RESEARCH ARTICLE

The carbon footprint of milk during the conversion from conventional to organic production on a dairy farm in central Germany

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Abstract

Dairy products play an important role in human nutrition, but at the same time, the dairy sector is a major contributor to global warming. The conversion from conventional to organic milk production could reduce the carbon footprint due to the elimination of synthetic fertilizers and strong reliance on closed on-farm nutrient cycling. We present one of the first studies to comprehensively estimate the climate-change impacts of the conversion to organic production of a large-scale dairy operation in central Germany. We used detailed farm data and a carbon footprint approach based on the IPCC tier-2 methodology to estimate greenhouse gas (GHG) emissions associated with feed production, animal husbandry, and animal rearing. Our results show that the carbon footprint per kg of energy-corrected milk (ECM) decreased by 9% during the first year of conversion to organic milk production. Conversely, livestock emissions per kg ECM increased by 12% in the first conversion year due to the increase in methane emissions from enteric fermentation, but this increase was more than offset by the decrease in emissions from feed production. Emissions from internal and external feed production per kg ECM decreased by 17% and 29%, respectively. Our study helps to understand how individual emission sources change as a result of a farm's conversion to organic production. This research is important and timely, as the European Union is pursuing ambitious goals to increase the area under organic farming, although the impact of the conversion period on GHG emissions has been insufficiently studied.

Keywords Greenhouse gases · Global change · Organic conversion

1 Introduction

Dairy products are an integral source of protein in human diets, particularly in economically rich nations. The demand for milk products has rapidly increased in a number of developing countries (Handford et al. 2016), and the dairy sector generates incomes for millions of farmers worldwide. The dairy sector has created multifunctional landscapes (Clay

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et al. 2020), but since it accounts for approximately 30% of greenhouse gas (GHG) emissions of the global livestock sector and 4% of total global anthropogenic GHG emissions, it is also a major contributor to global warming (Gerber et al. 2013). Milk production emits three key GHGs: methane (CH_4, enteric and manure), carbon dioxide (CO_2, energy use and land-use change), and nitrous oxide (N_2O, feed production and excreta) (Place and Mitloehner 2010). The dairy sector has a key role in reducing GHG emissions from agriculture.

Livestock intensification through improved breed and herd management (e.g., reducing the replacement rate, extending cows' lifespan, increasing calving intervals, (Novak and Fiorelli 2010; Vellinga and de Vries 2018; Weiske et al. 2006)), dietary changes (e.g., concentrate feed, which could lead to higher milk production per cow (Jiao et al. 2014)), and higher on-farm feed yields may decrease the carbon footprint of milk (Jayasundara et al. 2019). To decrease the carbon footprint of milk, a detailed understanding of the sources of GHG emissions in milk production, including feed production

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and herd management, is key (de Boer 2003). However, highly intensive dairy farms already prevail in industrialized regions such as North America and Europe, and their potential to decrease emissions is often limited, mainly due to feed digestibility already being at a very high level (Gerber et al. 2013). In addition to positive effects on the carbon footprint of milk, intensive dairy production is often associated with substantial site-specific social and environmental costs such as loss of biodiversity, animal welfare, and natural landscapes (Clay et al. 2020). Sustainable intensification is a scientifically popular concept for increasing food production while simultaneously improving economic, environmental, and social performance (Llanos et al. 2018). However, several studies point to the difficulty of achieving a clear "win-win-win" effect across all sustainability dimensions in reality (Balaine et al. 2020; Firbank et al. 2013; Salou et al. 2017).

A third and often-proposed approach to decrease GHG emissions of agricultural production is the conversion from conventional to organic production (Lamine and Bellon 2009; Pelletier et al. 2008). Decreasing farm inputs by avoiding synthetic fertilizers decreases N_2O emissions (Skinner et al. 2019), and the focus on building up soil organic carbon content (SOC) and thus increasing carbon sequestration in the soil, may alter local GHG budgets favorably (Knudsen et al. 2019). However, this effect must be balanced against lower yields of crops and livestock under organic practices and thus the potential for increased land demand. Studies based on life cycle assessment (LCA) have shown that the reduced input use per kg of milk under organic production is offset by lower milk yields and lower feed conversion ratios, resulting in higher CH_4 emissions per kg of milk than that under conventional production (Smith et al. 2019).

Calculating a product's carbon footprint is an ISO standardized assessment method (ISO 2018) that is based on the LCA approach (ISO 2006a, 2006b) but centered on estimating the GHG emissions of a product's life cycle. The calculation of carbon footprint has frequently been used to estimate the GHG emissions of conventional milk production (Casey and Holden 2005; Castanheira et al. 2010; de Léis et al. 2015; Ross et al. 2014). Much less empirical evidence is available for organic milk production, and few studies have used detailed real-farm data to estimate GHG emissions (Hietala et al. 2015). Moreover, to our knowledge, no published studies have explicitly assessed on-farm GHG emissions that occur during a farm's conversion from conventional to organic milk production. Many studies have compared conventional and organic milk farms (Kristensen et al. 2011; Meier et al. 2015), although production and site conditions are rarely identical, which can lead to erroneous inferences about the environmental effects of organic versus conventional production (de Boer 2003; Meier et al. 2015).

This research gap is unfortunate because most European Union (EU) member states pursue ambitious goals for the development of their organic production sectors. For example, the German government aims to increase the share of area under organic farming of total agricultural land from 9.6% in 2020 to 20-30% by 2030. Recently, the European Commission presented an Action Plan for the development of organic production with a target of 25% of agricultural land under organic farming by 2030. An improving policy environment and increasing demand and higher prices for organic food in the EU are the most important drivers of the current trend toward organic farming (European Comission 2019; Niegsch and Stappel 2020; UBA 2018). Since the EU will continue to promote conversion to organic agriculture and climate change is one of the most important environmental problems at present, concerted research is required to assess impacts of conversion to organic production on greenhouse gas emissions.

The goal of this study was to estimate the GHG emissions of milk production of a large-scale dairy farm in Germany during conversion from conventional to organic production (Fig. 1). Our first objective was to collect detailed farm data to cover all on-farm and off-farm activities, including external and internal feed production, animal husbandry, and animal rearing. Our second objective was to develop an attributional cradle-to-farm-gate LCA approach to cover all relevant sources of GHG emissions and to estimate the carbon footprint of milk in a conventional production year (2017) and the first year of conversion to organic milk production (2018).

Fig. 1 One of the outdoor stables of the dairy farm studied, located in central Germany. The dairy farm produced milk conventionally until 2017 and started converting to organic production in 2018. The picture was taken in 2017, prior to the conversion to organic production (own photograph).

2 Methods

2.1 Study area and study farm

This study was based on detailed data from the dairy farm *Hof Pfaffendorf*, located in Central Saxony-Anhalt, Germany. Central Saxony-Anhalt is characterized by relatively low annual precipitation (a mean of 516 mm from 1991 to 2020, (LLG 2021)), but due to its location inside the highly fertile Eurasian Chernozem belt, it is one of the most productive cropland regions in Germany and the EU (Eurostat 2020). Saxony-Anhalt plays a small role in Germany's milk production, producing only 3% of total milk production in 2020 (BLE 2021). However, it is second in milk yield of all provinces in Germany, with a mean annual yield of 9531-kg energy-corrected milk (ECM) per cow (LKV 2019; MULE 2017), which reflects the dominance of intensive production systems. In 2020, 108 ha or 9% of the total cultivated land was managed organically in Saxony-Anhalt (MULE 2021). Like at the federal level in Germany, the state government in Saxony-Anhalt is aiming to increase the share of organic products to 20-30%.

With a dairy herd size of 694 (2017) and 669 (2018) of the Holstein-Friesian cattle breed (mean herd size of 203 in Saxony-Anhalt in 2020), the study farm *Hof Pfaffendorf* is a large-scale intensive dairy operation. At 9244 kg ECM per cow, the milk yield in 2017 was well above the German mean (7763 kg ECM per cow, (FAOSTAT 2020)). In 2018, the study farm started the conversion from conventional to organic production certified by the organic label of the EU, which requires every aspect of the operational business to comply with its organic directive (EC 2017). The associated operational changes included mainly adjustments to on-farm feed production (i.e., avoidance of synthetic fertilizers) and animal husbandry (i.e., modified use of pharmaceuticals). Since the animals received slightly more space during the conversion to the organic system, the herd size was reduced marginally in 2018 (Table 1). The conversion to organic production also led to a decrease of 11% in milk yield. With an area of 717 ha in 2017 and 654 ha in 2018, the study farm was larger than the mean organic farm in this region (166 ha in 2018, (MWL 2020)).

From May to July 2018, precipitation in the study region remained at a monthly mean of 23 mm, well below the long-term monthly mean of 57 mm (LLG 2019a). This dry summer period influenced crop cultivation in 2018, but most of the negative impacts could be compensated through irrigation (personal communication with the farm manager) and the dominant soil type (Chernozem), which has a high water holding capacity due to its texture. However, the summer drought still decreased yields of grain and silage maize (Table S1).

2.2 Farm data

To examine GHG emissions during the conversion to organic production, we collected detailed farm data from 2017 (conventional production) and 2018 (first year of organic conversion). These data cover all on- and off-farm activities, including external and internal feed production, animal husbandry, and animal rearing.

2.3 Crop cultivation

A large share (58% in 2017 and 42% in 2018, Table S2) of the amount of forage fed to the dairy cows, heifers, and calves was produced on-farm or within the farm network, which includes

Table 1 Key figures of crop farming and animal husbandry at the dairy farm studied. ECM: energy-corrected milk.

Characteristic	2017	2018
Study site	Central Saxony-Anhalt	
Husbandry system	Stable-based year-round	
Manure handling	Slurry pit with natural crust cover	
Cattle breed	Holstein-Friesian	
Production system	Conventional	Organic
Farm size [ha]	717	654
Farm network area [ha]	3321	3272
Mean dairy herd size [head]	694	669
Mean calf herd size [head]	440	425
Total amount of milk produced [t_{ECM} year^{-1}]	6412	5557
Total amount of beef produced [t year^{-1}]	21.9	19.5
Milk yield [kg_{ECM} cow^{-1}]	9244	8292
Milk fat content [%]	4.0	4.0
Milk protein content [%]	3.3	3.3

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five locally producing crop farms. Within the network, machinery, equipment, and fertilizers are exchanged. The manure accumulated at the study farm is used as organic fertilizer within the farm network. Three of the five crop farms in the farm network were under organic production in 2017 and 2018. They produced organic feed crops that the study farm used while it was still under conventional production in 2017 (Table S2). The study farm was converted to organic crop production in 2018. The fifth farm in the network continued conventional production in 2018, but its crops were not fed to the cows of the study farm. Synthetic and organic fertilizer use for the crops cultivated at the dairy farm and in the farm network are reported in Table S3. We used the software DüProNP (LLG 2019b) and its precipitation parameters for Saxony-Anhalt to estimate synthetic and organic fertilizer demand for all feed crops due to a lack of farm data on fertilizer application amounts. Based on site- and soil management–specific information, DüProNP calculates nutrient stocks in the soil. It then estimates the difference between nutrient stocks and nutrient requirements (following the EU Fertilizing Products Regulation) that can be met by applying organic and synthetic fertilizers. We found good agreement between estimated fertilizer demand and the small amount of fertilizer use data that the farm provided. To calculate the amounts of N, P, and K added to the soil via manure application, we used the manure analysis report from 2017 and 2018, which was prepared for the study farm by a commercial laboratory (Table S4).

## 2.4 Animal rearing and husbandry

2.4.1 Housing and cow life cycle

Animal husbandry on the farm is divided into a rearing facility and a dairy facility (Fig. 2). In both production years considered and despite the conversion to organic production, dairy cows, heifers, and calves were kept in a stable year-round. The housing system is a loose pen with laying stalls, and animal manure is stored in a slurry pit with a natural crust cover.

A dairy cow's life cycle at the dairy farm begins with the mother cow giving birth at the dairy facility (Fig. 2). The calves stay at the dairy facility for 3 months and are then transferred to the rearing facility. Here, the calves are reared for 26 months until puberty, followed by the replacement of the dairy cows by sexually mature heifers at the dairy facility. After the first calving, the first lactation period begins, which lasts a mean of 413 days. Finally, 289 days after the third calving, the old dairy cows were slaughtered. The milk-production period of a cow at the farm corresponded to 2.7 lactation cycles for both production years considered. The carcass weight and the number of cows slaughtered, and the corresponding amount of beef produced are shown in Table S5.

2.4.2 Feed and equipment

For management reasons, the study farm divides calves, heifers, and dairy cows into ten categories structured by age and weight (Table S6). Calves are grouped according to body weight (300, 400, 450, and 500 kg), while dairy cows are grouped by their activity: young dairy cows during the first lactation (B1+2 and B3+17+19), mature dairy cows after the second calving (B7 and HL), and dry cows during the dry periods before calving (B18 and TS). Each category received specific feeds that differed in dry matter (DM) content, ash content, protein content, and net energy content for lactation (Table S7). We included electricity consumption for operating barn equipment in the model (Table S8). Because fuel inputs for feed cultivation were available only for the dairy farm, we approximated fuel inputs for the other network farms based on the area-weighted mean (Table S8).
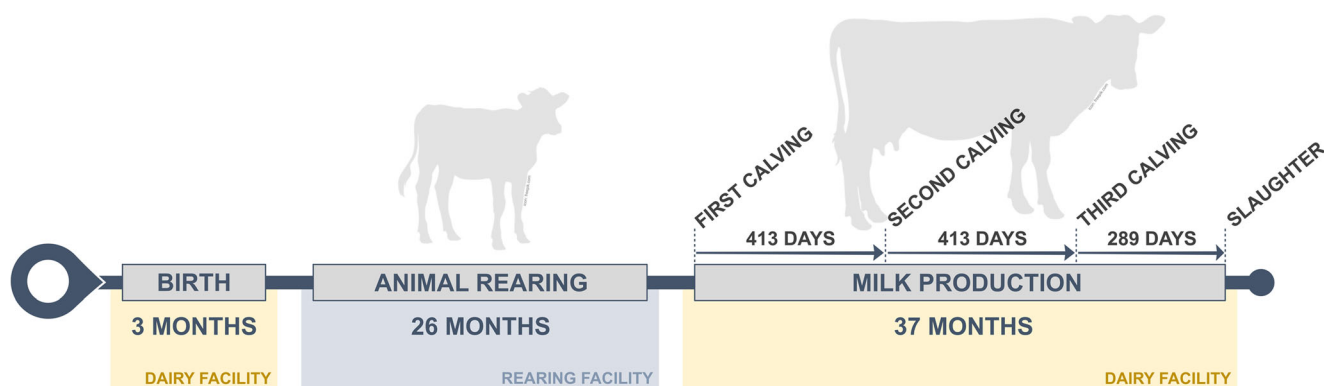
Fig. 2 Phases of the typical cow life cycle during conventional milk production and the conversion to organic production at the dairy farm studied. Each rectangle illustrates a change in the husbandry facility. Arrows above the milk production phase represent specific life stages of cows.

2.5 Carbon footprint estimation

2.5.1 System boundary and functional unit

We used an attributional cradle-to-farm-gate approach to estimate the carbon footprint of milk under conventional production (2017) and during the first year of conversion to organic production (2018) at the study farm (Fig. 3). The attributional approach aims to describe and connect all relevant physical flows to a product life cycle (Schrijvers et al. 2016). We quantified all GHG emissions that occur during external input supply (e.g., synthetic fertilizer), external and internal feed production, animal husbandry, and animal rearing. Buildings, equipment, and machinery were not included when estimating the carbon footprint because they remained virtually unchanged during the conversion to organic production. We estimated the carbon footprints of both production years using the functional unit of 1 kg ECM leaving the farm gate (Fig. 3). We used Equation 1 to calculate kg raw milk to ECM (GfE 2001):

$$kg\ ECM = raw\ milk\ (kg\ day^{-1})$$

$$\times \frac{\left[0.038 \times fat\ (g\ kg^{-1}) + 0.021 \times protein\ (g\ kg^{-1}) + 1.05\right]}{3.28}$$

Beef as a byproduct of milk production was included in our carbon footprint system (see section 2.5.2.). The emission factors used to estimate the GHG emissions of external inputs and feed production, animal husbandry, and animal rearing are reported in Tables S9 and S10.

2.5.2 Coproduct handling

We performed system expansion to consider the impact of coproduct (beef) emissions on the net carbon footprint of milk. In attributional studies, system expansion should, wherever possible, be applied to address multifunctionalities (Schrijvers et al. 2016). System expansion is particularly recommended when conventional and organic production systems are compared, since it is especially useful to capture system-specific differences that influence the relation between milk and beef emissions (Flysjö et al. 2012; Kristensen et al. 2011). Specifically, lower milk yield is associated with higher beef production under organic production, while the opposite typically characterizes conventional systems (Flysjö et al. 2012; Kristensen et al. 2011; Meier et al. 2015). To estimate this "beef credit", we multiplied the amount of beef produced (Table S5) by the mean carbon footprint of German beef produced from dairy cattle (Table S9) and subtracted this value from the carbon footprint of milk. The "beef credit" included only beef produced from dairy cows, since the farm sold no calves for slaughter in either year.

2.5.3 Life cycle inventory and impact assessment

GHG emissions of animal husbandry rearing and manure management were calculated using the IPCC tier-2 methodology (IPCC 2006, 2019). This approach provides an iteration of functions to estimate CH_4 emissions from enteric fermentation and both CH_4 and N_2O emissions from livestock manure management systems. These functions relate animal activity to embodied GHG emissions. Originally, the IPCC

Fig. 3 Production system boundaries of this study, which include four main processes (gray-headed rectangles). Gray arrows represent equipment flows between the processes. Blue arrows represent the flow of feed rations. Orange arrows represent the flow of manure from the rearing and cattle facilities to crop cultivation. Green arrows represent the two end products that leave the production system: milk and beef. Pink arrows represent the corresponding greenhouse gas (GHG) emissions.

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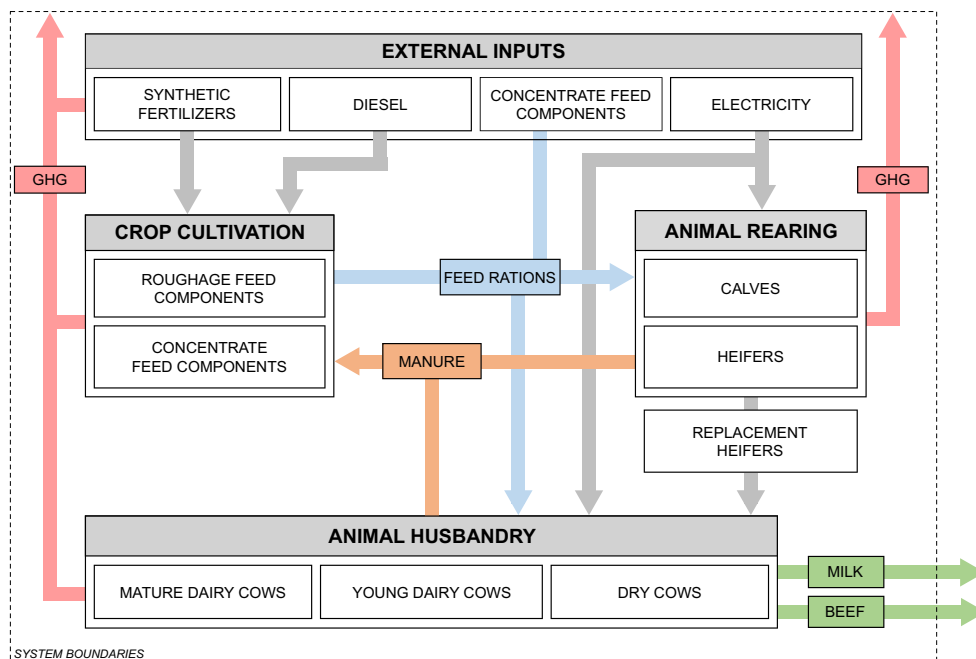
methodology was created to estimate national GHG emission inventories, but it has also been often used in the context of carbon footprint (Gollnow et al. 2014; Mogensen et al. 2014; van der Werf et al. 2009; Vergé et al. 2013). Since all manure was applied to farm network soils as organic fertilizer, we did not attribute the indirect N_2O emissions resulting from volatilization and leaching losses to livestock facilities; instead, we added these emissions to the indirect N_2O emissions from internal feed production. We could not estimate emissions from on-farm silage processing due to insufficient data provided by the farm. This added a minor source of uncertainty to estimated emissions of grass silage and maize silage production. We attributed 22% in 2017 and 15% in 2018 of GHG emissions from the rearing facility to the total emissions of the milk production system since these shares equaled the shares of heifers in the cattle herd. The share decreased from 2017 to 2018 because the number of heifers shrank. This was due in part to the conversion's requirement to provide more space per young animal and in part to drought conditions during the summer of 2018, because selling more animals partially compensated for drought-related revenue losses.

To estimate GHG emissions from external feed production, we multiplied the total mass of each externally produced feed by its corresponding emission factor (Table S9), which represents conventional production. Conventional feed is restricted under organic production, but the conventionally produced feed remaining from previous years can still be used during the first conversion year. Since all external feed was produced conventionally in 2017 and no additional external feeds were purchased in 2018, we used the same emission factors for both production years. Most concentrates and minerals were externally produced (Table S2). We lacked detailed information on the regional origin of the external feed, but based on personal communication with the farm's managers, we assumed that the raw materials were both cultivated and later processed in feed mills in Germany. Consequently, we used the mean transport distance by truck in Germany, which is 84 km (European Comission 2018), for transport of both the raw materials to feed mills and the processed feed (from feed mills) to the study farm. We assumed that all transport was performed by truck (i.e. no barges or trains). To estimate GHG emissions from the transport of each feed, we multiplied the total transport distance (transport of raw materials to feed mills plus transport of feed to the study farm, i.e., 168 km) by the corresponding emission factor for transport (Table S9). To estimate emissions from the production and application of synthetic fertilizers, we multiplied the amount of each fertilizer applied by its corresponding emission factor (Table S9). Based on the amount of feed per animal, we then related the feed-specific emissions from feed production and feed transport to one livestock unit. Finally, we normalized the emissions per livestock unit based on the amount of fodder crops fed.

To estimate GHG emissions from internal feed production, we applied the IPCC tier-2 methodology. In addition to functions for estimating GHG emissions from animal husbandry, the method also includes iterative steps to estimate emissions from soil management. Internal feed production emissions included direct and indirect N_2O emissions for each fodder crop cultivated.

We estimated GHG emissions from electricity use for all farm operations based on the emission factors of the German electricity mix for 2017 and 2018 (Icha 2020). We used global warming potentials of 1, 25, and 298 to convert CO_2, CH_4, and N_2O emissions, respectively, to CO_2 equivalents (CO_2-eq) (IPCC 2007). To model and calculate emissions from animal rearing, animal husbandry, and internal feed production, we used Excel 2019 (Microsoft Corporation 2020). We used OpenLCA 1.10.2 (GreenDelta 2020) to model and calculate emissions from external inputs. We performed statistical analysis (means, weighted means, confidence intervals, and standard deviations) using R 3.5.0 (RStudio Team 2020).

2.5.4 Uncertainty analysis

To calculate the uncertainty in each of the main processes, we applied the error-propagation approach (IPCC 2006), which is based on combining known uncertainties in farm data (e.g., fertilizer use), input parameters (e.g., aboveground:belowground biomass ratios of feed crops; Table S10), and emission factors (e.g., for external feed; Table S9). Since the deterministic farm data had no variability, we estimated the uncertainty in flows and processes using the uncertainty in emission factors and the quantities of flows (Fig. 3, arrows), which represented all material flows (i.e., farm data) and estimated emission flows in the model. When studies reported uncertainties in emission factors, we used them; if they were not reported, we searched the literature for two or more emission factors that most closely represented the content and spatial location (local scale before national scale) of the flow and used the standard deviation of these emission factors as the uncertainty estimate.

2.6 Systematic literature review

To validate and contextualize the results of our study, we conducted a systematic literature review of LCA and carbon footprint studies of dairy farms in industrialized countries that defined system boundaries similar to those in our study and used the functional units 1 kg ECM or 1 kg fat-and-protein-corrected milk (FCPM) at the farm gate. We included both ECM and FCPM functional units to

maximize the number of studies used in this review to enhance the quality of the comparison, although it adds a minor source of uncertainty to the review. We excluded studies that included changes in SOC in carbon footprints because their larger system boundaries made them difficult to compare to our study. We also excluded studies of year-round grazing systems because they are not directly comparable with German production conditions. Overall, we included 22 studies, with a total of 92 carbon footprints. Most of the studies were based on real farms (17 studies), but we also included studies that used modeled farm data (five studies) if the farm data were similar to German production conditions. We retrieved data for milk yield, feeding efficiency, enteric CH_4 emissions, and off-farm emissions from the studies. We grouped the results by type of cattle breed (5 Jersey, 24 Holstein-Friesian, 10 Fleckvieh),

type of diet (18 non-grazing, 53 mixed-system), production intensity (28 intensive, 23 extensive), and production system (41 conventional, 26 organic) (Table S11).

3 Results

3.1 Total GHG emissions

Our assessment, based on detailed farm data and IPCC tier-2 methodology, revealed that the carbon footprint for 1 kg of ECM decreased from 1.18 ± 0.15 in 2017 to 1.08 ± 0.14 kg CO_2-eq per ECM in 2018 (i.e., by 9%) (Table 2), the first year of conversion to organic production. Total GHG emissions of the farm decreased by 20% (from 7544 t CO_2-eq in 2017 to 6012 t CO_2-eq in 2018), while the milk yield decreased by

Table 2 Greenhouse gas (GHG) emissions caused by producing 1 kg of energy-corrected milk (kg CO_2-eq per kg ECM) in the last year of conventional production (2017) and the first year of conversion to organic production (2018). Numbers in parentheses indicate the total uncertainty (standard deviation) in emission sources, calculated using the error-propagation approach.

Emission source	GHG emissions (kg CO_2-eq kg ECM^{-1})	
	2017	2018
Livestock emissions	**0.53 (±0.09)**	**0.60 (±0.10)**
CH_4 from enteric fermentation	0.43	0.49
CH_4 from manure	0.07	0.07
N_2O from manure	0.03	0.03
Internal feed production	**0.16 (±0.02)**	**0.11 (±0.01)**
Direct N_2O from crop/soil	0.05	0.04
Indirect N_2O from crop/soil	0.02	0.02
Diesel use	0.02	0.06
Synthetic fertilizer use	0.07	n/a
External feed production	**0.41 (±0.11)**	**0.29 (±0.09)**
Minerals	0.02	0.02
Grass silage	0.01	0.001
Maize silage	0.12	0.12
Oils and fats	0.01	n/a
Rapeseed meal	0.16	0.04
Beet pulp	0.09	0.08
Protein supplements	n/a	0.01
Fodder beans	n/a	0.02
Fodder peas	n/a	0.01
Milk replacer	0.002	n/a
Electricity	**0.08 (n/a)**	**0.09 (n/a)**
Animal rearing	**0.04 (±0.00)**	**0.02 (±0.00)**
Livestock emission total	0.02	0.01
Internal feed production	0.02	0.01
External feed production	0.003	0.003
Electricity	0.002	0.002
Beef credit	**−0.03 (±0.00)**	**−0.03 (±0.00)**
Total "on-farm"	0.68	0.70
Total "off-farm"	0.49	0.39
Total emissions	**1.18 (±0.15)**	**1.08 (±0.14)**

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11% (9244 and 8292 kg ECM per cow from 2017 to 2018, respectively). Thus, the decrease in milk yield reduced the savings in GHG emissions per kg ECM.

During the first conversion year, total on-farm GHG emissions increased by 3%, while off-farm emissions decreased by 20% (Table 2). Therefore, the share of off-farm emissions in total GHG emissions of the farm decreased from 41% in 2017 to 35% in 2018. Each emission source changed differently during the conversion to organic production. Livestock emissions were the largest source in both years, followed by external feed production and internal feed production, both of which had lower emissions in 2018 than in 2017. From 2017 to 2018, GHG emissions from on-farm electricity use increased by 11%, while emissions from animal rearing decreased by 50%. Emissions from beef production (i.e., the "beef credit") remained unchanged at a low level during the conversion to organic production (Table 2).

3.2 Livestock emissions

From 2017 to 2018, livestock emissions increased from 0.53 to 0.60 kg CO_2-eq per kg ECM (12%, Table 2). Therefore, the contribution of livestock emissions to the carbon footprint of milk increased from 45% in 2017 to 56% in 2018. This increase was mainly due to the increase in CH_4 emissions from enteric fermentation, which represented 81% and 82% of total livestock emissions (or 36% and 45% of total GHG emissions) in 2017 and 2018, respectively.

By enteric fermentation, a dairy cow emitted a mean of 3954 and 4059 kg CO_2-eq in 2017 and 2018, respectively. At the product level, this equaled an increase from 0.43 kg CO_2-eq per kg ECM in 2017 to 0.49 kg CO_2-eq per kg ECM in 2018 (or from 35 to 45% of total emissions). In contrast, enteric CH_4 emissions from calves decreased slightly, from a mean of 408 to 399 kg CO_2-eq per animal from 2017 to 2018, respectively. This decrease resulted from the change in the calf herd structure, in particular due to fewer calves in higher weight categories, but it had almost no effect on the carbon footprint of the milk (Table S6).

Enteric CH_4 emissions depended strongly on the quality and feeding efficiency of the animal feed rations. We were able to investigate feeding efficiency based on our detailed farm data. Feeding efficiency, expressed as milk yield per kg of feed DM intake (DMI), of the Holstein-Friesian cows decreased slightly in all age categories except B3+17+19 (cows during their first lactation) from 2017 to 2018 (Table 3). On average, feeding efficiency weighted by the number of animals decreased from 1.55 kg ECM per kg DMI in 2017 to 1.50 kg ECM per kg DMI in 2018. Other robust indicators for energy turnover through feeding are net energy for lactation (NEL) and the share of digestible energy in the gross energy of a feed (DE). The NEL decreased for categories B1+2, B3+17+19 (both cows during their first lactation), and HL (mature

cows) by 2.6%, 4.3%, and 7.0%, respectively, from 2017 to 2018. The NEL of B7 (mature cows) and TS (dry cows) increased by 1.1% and 3.6%, respectively. The weighted mean NEL decreased by 2.7% between the 2 years. The DE of feed rations in each category followed a similar pattern. The DE of B7 and TS increased from 2017 to 2018 by 1.7% and 4.0%, respectively, while those of B1+2, B3+17+19, and HL decreased by 2.4%, 4.3%, and 8.5%, respectively. The slightly lower feeding efficiency in 2018 was due to the higher share of roughage in feed rations that year. For example, the mean roughage amount fed to HL, per animal per day, increased from 10.1 kg in 2017 to 13.2 kg in 2018, while the amount of concentrate fed to HL decreased by almost the same amount (from 13.4 to 10.3 kg) (Table S7).

3.3 GHG emissions of external and internal feed production

The contribution of GHG emissions from external feed production to the carbon footprint of milk decreased during the conversion to organic production, from 35% in 2017 to 27% in 2018, mainly due to much lower dependence on externally produced and emissions-intensive rapeseed meal in 2018 (Table S9). In 2017, the farm purchased large amounts of rapeseed meal (22% of total feed purchases), which contributed 1012 t CO_2-eq or 39% of total dairy herd emissions of external feed in this year. In 2018, the amount of purchased rapeseed meal decreased by 79% (to 6% of total feed purchases) and consequently the associated emissions of the dairy herd decreased to 210 t CO_2-eq (i.e., 13% of total emissions of external feed). In absolute terms, GHG emissions of the externally produced fodder decreased from 2621 to 1626 t CO_2-eq (i.e., by 38%) from 2017 to 2018, respectively. In the first conversion year 2018, the farm purchased much less external feed, which reduced the GHG emissions from this source by 29% (from 0.41 to 0.29 kg CO_2-eq per kg ECM) from 2017 to 2018.

In 2018, the farm compensated for previously externally produced feed with increased internally produced organic feed, particularly maize silage. Although the share of internal feed increased, the emissions of internal feed production also decreased from 2017 to 2018 (−0.04 kg CO_2-eq per kg ECM or by 45%). In absolute terms, GHG emissions of internally cultivated feed crops decreased from 984 to 622 t CO_2-eq (i.e., by 37%) from 2017 to 2018, respectively. This decrease was driven mainly by cultivation of a legume (soybean) and perennial grass, which resulted in decreased GHG emissions, due to lower N_2O emissions from N fertilizer application, lower CO_2 emissions from synthetic fertilizer production, and lower CO_2 emissions due to annual soil cultivation. Fertilization of internal feed crops changed greatly due to the conversion to organic production. In 2017, 125 t of N was applied in synthetic fertilizers and only 14 t of N was applied in manure. In that year, GHG emissions from

Table 3 Feeding efficiency, net energy for lactation (NEL), and share of digestible energy in gross energy (DE) of feed by age category of dairy cows in 2017 and 2018. Age category abbreviations represent young dairy cows during the first lactation (B1+2 and B3+17+19), mature dairy cows after the second calving (B7 and HL), and dry cows during the dry periods before calving (B18 and TS). The weighted mean was calculated according to the number of animals in each age category. ECM: energy-corrected milk, DM: dry matter, DMI: dry matter intake.

Age category	Feeding efficiency		NEL		DE	
	$[\text{kg}_{ECM}\ \text{kg}_{DMI}^{-1}]$		$[\text{MJ}\ \text{kg}_{DM}^{-1}]$		[%]	
	2017	2018	2017	2018	2017	2018
B1+2	1.46	1.44	6.97	6.79	72.5	70.8
B3+17+19	1.29	1.30	7.09	6.80	74.0	70.8
B7	1.76	1.61	6.14	6.20	64.5	65.6
HL	1.55	1.53	7.24	6.77	77.0	70.5
B18	-	-	6.63	6.63	69.3	69.3
TS	-	-	5.42	5.62	57.4	59.8
Weighted mean	**1.55**	**1.50**	**6.73**	**6.55**	**70.8**	**68.6**

synthetic N fertilizer production represented 46% of GHG emissions of internal feed production. Nonetheless, using manure instead of synthetic fertilizers saved 90 t CO_2-eq compared to producing synthetic fertilizers with equivalent amounts of available N, P, and K. In 2018, no synthetic fertilizer was used, and the amount of N applied in manure increased to 52 t. We estimated that producing synthetic fertilizers with equivalent amounts of available N, P, and K would have emitted 335 t CO_2-eq. On the other hand, the need for more mechanical weed control in organic crop production resulted in 167% higher emissions per t of feed in 2018 than in 2017 (40 and 15 kg CO_2-eq per t feed, respectively), but the resulting increase in milk carbon footprint (+0.05 kg CO_2-eq per kg ECM) was lower than the savings from replacing synthetic fertilizers (-0.07 kg CO_2-eq per kg ECM).

In 2017, 33% of the total sown area was already under organic production (winter wheat, some soybean, and some grain maize), while the rest was under conventional production (spring and winter barley, perennial grass, and silage maize). In 2018, all internal feed crops were produced organically, which drastically changed the contributions of emission sources (Fig. 4). Except for soybean, the main source of emissions of all conventionally produced feed crops in 2017 was N_2O emissions from N fertilizer application and CO_2 emissions from synthetic fertilizer production. Because organic agriculture prohibits application of synthetic fertilizers, emissions in 2018 were caused mainly by greater diesel consumption, which reflects the need for more mechanical weed control in organic production systems. Total diesel use in both years was nearly the same (Table S8). However, these diesel amounts were used to produce nearly three times as much crop DM in 2017 as in 2018; thus, GHG emissions from diesel use

(per t of DM) were nearly three times as high in 2018 as in 2017. Consequently, the main source of emissions in 2018 was organically produced feed crops. Soybean and cereals (including winter wheat, winter barley, and spring barley) had the highest relative GHG emissions from diesel use in 2018, while maize (both grain and silage) had the lowest. N_2O (both direct and indirect) was the main source of emissions embodied in production of maize and perennial grass.

Due to converting to 100% organic crop production and replacing synthetic fertilizers with organic manure, emissions per kg DM decreased by 29% for perennial grass, 50% for maize (both silage and grain) and winter wheat, and as much as 82% for spring barley (Table S12). For soybean, an N-fixing crop, nearly half of the total sown area was already grown organically in 2017. Emissions from organic soybean cultivation in 2017 were 0.2 kg CO_2-eq per kg DM, twice as high as those under conventional production (Table S12). The following year, emissions increased to 0.6 CO_2-eq per kg DM due to lower yields in 2018 and higher diesel use in organic production. GHG emissions from diesel use for total soybean production increased by 26% from 2017 to 2018.
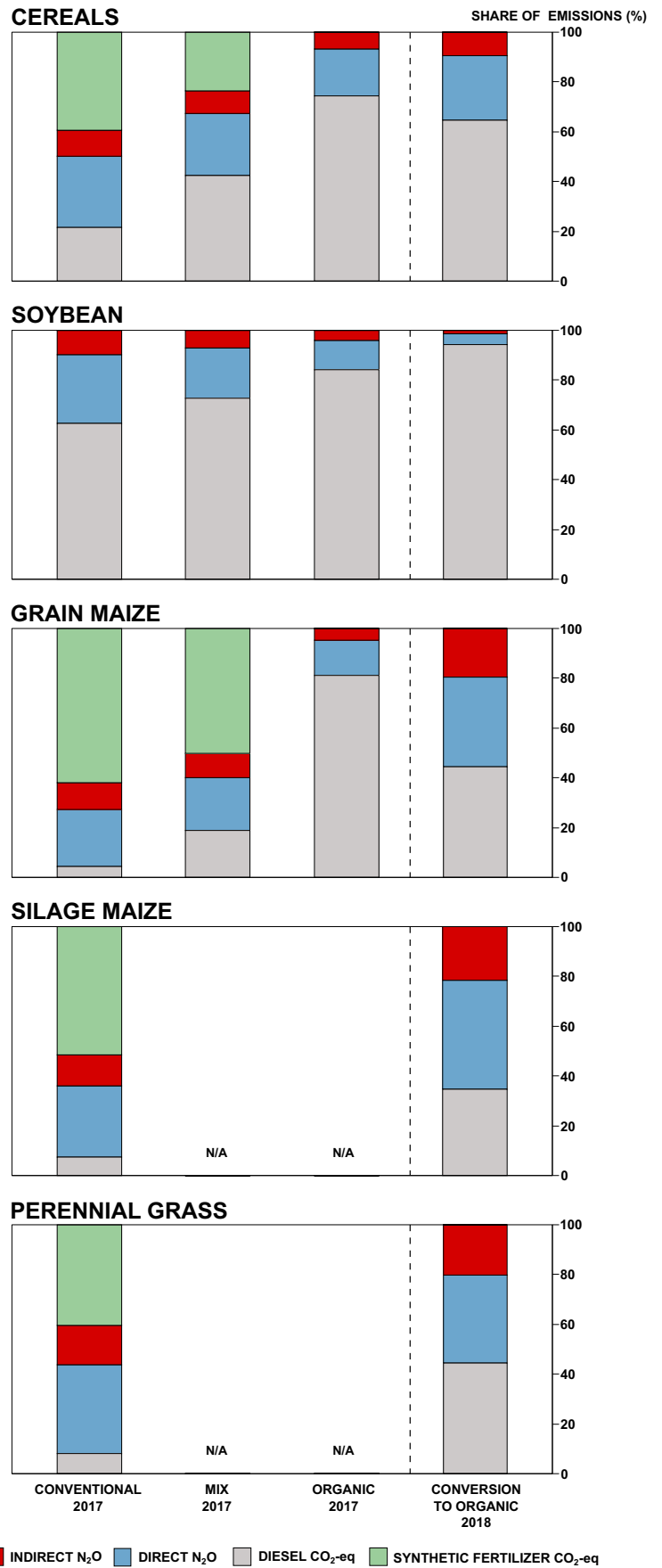
3.4 Systematic literature review

Based on the studies in our review, the Holstein-Friesian breed had, on average, the highest milk yield, the highest feeding efficiency, milk with the lowest carbon footprint, and the lowest enteric fermentation emissions per kg ECM (Fig. 5). Non-grazing dairy farms had lower mean carbon footprints (0.90 kg CO_2-eq per kg ECM) and significantly higher feeding efficiencies (1.36 kg ECM per kg DMI) than mixed-diet dairy farms (1.10 kg CO_2-eq per kg ECM and 1.09 kg ECM per kg DMI, respectively). Intensive farms had lower mean carbon footprints (1.14 kg CO_2-eq per kg ECM) but significantly higher off-farm emission shares (27.5%) than extensive farms (1.24 kg CO_2-eq per kg ECM and 5%, respectively). The mean carbon footprint of milk of conventional farms was 12% lower than that of organic farms. Conventional farms had a higher mean carbon footprint of milk (1.13 kg CO_2-eq per kg ECM) and a lower mean milk yield (8089 kg per year) than our study farm in 2017. The organic farms reviewed had, on average, a higher mean carbon footprint of milk (1.24 kg CO_2-eq per kg ECM) and a much lower mean milk yield (6622 kg per year) than our study farm in 2018 (Fig. 5).

4 Discussion

In this study, we used detailed farm data and the IPCC tier-2 approach to estimate the carbon footprint of milk production at *Hof Pfaffendorf*, a large-scale dairy farm in central Germany. Our single-farm approach allows assessment of GHG emissions that resulted only from the conversion from conventional

Fig. 4 Relative greenhouse gas emissions per t of dry matter of internal feed produced in 2017 and 2018, influenced by the conversion from conventional to organic production. In 2017, some internal feed was produced both conventionally and organically, which resulted in mixed emissions (first three bars). Cereals include winter wheat, winter barley, and spring barley.

CEREALS

SHARE OF EMISSIONS (%)

SOYBEAN

GRAIN MAIZE

SILAGE MAIZE

PERENNIAL GRASS

| CONVENTIONAL 2017 | MIX 2017 | ORGANIC 2017 | CONVERSION TO ORGANIC 2018 |

■ INDIRECT N_2O ■ DIRECT N_2O ■ DIESEL CO_2-eq   ■ SYNTHETIC FERTILIZER CO_2-eq

to organic milk production, because most production and site conditions (e.g., soil, climate, and farm structure), which may influence emissions, did not change. During the farm's conversion from conventional (2017) to organic production (2018), the carbon footprint of the milk produced decreased from 1.18 to 1.08 kg CO_2-eq per kg ECM, respectively. This decrease (9%) occurred despite the decrease in milk yield (11%) and increase in livestock emissions due to a higher share of roughage. In general, farms with lower milk yields have relatively high product-related GHG emissions (Lorenz et al. 2019). The lower carbon footprint of milk during the conversion in 2018 was driven mainly by the decrease in emissions from feed production, which outbalanced higher livestock emissions.

4.1 Livestock emissions

This study underscores the great importance of emissions from enteric fermentation in both conventional and organic production systems. This finding is consistent with the results of the studies in our review, which also showed slightly higher absolute and relative enteric CH_4 emissions under organic milk production (Fig. 5). The increase in enteric CH_4 emissions during the first year of conversion to organic production was due to lower feeding efficiency of the cattle feed ration. Increasing shares of roughage in the feed ration may reduce milk yield (Hörtenhuber et al. 2010). A higher share of roughage combined with a lower share of concentrates decreases digestive capacity (DLG 1997). Due to feeding less concentrates in 2018, cows' gross energy requirements increased,

which increased feed demand. For the studies in our review, organic farms had a 16% lower mean feeding efficiency and 19% lower mean milk yield than conventional farms. In our study, the smaller decrease in feeding efficiency and milk yield from 2017 to 2018 (3% and 10%, respectively) illustrates that conversion to organic production and the drastic changes in feed rations did not significantly decrease the feeding efficiency or milk yield of dairy cows. These results are not surprising, since the milk yield of the highly efficient Holstein-Friesian breed decreases only slightly as concentrates in the feed decrease, due to their high genetic potential (Gruber et al. 1995; Haiger and Knaus 2010). Therefore, the Holstein-Friesian breed is especially productive and relatively climate-friendly under organic production, particularly if located in grassland-dominant regions (Haiger and Knaus 2010). These findings are in line with the results of our literature review, in which the Holstein-Friesian breed showed the highest milk yield and feeding efficiency and the lowest carbon footprint of milk. Therefore, using productive breeds may be an effective strategy to reduce enteric CH_4 emissions in organic dairy systems (Brito and Silva 2020). Additionally, adjustments to feed rations, such as replacing alfalfa silage with maize silage or increasing the share of maize silage on a cow's feed ration, as observed in our study farm, decrease the amount of CH_4 emitted by enteric fermentation (Brito and Silva 2020; Hassanat et al. 2013). This is mainly due to the higher starch content of cereal forages, which promotes production of propionate over acetate and thus reduces enteric CH_4 production in the cow's rumen (Beauchemin et al. 2009).
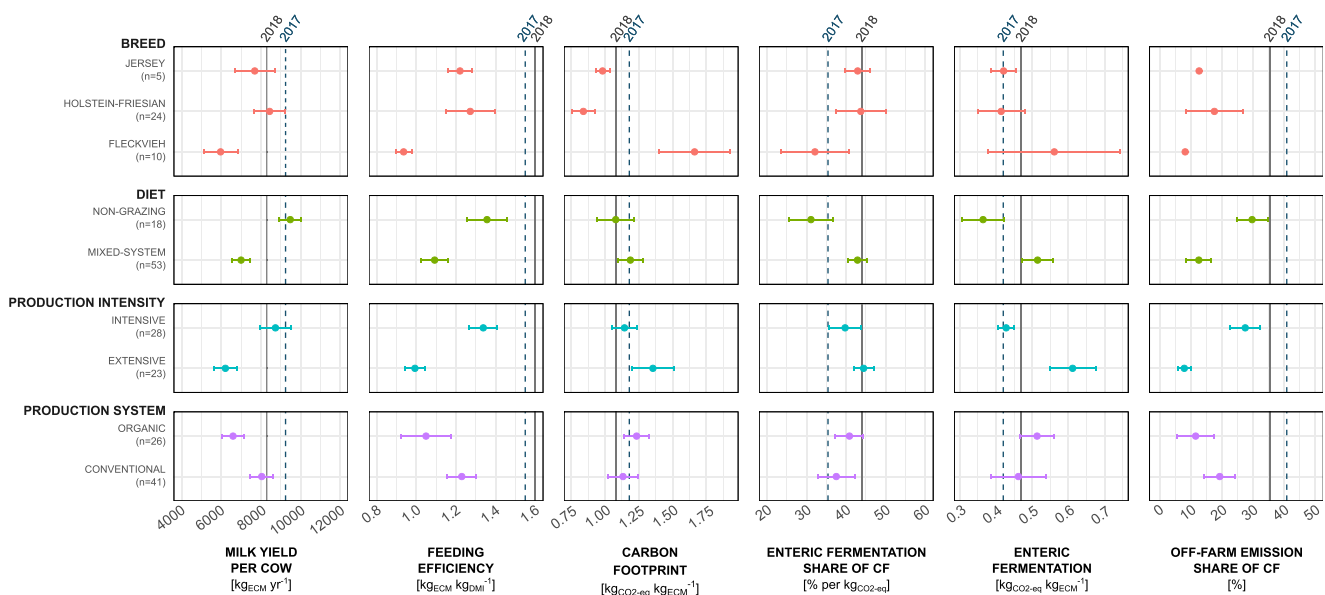
Fig. 5 Results of the systematic literature review of six parameters (milk yield, feeding efficiency, carbon footprint, enteric fermentation in %, enteric fermentation per kg energy-corrected milk (ECM), and off-farm emissions) grouped into three categories, each with two subgroups. Points represent the mean, and the range represents the 95% confidence interval. For each parameter, the results of this study for 2017 and 2018 are shown as vertical dashed or solid lines, respectively. DMI: dry matter intake.

4.2 External feed production

Farms with a high share of externally produced feed—particularly conventional farms—tend to cause high GHG emissions from their feed supply due to additional transport emissions (Boer 2003; Guerci et al. 2013; Haas et al. 2001; Penati 2009). In 2017, the farm purchased large amounts of rapeseed meal, which has relatively high associated emissions "(Sonesson et al. 2009; Wernet et al. 2016, see also table S8): 1012 t CO_2-eq (i.e., 39% of total emissions of external feed). In 2018, 79% less rapeseed meal was purchased, and the associated emissions decreased to 210 t CO_2-eq (i.e., 13% of total emissions of external feed). Furthermore, GHG emissions from transportation were lower due to increased internal feed production in 2018. We used conventional feed emission factors in both production years because the farm used only the conventional external feed that remained from previous years in the conversion year 2018.

From 2017 to 2018, the share of off-farm emissions in total emissions decreased from 41 to 35%, respectively. The lower share of off-farm emissions from organic production is also reflected in the studies reviewed: a mean of 19% for conventional farms versus 12% for organic farms. The high off-farm emissions at *Hof Pfaffendorf*, under both conventional production and conversion to organic production, are a typical indicator of intensive production systems that use large shares of externally produced concentrates (Guerci et al. 2013).

However, the large amounts purchased and thus high share of off-farm emissions in 2018 were enhanced by drought-induced crop losses (DWD 2018). Drought conditions during the summer of 2018 decreased crop yields (Table S1), which required the farm to purchase more external feed in this year. To estimate what the share of off-farm emissions would have been without the yield-limiting drought impact, a crop's yield in 2018 (organic) was assumed to be 30% lower than it had been if cultivated conventionally in 2017 (Schrama et al. 2018; Seufert et al. 2012). This yield reduction also corresponds well with the farm data (Table S1, see barley and wheat). If a crop was already cultivated organically in 2017, we assumed that it had the same yield in 2018. Using both assumptions, our model shows that the share of off-farm emissions in 2018 would have been approximately 26% (instead of 35%). This scenario clearly shows that the conversion to organic production would have decreased the share of off-farm emissions even more had the drought in 2018 not been as severe. We hypothesize that drought and inferior feed quality strengthen the reduced milk yield, thus increasing the GHG emissions of milk production (Hempel et al. 2019). Therefore, our results indicate that the carbon footprint of milk would have been even lower had 2018 had average weather conditions. However, it lay beyond the scope of this study to disentangle effects of weather on milk yields and GHG emissions from those of the conversion to organic production.

4.3 Internal feed production

Our results confirm other studies that showed large climate-change impacts of synthetic fertilizers in conventional systems (Arsenault et al. 2009; Knudsen et al. 2014; Meisterling et al. 2009). Producing feed, including the associated NPK fertilization, for one cow in 2017 emitted 653 kg CO_2-eq. A similar study reported that producing the synthetic N fertilizer required to produce the annual feed for one cow emitted 472–778 kg CO_2-eq, depending on the scenario (Zehetmeier et al. 2012). On our study farm, 46% of the GHG emissions of internal feed production were caused by the production of synthetic fertilizers in 2017. This share is similar to that in a study conducted in Sweden that revealed that emissions from synthetic fertilizer production represented 40% of total GHG emissions of wheat production (excluding those from transport and drying of feed) (Sonesson et al. 2009). Previous studies also showed that GHG emissions from synthetic fertilizer production (mainly CO_2) are approximately twice as large as those from fertilizer application (mainly N_2O) (O'Brien et al. 2014; Zehetmeier et al. 2012). In our study, both emission sources had similar proportions in both years because the farm could replace some synthetic fertilizers using integrated manure management.

Total N_2O emissions decreased from 435 to 296 t CO_2-eq per animal from 2017 to 2018, respectively, but this was due to the overall lower N input, not to the higher N-use efficiency, because N input is the main contributor to N_2O emissions (Petersen et al. 2006). In 2018, only manure was applied to the fields; therefore, total N input was significantly lower than in 2017. Another study indicated that emissions from manure are as high or higher than those from synthetic N fertilizer, arguably due to greater N input when only manure is used to fertilize crops (Han et al. 2017). The lower N inputs contributed to the lower crop yields in 2018 (Table S1). N_2O emissions per kg ECM were 0.047 kg CO_2eq per kg ECM in 2017 and 0.036 kg CO_2eq per kg ECM in 2018. Total internal feed production emissions were lower in 2018 because high emissions associated with the production of synthetic fertilizer were eliminated during the conversion to organic production. For crops that were already cultivated organically in 2017 (i.e., grain maize, soybean, winter wheat, and spring barley), drought decreased yields in 2018 (by 25% for organic winter wheat compared to 2017, Table S1), resulting in higher emissions per kg DM. In addition, no fertilizer was applied to organic winter wheat or organic spring barley in 2018, which also explains their lower yields.

Since we did not have actual data, we used official fertilization recommendations from the state of Saxony-Anhalt (LLG 2019b). These data, based on local nutrient stocks, soil type and texture, and climate data, agree well with fertilizer

requirements in the region (see 2.3). However, actual fertilizer rates are usually higher than requirements because farmers often lack fine-tuned temporally and spatially explicit information on crop N demands that would enable them to apply fertilizer exactly when needed and thus optimize crop N-use efficiency (Venterea et al. 2012). Unpredictable weather events such as heavy precipitation may also trigger N losses (e.g., N_2O, nitrate) and thus reduce N-use efficiency (Han et al. 2017; Panhwar et al. 2019). Therefore, we likely underestimated the actual GHG emissions due to synthetic fertilization in 2017.

Manure and other organic fertilizers can increase SOC stocks (Gross and Glaser 2021; Lal 2004; Maillard and Angers 2014) and thus decrease the net carbon footprint of milk, which indicates benefits of emission savings due to integrated manure management. Our study farm relied on integrated manure management, particularly since the conversion to organic production in 2018, when manure application was the only fertilization. We could not consider SOC in this study, however, due to a lack of important data, such as the carbon content of manure and local soil samples for both production years.

GHG emissions of diesel use increased from 95 to 326 t CO_2-eq from 2017 to 2018, respectively, which reflects the much higher demand for farm machinery under organic production (Knudsen et al. 2014; Meisterling et al. 2009). For grain maize, the drought decreased diesel use and diesel emissions due to lower yields and thus less use of machinery (Fig. 4). Generally, due to the absence of synthetic herbicides in organic production, machinery is used mainly for mechanical weeding (Bos et al. 2007; Jeswani et al. 2018; Knudsen et al. 2014; Meisterling et al. 2009). However, our results show that the GHG emission savings due to the avoidance of synthetic fertilizers were higher than the additional GHG emissions that resulted from increased machinery use in the conversion year.

4.4 Coproduct handling and beef credit

Expansion of system boundaries is especially important if milk production systems consider multiple outputs (e.g., milk and beef) to address multifunctionalities and identify plausible mitigation options (Mazzetto et al. 2020; Schrijvers et al. 2016). Most studies in the literature review allocated GHG emissions among coproducts based either on their economic values or on biological relationships, such as protein content. Kristensen et al. (2011) calculated a lower carbon footprint when applying system expansion instead of economic allocation. Other system-expansion studies calculated relatively small emission shares of 45–77% allocated to milk (Baldini et al. 2017). We estimated emission shares of 97.0% (2017) and 97.3% (2018). These estimates are, with one exception (97.0%, (Casey and Holden 2005)), higher than all shares in the studies in our review. The carbon footprint of 9.54 kg CO_2 eq per kg beef that we used to calculate beef emission savings

was relatively low and represents beef emissions of an average German dairy cattle system (IINAS 2019). Beef emissions from dual-purpose (milk and beef) systems are usually much lower than those from systems that produce only beef (Crosson et al. 2011). Consequently, the beef credit in our production system reduced the GHG emissions by 0.03 kg CO_2-eq per kg ECM in 2017 and 2018. Zehetmeier et al. (2014), for example, used a range of 15.6–37.5 kg CO_2-eq per kg beef from systems that produced only beef and thus estimated much higher credits for beef output.

On average, a cow in an organic milk production system has more lactations and produces more beef than one in a conventional production system (Flysjö et al. 2012). Interestingly, however, in this study, beef production per cow decreased slightly due to conversion to organic production. This result suggests that continuing intensive production while reducing the herd size (in part caused by selling more heifers due to the drought) led to milk-beef dynamics that deviated from our expectation that the conversion would produce more beef than that under conventional production in 2017. In the long term, however, conversion to organic production is expected to lead to a greater decrease in milk yield, an increase in beef production, and thus a larger beef credit.

5 Conclusion

We present one of the first studies to assess climate-change impacts caused during the first year of conversion from conventional to organic production of a large-scale dairy operation. The single-farm approach enables effective interpretation without drawing biased conclusions due to site-specific differences such as soil, climate, and farm structure between conventional and organic farms. Based on a cradle-to-farm-gate carbon footprint approach, we estimated a decreased carbon footprint of milk during the conversion from conventional to organic production, mainly due to a decrease in GHG emissions from external and internal feed production. Our study indicates that the climate-change effect of milk production can be reduced if productivity in feed production, animal husbandry, and animal rearing can be kept high during the conversion to organic production. In our example, the highly productive dairy breed (Holstein-Friesian) certainly played a large role in keeping feeding efficiency almost unchanged. Thus, livestock emissions did not decrease greatly, but feed rations changed substantially. The results of this study highlight that the concept of sustainable intensification is not unrealistic in practice. We were able to use detailed farm data, which helped us to understand details of the processes and material flows on the farm. Nonetheless, our 2-year study is not sufficient for capturing long-term climate-change impacts of the conversion to organic production. Moreover, our study represents large-scale dairy operations with access to feed cultivated on fertile

soils, and further research is needed to assess how dairy operations with other characteristics would perform during the conversion. More research should also focus on other important environmental impacts (e.g., biodiversity, water and air pollution, land occupation) and potential scale effects (e.g., farm size) during the conversion of conventional milk farms to organic production.

Declarations

Ethics approval   Not applicable

Consent to participate   Not applicable

Consent for publication   All the data presented have been anonymized. The owners of the farm studied gave their informed consent to their publication for research purposes.

Conflict of interest   The authors declare no competing interests.

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