of the Dutch conventional system are slightly larger than WFs of Mekonnen & Hoekstra, but for the Spanish system our WFs are smaller. However, a comparison of the Dutch organic milk to the Unicla milk studied by Roibás et al. (2016) shows similar results.

LFs are relatively large compared to other studies with a LF of 1.30 m^2/kg FPCM for the Dutch conventional system, 1.93 m^2/kg FPCM for the Dutch organic system and 2.26 m^2/kg FPCM for the Spanish system. O'Brien et al. [43] found a total LF of 0.93 m^2/kg FPCM for an intensive dairy farm, and De Boer [44] a total LF of 0.97 m^2/kg FPCM for a conventional Dutch system, and 1.18 m^2/kg FPCM for an organic system. An explanation for our relatively large LF could be that data were taken for the period of 1996–2005, when yields were smaller than today.

Our results for the Dutch and Spanish conventional and the Dutch organic dairy system indicate CFs in between CFs of other studies. This study found a CF of 0.76 kg CO_2e per kg FPCM for the Dutch conventional, 0.94 for the Spanish conventional, and 0.95 for the Dutch organic system. Some studies give larger CFs. For example, Noya et al. [45] give a CF of 1.32 kg CO_2e per kg FPCM in Spain, Thomassen et al. [46] and Thomassen et al. [47] CFs of 1.40 and 1.36, respectively, in the Netherlands, while Flysjö et al. [48] give a CF of 1.00 kg CO_2e per kg ECM in New Zealand and 1.16 kg CO_2e per kg ECM in Sweden. Other studies give a smaller CF. For example, de Léis et al. [49] found a CF of 0.54 kg CO_2e per kg ECM in Brazil for an intensive dairy system mainly caused by small enteric fermentation emissions.

Conclusions

Green, blue and grey water (WFs), land (LFs) and carbon footprints (CFs) of milk, beef and veal from three dairy systems in Europe, a conventional Dutch and Spanish system, and a Dutch organic system differ, depending on feed use, feed origin and production efficiency. However, results also depend on the system boundary and indicator selection. Changing the traditionally applied system boundary that only includes the dairy system and include calves that leave the farm at the age of two weeks increased the total CF by 8 to 15%. Indicator choice also generates huge differences. If the GWP20 is applied to calculate CFs instead of the GWP100, CFs double.

The Dutch conventional system has relatively small footprints compared to the other systems. Its green, blue and grey WFs per kg FPCM are 0.62 m^3, 0.09 m^3 and 0.14 m^3, respectively. The Spanish conventional system shows green, blue and grey WFs of 0.67 m^3, 0.15 m^3 and 0.09 m^3 per kg FPCM. These footprints are relatively large due to feed import. The Dutch organic system has larger footprints than the Dutch conventional system due to its lower efficiency. For the WF, the green, blue and grey WFs are 0.84 m^3, 0.13 m^3 and 0.26 m^3 per kg FPCM. The LF of the Dutch conventional system is 1.30 m^2 per kg FPCM, while the Dutch organic system has a LF of 1.93 m^2 and the Spanish system a LF of 2.26 m^2 per kg FPCM. The relatively large Spanish LF is due to large feed import from countries where yields are lower than in Europe.

For the CF based on the GWP100, the Dutch conventional system also shows the smallest footprint of 0.76 kg CO_2e./kg FPCM, while the Spanish conventional and Dutch organic systems have similar CFs of 0.94 and 0.95 kg CO_2e./kg FPCM, respectively. For beef and veal, the Spanish conventional system has the largest CFs with a relatively large contribution of methane from enteric fermentation. In addition, there is a large contribution of feed production and transport. To make comparisons with other studies possible, the study also applied the GWP100. However, the GWP20 might give a more accurate CF, because the GWP100 does not properly represent short-lived methane emissions.

Indicator choice has a large influence on final results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All calculations and data sources are available in the Supporting Information.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2023.100217.

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