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LCA FOR AGRICULTURE

Transforming the feeding regime towards low-input increases the environmental impact of organic milk production on a case study farm in central germany

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Abstract

Purpose Despite the direct effect of the feeding regime on the environmental impacts of dairy farming systems, its level of intensity, particularly in organic systems, has rarely been investigated. This study compares the environmental impact of a high-input feeding regime with a grassland-based, low-input feeding regime scenario within an organic milk production system conducted on Gladbacherhof, the research farm of Justus Liebig University Giessen, in Central Germany.

Methods An integrated Life Cycle Assessment (LCA) analysis was performed from a cradle-to-farm gate perspective to quantify five environmental impacts, namely Global Warming (GW), Non-Renewable Energy Use (NREU), Land Use (LU), Terrestrial Acidification (TA), and Freshwater Eutrophication (FE). All agronomic data of the Gladbacherhof research farm, averaged over the years 2010–2017, were included. When not directly measured on the farm, ecoinvent data were included.

Results and discussion Contrary to our hypothesis, the results suggest that a grassland-based low-input system has a higher environmental impact as compared to a high-input system for each of the five impact categories when using fat and protein-corrected milk (FPCM) as the functional unit. A 50% reduction in concentrates and exclusion of maize silage from the feed ration in the modelled low-input production system lead to a 20% drop in milk yield. To balance the energy content in low-input feeding ration, longer grazing period and higher amount of hay, alfalfa, and grass silage are required. This in turn results in higher emissions from enteric fermentation, manure management, and feed production and hence in higher environmental impact, particularly for GW, TA, and FE.

Conclusions This study is one of the few that directly explores the environmental impact of feeding intensity in an organic milk production system. Nevertheless, there is a lack of research on consolidated emission factors for several greenhouse gas (GHG) sources in organic livestock and cropping systems to perform more robust carbon footprint calculations that comply with the Intergovernmental Panel on Climate Change (IPCC) Tier 3 GHG reporting guidelines. To generalize the results at the regional or national scale, direct comparisons with a larger number of organic farms representative of high-input and low-input intensities are still essential.

Keywords Climate change · Environmental impact · Life Cycle Assessment · Organic dairy farming · Feeding regime

1 Introduction

In recent years, there has been an increasing focus on the contributions of livestock production to climate change. Livestock production systems are responsible for the greenhouse gas (GHG) emissions in the form of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). According to Life Cycle Assessments (LCA) of Steinfeld et al. (2006), Bellarby et al. (2013), and Twine (2021), the livestock sector including land use change (LUC) contributes to 18% and to between 12 and 17% of total GHG emissions, at global and European levels, respectively. Beef and dairy cattle are the largest contributors to total livestock GHG emissions in the EU, because of the high product-related emissions associated with beef and the high consumption of dairy products in comparison to other livestock products (Bellarby et al. 2013). Dairy supply chains have also shown other environmental impacts such as acidification, eutrophication, and

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Extended author information available on the last page of the article land and energy use based on the farming system and the location of the production facility (de Vries and de Boer 2010).

Organic farming systems, which in general avoid to use synthetic fertilizers and pesticides, promote crop rotations and focus on soil fertility and closed nutrient cycles (Muller et al. 2017), possess a great potential towards sustainability in terms of environmental impacts, non-renewable energy inputs, animal welfare, biodiversity, and soil fertility (Cederberg and Mattsson 2000; de Vries and de Boer 2010; Guerci et al. 2013; Pimentel and Burgess 2014). Though there is a wide variety of systems defined as organic, these systems are often perceived with lower GHG emissions as an offset of lower yields (Nemecek et al. 2011; Schader et al. 2014; O'Brien et al. 2023). However, some studies have shown that this can be refuted if previously ignored emission sources such as land use change are included in the analysis (Hörtenhuber et al. 2010). Therefore, further research on potential sources of GHG emissions is warranted to optimize mitigation strategies for organic dairy production.

Three main sources of environmental impacts from dairy production are enteric fermentation, feed production, and manure management (Cederberg and Flysjö 2004; Flysjö et al. 2011; Djekic et al. 2014; O'Brien et al. 2023). When product-related, more than half of the total GHG emissions are due to methane emissions released from enteric fermentation (Flachowsky and Hachenberg 2009; Reinsch et al. 2021; O'Brien et al. 2023). Feed production is the second largest contributor to GHG emissions, followed by manure storage, spreading, and handling, associated with nitrogen oxide emissions (Aguirre-Villegas et al. 2022). It is important to note the manure management emissions can vary significantly across different dairy farms, depending on specific management practices and regional conditions. Additionally, the extend of emissions from enteric fermentation and manure is influenced by the composition of the diet (Hörtenhuber et al. 2011; Laca et al. 2020; Reinsch et al. 2021). Therefore, changing the feeding regimes holds a great potential for mitigating emissions from enteric fermentation, crop production, and manure storage. A meta-analysis carried out by Lorenz et al. (2019) evaluating different feeding regimes has shown that the grazing system has lower global warming (GW) in comparison to mixed and confined systems, if the productivity of the cows is maintained. Alternatively, changing the feeding regime in order to mitigate emissions from enteric fermentation bears the risk of pollution swapping, which could lead to higher emissions from activities like manure management or forage production (Muller and Scholtz 2014). It is important to highlight that in dairy farming, the most substantial portion of energy inputs is attributed to forage production, whereas production of concentrate feed and maize silage are the major contributors to mineral nutrient reduction in soil (abiotic depletion) (Castanheira et al. 2010). On the other hand, a study has shown that a high availability of forage mitigates the effect on eutrophication but could have a greater impact on the occupation of farmland (Romano et al. 2021a). With regard to organic farming, the decline in productivity increased acidification potential, eutrophication potential, and land occupation per unit of product relative to conventional systems (O'Brien et al. 2023). Converting to organic production generally decreased emissions from internal and external feed production, while increasing product-related methane emissions from enteric fermentation.

Although the requirements of organic dairy farming systems differ between countries, it is generally mandatory to provide daily outdoor access with a high proportion of forage in the diet. The European Union (EU) guidelines for organic farming stipulate that grazing should be ensured for ruminants whenever feasible (EC 2007). Grazing is not only the most energy-efficient of all feeding systems (Frank et al. 2013), but also has positive effects on fertility and health parameters of dairy cows, especially claw diseases and integument alterations (de Wilt 1985; Burow et al. 2011, 2013; Armbrecht et al. 2019; Crossley et al. 2022). A grassland-based milk production system reduces feeding costs. Consequently, the farm is less vulnerable to fluctuating input prices and economic volatility (Hennessy et al. 2020). While crop cultivation, particularly maize cropping, causes a loss of soil organic carbon, grassland usually maintains high soil carbon stocks (Cambardella and Elliott 1994; O'Mara 2012; Phukubye et al. 2022). In addition, nitrogen leaching is lower on grassland compared to arable land (Payraudeau et al. 2007). Milk produced from grassland also contains a higher concentration of polyunsaturated fatty acids in comparison to milk produced from maize silage (Elgersma et al. 2003; Stypinski 2011). A grassland-based feeding regime could potentially lead to lower environmental impacts by mitigating GHG emissions. Given global climate change and ongoing environmental degradation, progress towards such low-input approaches is certainly beneficial. Grassland-based milk production systems are mainly intended to attain high area productivity and high feed conversion efficiency while minimizing the cost of production (Steinwidder et al. 2010) and reducing competition for human food (Ertl et al. 2015; Schader et al. 2015; Reinsch et al. 2021).

The feeding regime of dairy cows clearly affects the impact categories of the milk production system (Cederberg and Flysjö 2004). Depending on the type of diet, feed production accounts for a considerable portion of resources and plays a substantial role in GHG emissions. The growing interest in mitigation strategies along with the potential of grassland-based feeding regimes to diminish the environmental footprint of organic milk production systems provide a compelling incentive for further research. No previous study has been done with the same herd, in the same location, and under the same environmental conditions to explore how different feeding regimes affect the environmental impact of organic milk production including global warming potential, acidification, eutrophication, energy consumption, and water consumption. Therefore, the aim of this study is to compare a high-input feeding regime with a grassland-based low-input feeding regime scenario within an organic milk production system in Central Germany. We test the hypothesis whether switching from a high-input to a grassland-based low-input feeding regime affects the product-related environmental impact of organic milk production.

2 Material and methods

2.1 Study area and data collection

The study was conducted at Gladbacherhof, an organically managed research farm of Justus Liebig University Giessen, located in Villmar in the northwestern foothills of the Taunus Mountains in Central Germany (https://www.uni-giessen.de/fbz/fb09/forschung/lehreinrichtungen/Standorte_neu/gh). The farm is located at an altitude of 140–300 m a.s.l. with a mean annual rainfall of 663 mm and a mean annual air temperature of 9.8 °C (2000–2020). The soil texture is dominated by sandy and loamy clay with an average soil quality of 63 points within a 100-point scale based on the Muencheberg soil quality rating system (Mueller et al. 2007). The farm has been certified organic since 1983 and has been a member of the organic grower associations Bioland and Naturland since 1989 and 2020, respectively. The key requirements for the organic certification in Germany and Europe include providing animals with access to organic pastures and organic feed, prohibiting the use of synthetic fertilizers, pesticides, and growth hormones. Furthermore, organic farms must implement sustainable land management practices such as crop rotation, organic fertilization, and water conservation. The farm cultivates about 180 ha of land, of which 100 ha are arable land and 80 ha are grassland, and focuses on the propagation of cereal seeds, potatoes, and dairy farming. The crop rotation encompasses a variety of six different annual crops and 2 years of alfalfa as shown in Table 1. Holstein cows are kept in an early lactating (from 1 to 150 days in milk (DIM) and late lactating group (from 150 DIM until the lactation end). In total, 90 dairy cows are kept in a free stall barn with deep straw bedding. During the grazing season (April to October), pasture access is available for at least 4 h day^{-1}. Even during the grazing season, the main source of cows' dry matter intake (DMI) remains the feed provided in the barn. In no-pasture period (November to March), a partial mixed ration (PMR) based on maize silage, alfalfa-rye grass mixture silage, and concentrates (faba beans and cereals) is fed. In the grazing season, cows receive fresh alfalfa-rye grass in the feeding parlor besides the PMR. The main breeding objective is longevity. Manure and slurry are strategically applied to pasture and crop areas to meet the nutritional demands of the plants according to the specific needs of each crop or pasture.

Table 1 Crop rotation at Gladbacherhof for the period 2010–2017 (status quo, high-input system). Cover crops (mainly mustard and horseradish) are implemented between annual crops whenever it is possible

Year	Crop
Year 1	Alfalfa grass (*Medicago sativa*)
Year 2	Alfalfa grass (*Medicago sativa*)
Year 3	Winter wheat (*Triticum aestivum*) or triticale (×*Triticosecale)*
Year 4	Maize (*Zea mays*) or potatoes (*Solanum tuberosu*)
Year 5	Winter rye (*Secale cereal*)
Year 6	Faba beans (*Vicia faba*)
Year 7	Spelt (*Triticum spelta*)
Year 8	Summer wheat (*Triticum aestivum*) or summer oat (*Avena sativa*) or summer barley (*Hordeum vulgare)*

Primary and secondary data were used for the study. In cases where no primary data were available from the farm, secondary data (comprising less than 10% of the dataset) were sourced from the ecoinvent database (Ecoinvent 2018). Data on the current milk production at Gladbacherhof, i.e., high-input feeding regime, were collected from on-farm data and surveys over an 8-year period (2010–2017). Data on conversion to less intensive grassland-based production were obtained from the literature and the ecoinvent database. The intake of all feedstuffs was calculated based on the average daily intake of feed from on-farm data of the years 2010 to 2017. For the analysis, the feedstuff production was calculated based on the annual average of harvest data from 2010 until the harvest of 2017. Data were averaged from 2010 to 2017 to provide a comprehensive assessment of the long-term environmental impacts of organic milk production. This approach helps to minimize the influence of year-to-year anomalies, particularly the extreme drought conditions experienced from 2018 to 2020, which do not represent the long-term average state of the feeding regime on the farm under investigation. By focusing on overall trends, our findings are robust and reflective of the average framework conditions of milk production in the analyzed system.

2.2 High-input feeding regime (status quo)

The average concentrate input is 1600 kg cow^{-1} year^{-1}, and the diet of the high-yielding (freshly lactating) cows consists of up to 6 kg of dry matter (DM) maize silage and 8 kg of concentrates (DM) per day. Thus, the current intensity or input level of milk production at Gladbacherhof can be rated as "high-input" for organic dairy production in Germany (Wallenbeck et al. 2019). The diets for early and late lactating cows in winter consist of grass silage, alfalfa silage, maize silage, and concentrate feed (cereal grains, faba beans, mineral feed) (Table 2). The composition of the concentrate feed varies, as leftovers from cereal propagation are often added to the mixture. The ingredients are faba beans, wheat, rye, triticale, and less frequently barley, oats and peas, or lupins. The roughage used at Gladbacherhof consists of grass silage harvested 4–5 times per year, alfalfa silage with 4 cuttings year^{-1}, and maize silage. In summer with pasture access of at least 4 h day^{-1}, fresh green fodder such as alfalfa grass or clover is added to the diet (Table 2). During the evaluation period, the same diet ingredients and feeding strategy, including the provision of fresh forage in the feeding parlor and access to grazing during the grazing season, were consistently used. The average milk yield is 8000 FPCM (fat and protein-corrected milk) cow^{-1} year^{-1} (Table 3). Female calves are kept at the farm for replacement and breeding purposes, whereas male calves are sold at the age of 14 days. The average age at first calving is 27 months, and the average calving interval is 396 days. The average number of lactations is 3.8, and the replacement rate is 26%.

2.3 Low-input feeding scenario

A low-input feeding regime that could potentially be implemented at the Gladbacherhof farm was elaborated as a scenario, taking into account the amount and nutrient content of feed available as well as arable and grassland availability on the farm. The primary goal of the low-input feeding regime was to eliminate the use of maize silage in the diet and to reduce the amount of concentrate fed to the animals, characterizing it as a grass-based system with a 20% reduction on the milk yield. This feeding regime has the benefit of reducing the land use competition for human food production, that is why feedstuffs from arable land such as maize and grain for concentrates are drastically reduced (Schader et al. 2015). The diet was balanced to meet the physiological requirements of low-input dairy cows by increasing the grass proportion (Table 2), and all the feed ingredients were produced on farm. The diets for low-input groups were calculated to meet the nutritional requirements for the target milk yield, which was set at 20% lower for the low-input group compared to the high-input (status quo). Nutritional requirements were estimated based on National Research Council (2001) recommendations, taking into account target milk yield and composition and cow's weight. In the same way, the estimate DMI for the low-input group was calculated according to National Research Council (2001) recommendations. The quality of the feedstuffs was assumed to be the same for both groups, as all feedstuffs used in the low-input diet were produced

Table 2 Composition of the diet at Gladbacherhof in summer and winter of early and late lactating groups and annual average for each feed ingredient (status quo, high-input system). The ration was calculated to meet 100% of the cow's nutritional requirements with approximately 10% leftover

Feed ingredient	High-input diet					Low-input diet				
	Winter		Summer		average	Winter		Summer		Average
	Early lactation	Late lactation	Early lactation	Late lactation		Early lactation	Late lactation	Early lactation	Late lactation	
Maize silage (kg DM cow^{-1} day^{-1})	8	6	8	6	7	0	0	0	0	0
Alfalfa silage (kg DM cow^{-1} day^{-1})	8	8	4	4	6	10	8	6	4	7
Grass silage (kg DM cow^{-1} day^{-1})	3	2	3	2	2.5	6	4	4	2	4
Hay (kg DM cow^{-1} day^{-1})	0	0	0	0	0	2	2	1	1	1.5
Fresh grass (kg DM cow^{-1} day^{-1})	0	0	6	6	3	0	0	12	12	6
Concentrate feed (maximum) (kg DM cow^{-1} day^{-1})	7	2	7	2	4.5	3.5	1	3.5	1	2.25

DM, dry matter

Table 3 Milk performance traits at Gladbacherhof for the period of 2010–2017 (status quo, high-input system)

Variable	Year								Mean	Standard deviation
	2010	2011	2012	2013	2014	2015	2016	2017		
Dairy cows (*n*)	91	89	90	89	92	91	88	89	89.9	1.36
Heifers (*n*)	20	14	17	15	13	14	12	15	15.0	2.51
Calves (*n*)	66	76	73	70	64	74	71	79	71.6	4.98
Total animals (*n*)	177	179	180	174	169	179	171	183	176.5	4.78
Milk (kg cow^{-1} year^{-1})	7710	7558	8099	8166	7920	8099	8511	8170	8029	296.7
Fat (%)	4.41	4.13	4.09	4.08	4.07	4.19	4.24	4.13	4.2	0.11
Protein (%)	3.13	3.15	3.21	3.12	3.13	3.15	3.24	3.20	3.2	0.04
Sold bull calves (*n*)	41	49	52	42	54	54	53	58	50.4	6.02
Sold heifers (*n*)	21	20	29	30	20	36	17	28	25.1	6.56

on-farm. The production of all feedstuffs was assumed to follow the same input, expenditure, and yield per area as the status quo. The nutrient and energy contents of all roughages and concentrates were also presumed to be the same in order to obtain comparable outcomes. The exclusion of maize silage and the 50% reduction in concentrates were the main differences between the status quo of the high-input feeding regime of the farm and the modelled low-input scenario. According to the different feed ration calculators (Bavarian State Research Center for Agriculture (LfL), 2019; State Office for Agriculture Hesse (LLH), 2019), the low-input diet was modelled with a daily milk yield of 17.5 kg FPCM cow^{-1}, resulting in an annual milk yield of 6400 kg FPCM cow^{-1}. Estimated feed intake, performance, and emissions for the low-input scenario are shown in Table 4.

2.4 Life cycle assessment (LCA)

The LCA approach used in this study is based on the ISO 14040 and 14044 standards (ISO 2006a, b). According to these standards, LCA comprises a four-step process: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment, and (iv) interpretation.

2.4.1 Goal and scope definition

The aim of this study is to compare the environmental impact of a high-input feeding regime (status quo) with a modelled grassland-based low-input feeding regime scenario within an organic milk production system in Central Germany.

The system boundaries for this study are from cradle-to-farm gate (Fig. 1). While the housing of dairy livestock and the relevant machinery and technical devices were taken into account, the handling of the milk outside the farm (i.e., transportation, processing in the dairy industry, cooling, packaging and distribution, consumption of the milk), veterinary treatments as well as other activities at Gladbacherhof not related to dairy production, such as cereal, potato, and egg production, were not considered in this LCA.

The functional unit is defined as 1 kg of fat and protein-corrected milk (FPCM), ensuring that the produced milk is always adjusted to contain 4.0% fat and 3.3% protein content, aligning with standard benchmarks for comparing various milks with varying compositions and originating from diverse production methods (FAO 2010). The subsequent equation was used to adjust milk with varying fat and protein content to FPCM:

$$FPCM(kg) = Raw\ milk(kg) \bullet (0.337 + 0.116 \bullet Fat(\%) + 0.06 \bullet Protein(\%)) \tag{1}$$

Table 4 Average milk yield and emissions (CH_4, NH3, N_2O) from enteric fermentation and manure management of the high-input (current system at farm) and low-input (scenario) production system

Production system	High-input	Low-input
Average yearly milk yield (kg FPCM cow^{-1} year^{-1})	8000	6400
Average daily milk yield kg FPCM cow^{-1} year^{-1})	22.0	17.5
Dry matter intake (kg FPCM cow^{-1} day^{-1})	19.2	18.7
CH_4 from enteric fermentation (g CH_4 kg^{-1} FPCM)	18.5	22.4
CH_4 from manure management (g CH_4 kg^{-1} FPCM)	3.9	4.9
NH_3 from manure management (g NH_3 kg^{-1} FPCM)	8.3	10.3
N_2O from manure management (g N_2O kg^{-1} FPCM)	0.21	0.28

FPCM, fat and protein-corrected milk

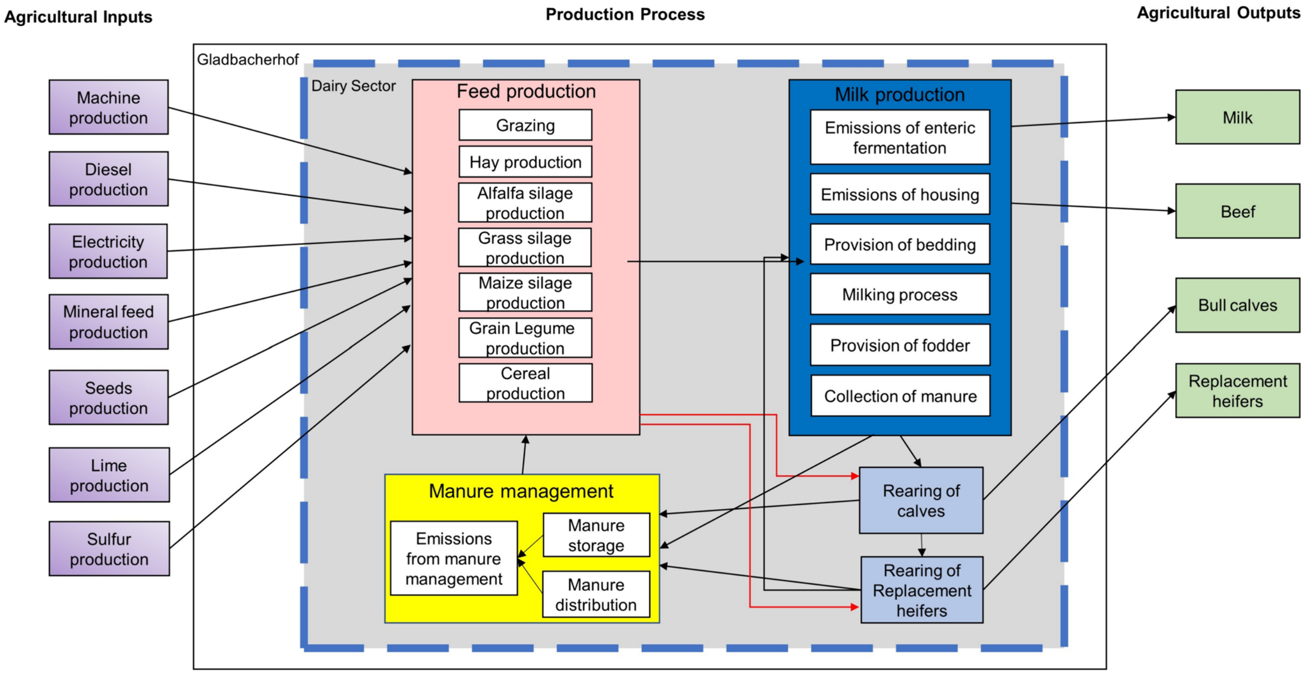

Fig. 1 System boundary (dashed blue line) of the LCA on organic dairy production at Gladbacherhof

Milk production on a dairy farm is typical for a multi-functional process. When analyzing multi-functional processes, it is essential to specify to what extent the environmental burdens of these processes are to be allocated to the product under investigation (Cederberg and Stadig 2003). In this study, an economic allocation procedure was used to allocate the environmental impact of the dairy farm to its co-products. Allocation was calculated based on the market prices of milk, sold calves, breeding heifers, and cull cows from 2010 to 2017. The resulting allocation of associated economic benefits and associated environmental impacts was 88% for the main product milk and 12% for the byproduct beef including breeding heifers, sold calves, and cull cows.

2.4.2 Inventory analysis

As cradle-to-farm gate was chosen as system boundary, the inventory analysis encompassed the production of all feed types and the utilization of all machinery inclusive of energy consumption. The inventory analysis was performed with data representative of milk production at Gladbacherhof from 2010 until 2017. Housing of dairy cows, heifers, and calves, including the construction of these buildings, as well as the milking process and total energy consumption were taken into account. The benefits of nutrients such as nitrogen contained in farmyard manure and slurry from dairy cows were proportionally calculated as benefits to cereal production systems.

2.4.3 Life cycle impact assessment

The ReCiPe method was employed to translate the input and output data into environmental impacts (Heijungs et al. 2013). Five categories were chosen for this study: global warming (GW), non-renewable energy use (NREU), land use (LU), terrestrial acidification (TA), and freshwater eutrophication (FE). For GW, emission data were converted to CO_2-eq using the following GW factors: CH_4: 25, N_2O: 298 (IPCC 2007). Since the production system under investigation does not rely on feed from outside the agricultural system, the LUC impact category was not taken into account. Soil carbon sequestration was excluded from the analysis. Biodiversity change assessment was also not included because it is challenging to assess biodiversity impacts based on the process data. The modelling of the product system and the calculation of environmental impacts were carried out using openLCA software, version 1.8 (GreenDelta 2018).

2.4.4 Uncertainty analysis

It is crucial to account for the variability in both the data used throughout the production system processes, as well as the underlying algorithms. Monte Carlo simulation was applied, in which a defined number of runs simulate a defined number of calculated outcomes for the applied environmental impact assessment. The Monte Carlo simulation is provided in openLCA. For all input streams in both scenarios, the standard deviation was taken into account, which was computed from data collected during the production period of 2010–2017. In addition, the standard deviation of the outputs (milk, heifers, and beef) was also taken into consideration. In this study, the analysis was conducted for 1000 iterations to show the distribution of the calculated outcomes for the selected impact categories of the high-input feeding regime at Gladbacherhof (status quo) and the modelled low-input feeding regime scenario.

3 Results and discussion

When interpreting results of the present study, it should be considered that the studied farm is representative for a European cold-climate organic dairy production system. Furthermore, it should be kept in mind that data collected at the Gladbacherhof represent a high-input feeding regime and that the low-input feeding regime was modelled. Figures 2, 3, 4, 5, and 6 show the environmental impacts of modelled low-input feeding scenario relative to those of the current high-input feeding regime for the milk production system at the farm. Results indicate that the contribution of low-input feeding to all five product-related impact categories is higher

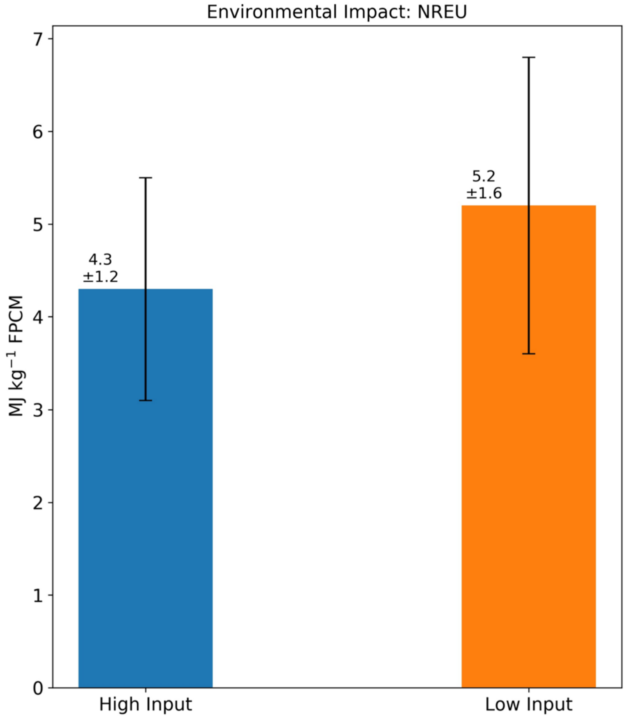

Fig. 3 Non-renewable energy use (NREU) contribution of high-input (status quo) and modelled low-input production system (scenario)

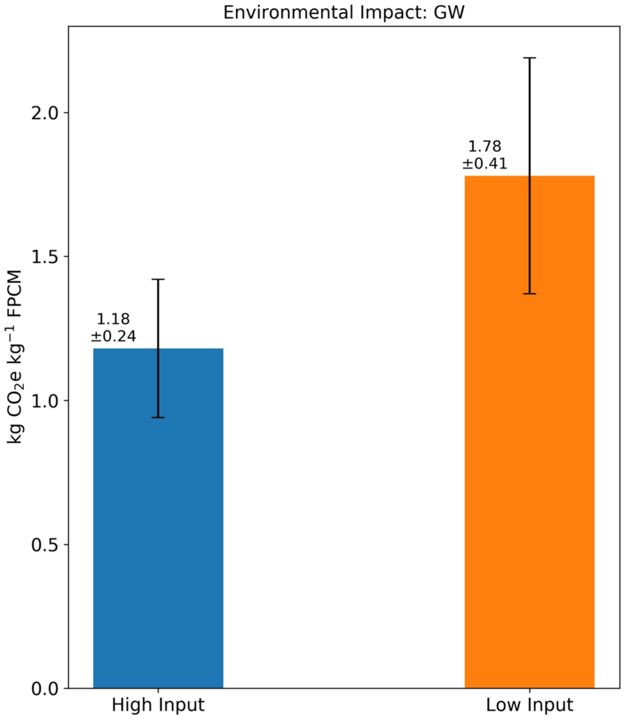

Fig. 2 Global warming (GW) contribution of high-input (status quo) and modelled low-input production system (scenario)

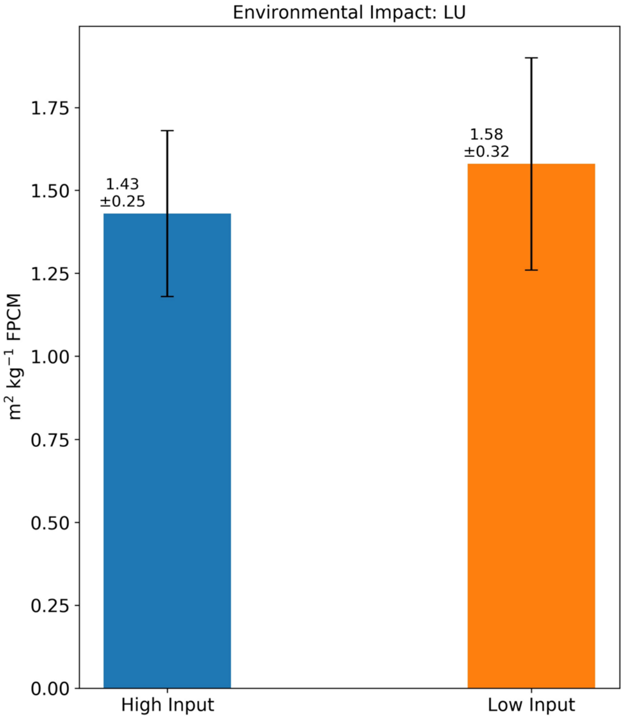

Fig. 4 Land use (LU) of high-input (status quo) and modelled low-input production system (scenario)

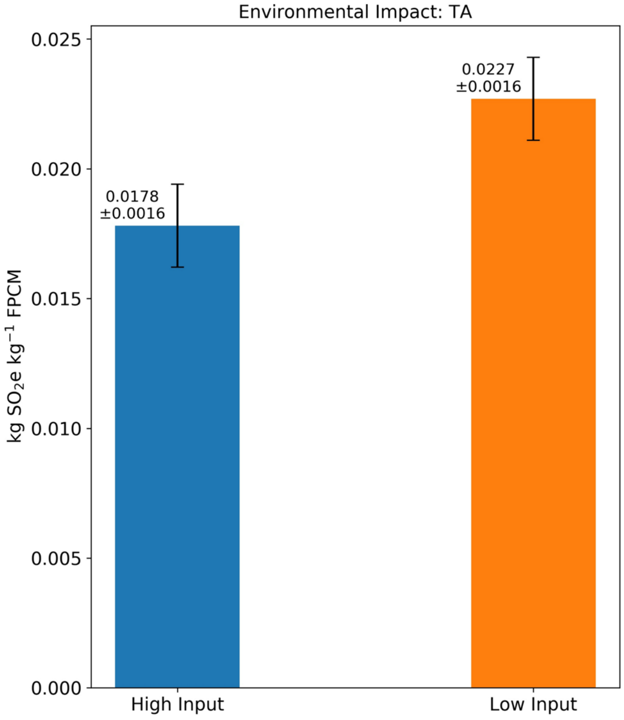

Fig. 5 Terrestrial acidification (TA) contribution of high-input (status quo) and modelled low-input production system (scenario)

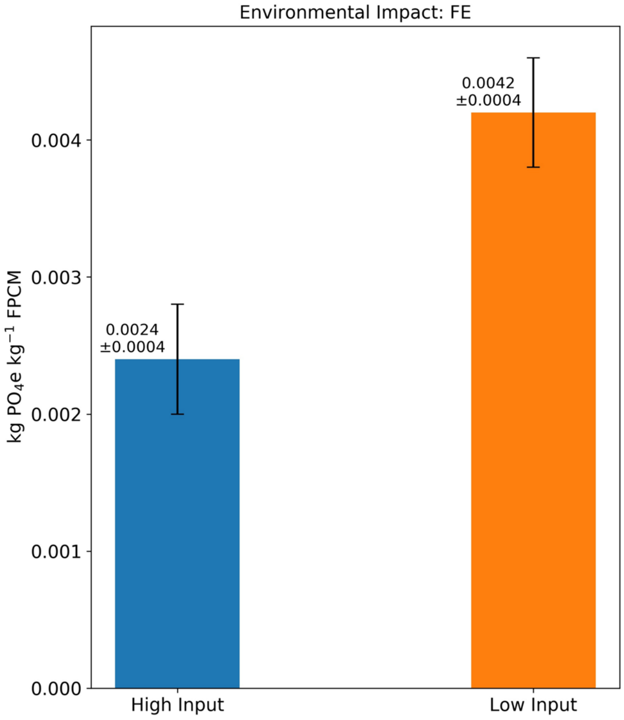

Fig. 6 Freshwater eutrophication (FE) contribution of high-input (status quo) and modelled low-input production system (scenario)

than that of high-input feeding regime. Therefore, we could not confirm the hypothesis of this study that switching from a high-input to a grassland-based low-input feeding regime will have a positive effect on the product-related environmental impact of organic milk production.

3.1 Global warming

In terms of the GW, the high-input feeding regime emits 1.18 ± 0.24 (mean ± standard deviation), whereas the low-input scenario emits 1.78 ± 0.41 kg CO_{2e} kg^{-1} FPCM (Fig. 2). Our results are in line with values reported in other studies of organic milk production systems ranging from 0.95 to 2 CO_{2e} kg^{-1} FPCM (Cederberg and Mattsson 2000; Weiske et al. 2006; Thomassen et al. 2008; Schader et al. 2014; Romano et al. 2021b). The main reason for observed differences between organic high- and low-input feeding regimes lies in the higher share of emissions generated from enteric fermentation and manure management for the low-input scenario (Table 4). We assume that the shift towards a grassland-based low-input scenario with reduced concentrate in the feed ration results in a mixture with lower digestibility, energy, and protein contents. In both production systems, feed production is a major contributor to the GW. The production of alfalfa and grass silage has a higher contribution to the GW kg^{-1} DM^{-1} feedstuff compared to the production of maize silage, when soil carbon sequestration is excluded from LCA. This can be attributed to the substantial yield of maize silage and the relatively higher machinery and diesel consumption required for the multiple cutting, swathing, harvesting as well as storage cycles of grass and alfalfa, which occur 4 to 5 times annually per hectare, in contrast to the single harvest of maize silage.

At Gladbacherhof, grazing is limited for half of the year due to the climatic conditions. The climatic conditions also affect the quantity and nutritional quality of the grassland (lower total dry matter amount and nutrient contents), which can be described as medium. When decreasing the concentrate content in the diet, the quality of all forages plays an important role in achieving high milk yields as reported by Loza et al. (2021). The authors showed that forage and grassland with higher quality could enhance milk yield and thus decrease environmental impact kg^{-1} FPCM. The meta-analysis conducted by Lorenz et al. (2019), which compared the carbon footprint of three dairy production systems, namely pasture-based, mixed, and confinement systems, concluded that there is no difference in the average carbon footprint values for 1 kg FPCM despite significant variation within each system. Regardless of the production system category, carbon footprint reduction can be achieved by increasing pasture intake and milk production per cow (Lorenz et al. 2019). It is crucial to consider that a great proportion of the emissions is attributed to enteric methane production, particularly in grazing systems where the enteric emissions account for over 50% of the total emissions (Reinsch et al. 2021; Mazzetto et al. 2022). For the low-input system at Gladbacherhof, the primary factor contributing to increased emissions could be the lower quality and availability of pastures during the summer seasons and the lower milk production. Lorenz et al. (2019) reported that when the cows are at the same production level, the low-input grazing system exhibits lower emissions, which was not the case in our study.

A great potential for mitigating GW lies in manure management, especially in manure application technology. Under favorable weather conditions, applying manure close to the ground or injecting it into the soil surface has the potential to decrease nutrient leaching and trace gas emissions. In our low-input scenario, the excreta may also be contributing to higher GHG emissions, since the cows spend more time grazing and depositing manure and urine directly on the soil, which increases the nitrous oxide production (Table 4) (Grossi et al. 2019). While in the confinement system, the slurry is stored in closed tanks, which reduces the total GHG emissions (Kupper et al. 2020).

The findings comprise the assessment of uncertainties presented as the standard deviations of the mean values (Fig. 2). Notably, it is unexpected that the uncertainties of the low-input scenario (0.41 CO_{2e} kg^{-1} FPCM) are nearly twice as high as those in the current milk production system (0.24 kg CO_{2e} kg^{-1} FPCM) at Gladbacherhof. This can be attributed to the higher variations of alfalfa and grass yields compared to those of maize silage.

3.2 Non-renewable energy use

The current high-input production system at Gladbacherhof consumes 4.3 ± 1.2 MJ kg^{-1} FPCM, whereas the low-input system needs 5.2 ± 1.6 MJ kg^{-1} FPCM (Fig. 3). The higher product-related energy consumption in the low-input scenario can be attributed to the steady and constant energy consumption for the housing and milking process, regardless of the amount of milk produced. The longer grazing period of the dairy herd reduces energy consumption in the low-input scenario. On the other hand, the increased amount of hay and alfalfa silage outweighs this benefit and ultimately leads to an overall increase in energy consumption for the low-input scenario. On dairy farms, the primary direct energy inputs are fuel consumption and electricity. Indirectly, crucial energy inputs involve the maintenance and operation of machinery, farm equipment, as well as the infrastructure of farm buildings and their associated equipment. The largest share of fossil energy consumption in dairy production is attributed to feed supply, which consists of activities such as cultivation, harvesting, and storage of feed (Cederberg and Mattsson 2000; Kraatz 2009; Gross et al. 2022). The milking process itself stands as the second largest source of energy consumption. Milk cooling also requires substantial amounts of energy. Previous studies investigating the energy consumption of organic milk production systems have reported a range of energy consumption between 1.2 and 6.3 MJ kg^{-1} FPCM (Haas et al. 2001; Thomassen et al. 2008; Flysjö et al. 2011). The difference can be attributed to the different approaches of dealing with indirect energy consumption. Indirect energy consumption is often excluded from such studies, and only direct energy consumption on the farm is taken into account. In this study, direct and indirect energy consumption are calculated and taken into account. This clarifies the relatively high energy consumption in both milk production systems. Nonetheless, the findings are within the range of what has been reported in other studies (Haas et al. 2001; Thomassen et al. 2008; Flysjö et al. 2011).

The standard deviation indicating uncertainties is relatively high, with 1.2 and 1.6 MJ kg^{-1} FPCM for the high- and low-input feeding regimes, respectively. Despite this variability, the differences between the two feeding regimes in the non-renewable energy input impact category are not statistically significant.

3.3 Land use

For LU, the deviation between the two investigated feeding regimes at Gladbacherhof is relatively small. The current high-input system requires an area of 1.43 ± 0.25 m^2 kg^{-1} FPCM, and the low-input scenario occupies 1.58 ± 0.32 m^2 kg^{-1} FPCM (Fig. 4). The total land requirement for the high-input system with an average of 8000 kg FPCM cow^{-1} $year^{-1}$ is 103 ha, whereas 91 ha are needed for the low-input scenario. Given that the yield levels (calculated as an average over the period of 2010–2017) are presumed to be the same for all crops and grassland in both production systems, only the alteration in feed components and their respective dietary ratios affects land use. In the high-input system, faba beans constitute over 35% of the concentrate feed. Due to the changed ratio of faba beans and cereals in the low-input system, less protein and more energy are required to formulate a balanced diet. Consequently, the concentrate in the low-input scenario contains a reduced amount of faba beans and a higher proportion of wheat. The increased land use in the high-input system could be attributed to the average wheat yields, which are twice as high as those of faba beans. Previous literature has reported results ranging from 1.3 to 3.5 m^2 kg^{-1} FPCM (Cederberg and Flysjö 2004; Thomassen et al. 2008; Nemecek et al. 2011; Verduna et al. 2020), indicating that our results are within this range, but relatively low compared to other organic dairy studies systems. This can be explained by the favorable pedo-climatic conditions at Gladbacherhof, which create good prerequisites for producing forage and concentrate feed from arable land.

Two important aspects that should be taken into account in LCAs are the impacts following changes in land use, and a potential competition between food for humans and feed for animals. This is an important aspect when evaluating long-term sustainability of organic dairy systems. As the global population continues to grow, the demand for food increases, and the pressure on land use intensifies. To address this issue, there is a need to shift towards more sustainable land use practices that prioritize the production of food for human consumption.

The uncertainty in land use is relatively high for both production systems. The standard deviation is 0.25 and 0.32 m^2 kg^{-1} FPCM for the high- and low-input feeding regimes, respectively. The relatively high standard deviation in both production systems can be attributed to the fluctuations in crop yields during the 8-year observation period.

3.4 Terrestrial acidification

TA is 0.0178 ± 0.0016 and 0.0227 ± 0.0016 kg SO_{2e} kg^{-1} FPCM for the high- and low-input regimes, respectively (Fig. 5). Acidification is mainly caused by SO_2, NO_x, HCl, and NH_3 emissions when combined with other molecules (Audsley et al. 1997). Our results are in line with previous studies of organic milk production systems in Western Europe, ranging from 0.01 to 0.022 kg SO_{2e} kg^{-1} FPCM (Cederberg and Mattsson 2000; Haas et al. 2001; Cederberg and Flysjö 2004; Thomassen et al. 2008). The major contributor to the acidification potential of milk production are NH_3 emissions (De Boer 2003). NH_3 mainly originates from handling, storage, and application of manure. Given that the handling and storage of manure are presumed to be the same for both production systems, only variations in manure quantity and milk yield can account for the difference in TA. Feed production has a marginal effect on TA in both feeding regimes at Gladbacherhof.

The uncertainty analysis shows low values for both production systems in this impact category. The maximum value of the high-input system is still lower than the minimum value of the low-input scenario indicating a remarkable difference for the TA impact category.

3.5 Freshwater eutrophication

For this category, the results are 0.0024 ± 0.0004 and 0.0042 ± 0.0004 kg PO_{4e} kg^{-1} FPCM for the high- and low-input feeding regimes, respectively (Fig. 6). The product-related emissions of the low-input scenario are almost twice as high as those of current milk production system at Gladbacherhof. The most important reasons are probably the longer grazing period and consequently higher nutrient inputs from cow urine in the low-input scenario. Our values are however relatively low in comparison to previous studies, in which the emissions ranged from 0.0032 to 0.0071 kg PO_{4e} kg^{-1} FPCM (Arsenault et al. 2009; Capper et al. 2009; Gac et al. 2010; Djekic et al. 2014). In previous studies, which compared conventional with organic milk production, higher FE was often reported in the conventional systems (Haas et al. 2001; De Boer 2003; Thomassen et al. 2008). This was mainly due to the use of phosphate and nitrogen fertilizers, as well as the use of concentrate feed introduced into the system. These studies also addressed the transfer of nutrients from the animal to the soil, but with a smaller impact than the use of phosphate and nitrogen fertilizers (Haas et al. 2001; Thomassen et al. 2008).

Calculated uncertainties are relatively low in this impact category. The maximum value of the high-input system is still lower than the minimum value of the low-input scenario, confirming a remarkable difference for the FE impact category.

3.6 Limitations and future research

In this study, it was not possible to directly compare a high-input and low-input feeding regime based on comprehensive measured data because the infrastructural conditions to run booth regimes in parallel on the farm were not available. However, we are optimistic about future prospects for addressing this limitation through the ongoing GreenDairy research project at Gladbacherhof. This project aims to facilitate future comparative experiments and provide real farm data for both high-input and low-input feeding regimes in organic dairy farming. The GreenDairy experiment operates on two independent herds under similar conditions, allowing for a thorough analysis of matter flow, encompassing compounds not just within the barn but also considering manure management and feed production.

Additionally, while our study utilized the standards and methodologies prevailing at the time of data collection, we recognize that adherence to the updated 2022 LCA guidelines would enhance comparability with other studies. The calculations for this study were performed prior to the release of these guidelines, which limits the comparability of our absolute values to other LCAs that have adopted the newer standards. Nevertheless, our primary objective was to conduct a relative comparison between the high- and low-input scenarios to assess the differential impacts of each system. This approach effectively addressed our research question and served as a scientific basis for the GreenDairy project, which began in 2022.

Another limitation of our study is the exclusion of soil carbon stocks, which are known to play a significant role in the environmental impact of agricultural systems. Crop cultivation, particularly maize cropping, causes a loss of soil organic carbon, while grassland usually maintains high soil carbon stocks. Including soil carbon stock data would provide a more comprehensive understanding of the environmental impacts. Future research should aim to incorporate these factors to better assess their influence on overall sustainability outcomes.

Moreover, while we utilized the same crop rotation for both high- and low-input systems, we recognize that this does not account for the potential differences in manure composition and quality resulting from the different feeding regimes. The impact of these differences on crop productivity and overall system performance was not considered. This is an important factor that could influence the environmental outcomes and is now being investigated in our GreenDairy project.

To scale up the study and draw broader conclusions, it is essential to conduct direct comparisons involving a larger number of organic farms that represent both high- and low-input feeding regimes. Additionally, there is a substantial knowledge gap concerning the effects of different intensity levels of organic dairy production systems on various ecological aspects such as biodiversity, economics, and animal welfare. Addressing this knowledge gap will be a critical focus of future research endeavors.

4 Conclusions

First, it should be considered that the studied farm is representative for a European cold-climate organic dairy production system, and second, that data collected at the Gladbacherhof represent a high-input feeding regime and the low-input feeding regime was modelled. Nevertheless, the data collected over the period from 2010 to 2017 can be considered as representative for this type of organic dairy system in Central Europe. The feeding intensity influences the environmental impact of milk production systems. This LCA study of an organic farm in Central Germany indicates that a grassland-based low-input feeding regime with alfalfa grown on arable land can have a higher product-related environmental impact compared to a high-input feeding regime. The higher environmental impact per kg FPCM of the low-input scenario is attributed to the reduction in concentrates and the exclusion of maize silage from the diet, leading to a decrease in milk yield by 20%. Conversion to a low-input system requires higher amounts of hay, alfalfa, and grass silage to maintain a sufficient energy intake. This results in higher emissions from enteric fermentation, manure management, and feed production and consequently higher environmental impact, particularly for GW, TA, and FE.

The assessment methods used in this study were able to capture the general characteristics of organic production. However, there is room for methodological advancements. Future assessments could benefit from more detailed modelling of crop rotations, manure management variations, and their effects on soil carbon stocks. Additionally, incorporating data that are more recent and integrating real-time experimental results from ongoing projects like GreenDairy would enhance the accuracy and relevance of the findings. Addressing these aspects will improve the ability to capture the complex dynamics of organic dairy farming and contribute to the development of more sustainable agricultural practices.

Notably, this study is among the few that directly compares the environmental impacts of high-input feeding regime with a modelled grassland-based low-input feeding regime within an organic dairy production system. Building on these findings, further research questions arise: What would be the outcomes if both feeding systems were studied simultaneously in a field research setting, where real data from both high- and low-input systems are collected, instead of using the low-input feeding regime as a scenario only? Would we observe similar GW values for each feeding regime, or would there be differences in carbon sequestration and soil fertility? Exploring these questions could provide deeper insights into optimizing dairy production systems for sustainability and reduced environmental impact.

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Author contribution Johannes Eisert: conceptualization, methodology, data curation, formal analysis, software, writing—review and editing. Amir Sahraei: writing—original draft, writing—review and editing. Deise Knob: writing—review and editing. Christian Lambertz: writing—review and editing. Werner Zollitsch: conceptualization, methodology, supervision, validation, writing—review and editing. Stefan Hörtenhuber: data curation, methodology, visualization. Iris Kral: software, methodology, data curation, validation. Lutz Breuer: supervision, funding acquisition, project administration, writing—review and editing. Andreas Gattinger**:** supervision, funding acquisition, project administration, writing—review and editing.

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Declarations

Conflict of interest The authors declare no competing interests.

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