



An LCA-based approach to integrate drained peatland emissions into the carbon footprint of dairy production: a case study from the pre-alpine region of Southern Germany

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Received: 11 August 2025 / Accepted: 6 November 2025
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Abstract

Purpose Current life cycle assessments (LCAs) of milk production often underestimate environmental impacts by overlooking significant greenhouse gas (GHG) emissions from drained peatlands. This study applied a novel approach to quantify the contribution of GHG emissions from drained peat soils to the carbon footprint (CF) of milk production in German pre-alpine dairy farms, addressing this critical knowledge gap.

Methods Carbon footprints (CFs) of milk production were calculated for three distinct dairy farms in Southern Germany, both with and without the inclusion of peatland emissions. Three methodological approaches were applied for emission quantification: (i) IPCC Tier 1, (ii) implied emission factors (EFs) from German national inventory reporting, and (iii) water table depth (WTD)-dependent response functions. A near-natural peatland reference scenario was also developed for contextualization.

Results and discussion Results reveal that peatland emissions are a highly significant contributor, more than doubling average milk CFs at farm-level. A positive correlation was found between the extent of drained peatland area and carbon emissions, with the CF from drained peat soils being 3 to 6.5 times higher than those from mineral soils if the entire farm area was located on drained peat soil (i.e., 'under full peatland drainage'). The chosen methodology significantly influenced CFs, where WTD-dependent approaches consistently yielded higher GHG estimates.

Conclusions These findings underscore the crucial importance of incorporating peatland emissions into dairy LCA studies for accurate environmental assessments. They highlight the urgent need for targeted mitigation strategies, especially water table (WT) management, to effectively reduce agriculture's climate impact.

Recommendations Future research and policy should prioritize developing and implementing effective WT management techniques. Encouraging the integration of peatland emission data into standard agricultural LCA methodologies is also vital to generate realistic and complete and to drive sustainable practices.

Keywords LCA · GHG emissions · Milk production · Drained peatland emissions · Water table management

Communicated by Thomas Jan Nemecek

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Abbreviations

AI	Artificial Intelligence
C	Carbon
CF	Carbon Footprint
CH ₄	Methane
CO ₂	Carbon Dioxide
CO ₂ -eq	CO ₂ equivalents
EF	Emission Factor
FU	Functional Unit
FPCM	Fat and Protein Corrected Milk
GBR	Gradient Boosting Regression
GHG	Greenhouse Gas

GWP	Global Warming Potential
LCA	Life Cycle Assessment
LMC	Land Management Change
LU	Land Use
LUC	Land Use Change
MCF	Methane Conversion Factor
N	Nitrogen
N ₂ O	Nitrous oxide
WT	Water Table
WTD	Water Table Depth

1 Introduction

Climate change is one of the most pressing global challenges, with greenhouse gas (GHG) emissions from agriculture playing a significant role in its progression. Global food production is responsible for approximately 10%–12% of anthropogenic GHG emissions, with livestock farming being a major contributor (Tubiello et al. 2021). An often overlooked but highly impactful factor are drained peatlands. Despite covering only a small percentage of land area, they rank among the largest agricultural and forestry-related emission sources in many European countries (Drösler et al. 2008; Tubiello et al. 2016).

Germany has approximately 1.8 million hectares of peatlands, of which around 95% have been drained, leading to significant carbon dioxide (CO₂) emissions (Tanneberger and Belous 2017; Wichmann and Nordt 2024). This phenomenon is especially pronounced in cattle dairy farming, as peatland drainage is predominantly used for grassland cultivation for feed production, thus strongly affecting dairy production. While the number of dairy farms in Germany varies greatly between the federal states, almost half of them (46% in 2023) are located in Bavaria (BLE 2024; Destatis 2024; Lfl 2024). Bavaria is characterized by higher milk production compared to other parts of Germany, with the highest rates found in the pre-alpine region of Bavaria, where dairy farming heavily relies on grasslands as dominant land use (LU) for feed production. In Bavaria, 220,000 hectares of peatlands exist, of which today almost 95% are drained for agriculture and forestry and nearly 50% are used as grasslands (Drösler 2024; Nitsch and Schramek 2021). The drainage of peat soil leads to aerobic decomposition and associated GHG emissions in Germany have been estimated to account for 53–55 Mt CO₂ equivalents (CO₂-eq) per year, contributing to at least 6.7% of total emissions nationwide (Tiemeyer et al. 2020).

These substantial emissions from the dairy sector represent a major opportunity for reducing GHG emissions. With dairy products playing an important role in human nutrition as well as being of high economic value, suitable mitigation

strategies to reduce emissions are needed. In response, various regulations have been introduced to monitor and mitigate these emissions. The German Climate Protection Act (Klimaschutzgesetz (KSG)) aims to reduce emissions from the agricultural sector by 10% by 2030 compared to 2020 baseline levels.

Life Cycle Assessment (LCA) is a widely used tool to quantify the environmental impact of agricultural products, such as milk production (Dijkman et al., 2018; van Der Werf et al. 2020) and represents one method frequently used to estimate the carbon footprint (CF) of production systems. Hereby, production is considered in terms of relative impact per unit of product, such as one kilogram or liter of milk (Gross et al. 2022; Yan et al. 2011).

However, several challenges contribute to uncertainties in emission calculations, including data availability, missing standardized guidelines, as well as the omission of emissions from soil organic carbon (SOC) stock changes (Müller et al. 2025; Yan et al. 2011). The discrepancy between LCA reporting and the UNFCCC (United Nations Framework Convention on Climate Change) framework, where soil and peatland emissions are accounted for under the LULUCF (Land Use, Land-Use Change, and Forestry) sector, further complicates accurate emission assessments (Müller et al. 2025; Protocol 1997; Watson et al. 2000).

Accounting for GHG emissions resulting from peatland drainage represents an indispensable factor in the calculation of the CF of milk production (Müller et al. 2025). Thus, more targeted research on drainage-based dairy systems is needed to translate estimated emissions into a precise multiplier effect on milk's CF. Against this background, this study aims to quantify the influence of peatland-derived emissions in dairy farming by calculating the CF of different farms in the pre-alpine region of Southern Germany (S-Germany) with and without accounting for emissions from drained peatlands in the respective LCA. The objectives of this study are (i) to assess the importance of peatland emissions for the overall carbon footprint of dairy production (ii) to analyze the influence of different approaches for accounting peatland emissions and (iii) to provide insights into potential mitigation strategies for reducing the climate impact of dairy farming.

By addressing these aspects, this research seeks to enhance transparency in CF calculations and to provide a more comprehensive understanding of dairy farming's role in agricultural GHG emissions.

2 Methods

In this study, the impact of agricultural use of peatland soils in dairy systems was evaluated in terms of its global warming potential (GWP) by applying a LCA approach. The following sections describe the different dairy farms considered, LCA methods, goal and scope of the study as well as the collected data.

2.1 Scope of the study

2.1.1 Dairy farm description

For the present study three different dairy farms in the pre-alpine region of S-Germany were assessed. For a detailed inventory, data was obtained from surveys and farm visits, with the year 2020 as baseline. Total on-farm land varies between 50 ha of an extensive dairy farm up to 120 and 130 ha on intensive dairy farms. All production systems show a dominant share of grassland and pastures, with a considerable proportion on drained peatlands. Average annual milk productivity per cow was 7174 L in the extensive and between 10,120 and 10,177 L in the intensive systems. Key characteristics of the analyzed farms are shown in Table 1.

2.1.2 System boundaries and functional unit

In the present study, the functional unit (FU) used is 1 kg of fat and protein corrected milk (FPCM), whereby milk yield was corrected to 4.0% of fat and 3.3% of protein according to FAO (2016).

Data were selected in a timeframe of 12 months from every farm, which was set as the time boundary commonly used for the evaluation of milk production. The system boundaries for the assessment were defined using a “cradle-to-gate” perspective. This means that processes after the farm gate (such as the transport of raw milk and subsequent milk processing) were excluded. The assessment therefore includes all life cycle processes, from resource extraction up to the point when the raw milk leaves the farm. Specifically, the included processes cover off-farm activities (e.g., fuel, energy and feed production including transport to the farm) and on-farm activities (e.g., feed production, animal husbandry, manure management and emissions from drained peatlands) (Fig. 1).

Medicines, equipment, machinery and buildings were excluded from the assessment, as they are considered not relevant for the present study.

2.1.3 Allocation of co-products

Dairy cattle farms are multifunctional systems, thus although the main purpose is milk production, co-products are obtained such as meat from calves and culled cows. To estimate the environmental impact of the product analyzed in the study, the overall impacts have to be distinguished between the products of the system’s output (i.e. milk and meat). For this purpose, biophysical allocation was used following the FAO (2016) guidelines for LCA studies (FAO, 2016).

Table 1 Main characteristics of the dairy cattle farms analyzed in the study

Farm structure			
	Farm 1	Farm 2	Farm 3
Total on-farm land (ha)	50	120	132
Arable cropland (ha)	0	11	30
Pastures and meadows (ha)	44	28	57
Drained peatlands (ha)	6 (12.0%)	81 (67.5%)	45 (34.0%)
Herd characteristics			
	Farm 1	Farm 2	Farm 3
Breed	Simmental cattle*	Simmental cattle*	75% Simmental cattle* and 25% Jersey cattle
Number of dairy cows	42	123	275
Replacement rate (%)	14.3	30.4	23.5
Milk yield (liter milk/cow/yr)	7,174	10,177	10,120
Grazing time (months/yr)	7	0	5

*Simmental cattle (also known as Fleckvieh) are a prominent dual-purpose breed, highly typical and widespread in Southern Germany, particularly in Bavaria, due to their robust nature and suitability for both high-quality milk and meat production

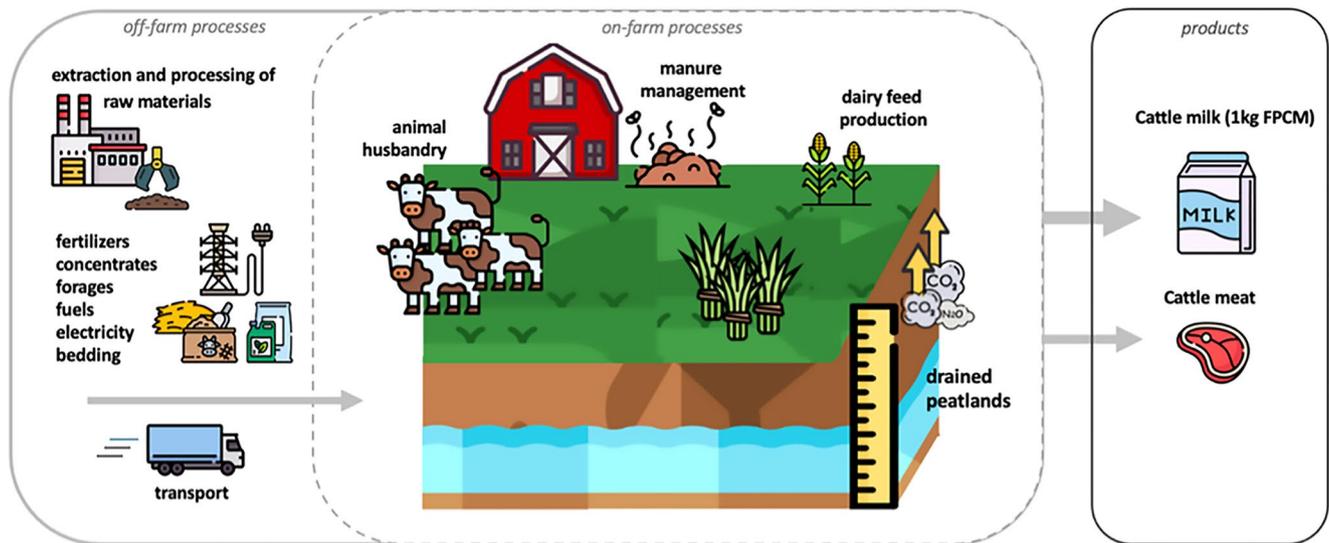


Fig. 1 System boundaries for cattle milk production and main emission sources at on- and off-farm level. FPCM: Fat and Protein Corrected Milk

Table 2 Main input and output flows of the farms analyzed

Inputs			
	Farm 1	Farm 2	Farm 3
Concentrates (kg DM/cow/yr)	0	1,095	1,8780
Fodder bought (total kg/yr)	0	639,000	1,074,000
Electricity (kWh/yr)	27,500	75,000	65,000
Diesel (liter/yr)	3,500	24,000	45,000
Mineral fertilizer (kg N/yr)	1,290	2,912	7,938
Outputs			
	Farm 1	Farm 2	Farm 3
Milk (kg FPCM/yr)	306,568	1,273,623	2,831,582
Meat (kg liveweight/yr)	4,368.65	278,612.6	45,061.25

2.2 Life cycle inventory analysis

2.2.1 Farm inputs and outputs

For a detailed farm inventory, farms were analyzed by field investigation and surveys, providing information about general farms' characteristics, management and the main input and output flows. The surveys covered all information on relevant input flows such as manure management, animal husbandry, feed management, concentrate composition, electricity and fuel consumption as well as the outputs, which are milk as the main product and meat as a co-product. An overview of the main input and output flows of the three different farms are shown in Table 2. Based on the collected data, two LCA models for each farm were set-up (i) with and (ii) without including emissions from grasslands on drained peat soils that were compared.

2.2.2 Estimation of emissions

Methane (CH_4) emissions from enteric fermentation were estimated using the Tier 2 approach outlined in the latest IPCC (2019) guidelines. Through farm surveys data of feed type and composition were collected. Gross energy (GE) was determined based on the estimated energy requirements of the animals as well as diet digestibility, while feed intake was derived from GE and feed energy density. CH_4 emissions from enteric fermentation were then calculated by applying a methane conversion factor (Y_m) of 6% for dairy cows. Emissions from manure management were also estimated following the IPCC (2019) guidelines. Manure management systems on the studied farms included solid storage, liquid slurry, and anaerobic digestion (only in Farm 3). Corresponding methane conversion factors (MCFs) were applied based on a warm temperate moist climate, with 2% for solid storage. For liquid slurry, MCFs of 24% and 29% were used in farms 1 and 2 respectively, according to the actual storage duration (3 and 4 months). For anaerobic digestion in farm 3, an MCF of 1% was assumed, reflecting best available technology, involving low leakage and high-quality gastight conditions.

Nitrous oxide (N_2O) emissions were calculated based on the nitrogen (N) excretion rate using IPCC (2019) methods. Direct N_2O emission factors of 1% for solid storage, 0.5% for slurry and 0.1% for anaerobic digestion were applied for manure management. For direct N_2O emissions from managed soils, a default emission factor of 0.016 kg N_2O -N/kg N (or 1.6%) was applied for N from mineral fertilizers, assuming conditions applicable to wet climates as per IPCC (2019) refined Tier 1 guidance. Indirect N_2O emissions, along with ammonia (NH_3) and nitrate (NO_3^-) losses, were

estimated using the Tier 1 approach from IPCC (2019). This includes indirect emissions resulting from atmospheric deposition of volatilized N (e.g., from manure management and fertilizer application), and from leaching and run-off of N from managed soils.

To account for off-farm emissions, purchased feed inputs (such as concentrates, grains, and forages) and bedding materials were evaluated across their full life cycle, from agricultural production to processing and transportation to the farm. These emissions were calculated using the Agri-footprint v4.1 database (Blonk Agri-footprint BV, 2019). Additionally, emissions from on-farm fuel consumption as well as electricity use were estimated using the Ecoinvent 3.3 (2016) database. Avoided GHG emissions of electricity production from anaerobic digestion were estimated considering average emissions of 314 CO₂-eq/kWh in Germany during 2020 (Nowtricity.com; Assessed May 2024). Land use change (LUC) emissions related to external feed inputs were included using Agri-footprint datasets, with calculations supported by the PAS 2050–1 Land Use Change Assessment Tool, utilizing historical LU data from FAOSTAT (FAO, 2016).

2.2.3 Emissions from drained peatlands

Peatlands, when drained for agricultural use such as grasslands, become significant sources of GHG emissions, primarily CO₂, N₂O and CH₄ (Mander et al. 2024; Tanneberger et al. 2020). These emissions mainly result from lowering of water table depth (WTD), soil aeration, and consecutive aerobic organic matter decomposition, as well as anaerobic organic matter decomposition in drainage ditches (Tiemeyer et al. 2024). In order to assess potential uncertainty in emission estimates, three different approaches have been explored (a) the IPCC methodology, (b) the methodology developed by Tiemeyer et al. (2020) and (c) WTDs-specific EFs (Tiemeyer et al. 2020). Moreover, to provide a comprehensive assessment and contextualize these emissions against a natural background (Pardo et al. 2024), a near-natural state peatland reference scenario was established, and its calculated emissions were subtracted from the results of each of the aforementioned three approaches.

Addressing the specific nature of peat soil loss is crucial for accurate LCA. Unlike conventional direct LUC emissions, which typically amortize a one-time C stock loss over years, emissions from drained peatlands represent a continuous Land Management Change (LMC) process (Müller et al. 2025). Aerobic decomposition continues at a high annual rate for the entire duration of the drainage, making the standard 20-year amortization period unsuitable and scientifically inconsistent with the long-term C loss dynamics.

Consequently, the calculated emissions for each method (IPCC Tier 1, Tiemeyer et al. (2020), WTD-specific EFs)

were treated as continuous annual emissions and were fully integrated into the life cycle inventory of the respective reporting year. This approach ensures that the significant and persistent climate impact of farming on peat soils, which often becomes the dominant emission source in dairy (Müller et al. 2025) is fully captured. The final annual impact attributed to the drained peatland was then allocated to the functional unit (FPCM) using biophysical allocation, consistent with LCA standards for co-products (milk and meat).

a) IPCC default approach.

The IPCC provides a tiered approach for estimating emissions from drained peatlands in its 2013 Wetlands Supplement (Hiraishi et al. 2014). This methodology is designed to estimate emissions based on LU and management practices and includes default values for emission factors (EFs) as well as country-specific data for higher-tier approaches (IPCC, 2013). With the Tier 1 approach default EFs are used for emission estimation of CO₂, CH₄ and N₂O for drained peatlands. EFs are based on land use typology as well as on the climate zone. Calculating the emissions for drained peatland with grassland cultivation, simply the drained peatland area (ha) is multiplied with the respective EFs of CO₂, N₂O and CH₄ (IPCC, 2013):

$$\text{CO}_2 \text{ emissions (t/yr)} = \text{EF}_{\text{CO}_2} \times A$$

$$\text{N}_2\text{O emissions (t/yr)} = \text{EF}_{\text{N}_2\text{O}} \times A$$

$$\text{CH}_4 \text{ emissions (t/yr)} = \text{EF}_{\text{CH}_4_{\text{land}}} \times A + \text{EF}_{\text{CH}_4_{\text{ditches}}} \times A$$

With EF_{CO₂} and EF_{N₂O} and EF_{CH₄ land} and EF_{CH₄ ditches} as default EFs for CO₂, N₂O and CH₄ (land surface emissions) based on climatic zone and land use and A as the area of drained peatland in hectares (ha).

For the emission calculations of the drained peatland area, we refer to the Tier 1 approach outlined by the IPCC 2013 Wetlands Supplement (Hiraishi et al. 2014). In this context, the default EFs for nutrient-rich drained grasslands in a temperate climatic zone is applied (Table 3, top), representing typical values for drained grasslands in temperate regions, which have been heavily influenced by agricultural practices and land management (Hiraishi et al. 2014). For CH₄ emissions, both land surface and drainage ditch emissions are considered (Table 3) (Hiraishi et al. 2014).

b) Implied national emission factors by Tiemeyer et al. 2020.

The methodology developed by Tiemeyer et al. (2020) offers a detailed approach for estimating GHG emissions from drained organic soils, including those used as grasslands (Tiemeyer et al. 2020). This approach, applied for Germany's national GHG inventory, is designed to account

Table 3 Default EFs according to the IPCC 2013 supplemental for wetlands regarding drained nutrient-rich grasslands in temperate climatic zones and implied EFs for grassland according to Tiemeyer et al. (2020)

Default emission factors according to the IPCC 2013 supplemental for wetlands	
CO ₂ -C (t C ha ⁻¹ yr ⁻¹)	6.1
CH ₄ _{land} (kg CH ₄ ha ⁻¹ yr ⁻¹)	16
CH ₄ _{ditches} (kg CH ₄ ha ⁻¹ yr ⁻¹)	58.25*
N ₂ O-N (kg N ha ⁻¹ yr ⁻¹)	8.2
Implied national EFs for grassland (Tiemeyer et al. (2020))	
CO ₂ -C _{organic} (t C ha ⁻¹ yr ⁻¹)	8.0
CH ₄ _{organic} (kg CH ₄ ha ⁻¹ yr ⁻¹)	21.7
N ₂ O-N _{organic} (kg N ha ⁻¹ yr ⁻¹)	4.2

*The CH₄ EF for drainage ditches is calculated by multiplying the IPCC Tier 1 default EF (1165 kg CH₄ ha⁻¹ yr⁻¹) by the indicative default ditch area fraction (0.05) for deep-drained grassland to express the emission on a total peatland area basis

for the variability in emissions based on LU, modelled WTD, and soil type. While the IPCC's Tier 1 method relies on default EFs based on broad LU categories, the approach by Tiemeyer et al. (2020) provides more refined EFs by specifically incorporating the distribution of spatial high-resolution modelled WTDs within each LU type, allowing for site-specific emission estimates based on WTD response functions (Tiemeyer et al. 2020). Emissions are primarily derived from a set of non-linear response functions that describe the dependency of CO₂ and CH₄ fluxes on the WTD, classified by the respective LU. These functions allow for the estimation of emissions based on WTD at a given site, taking into account the variability of emissions due to changing water levels and different LUs (Tiemeyer et al. 2020). For example, CO₂ emissions increase significantly as the water table (WT) is lowered, exposing more organic matter to aerobic decomposition. In contrast, CH₄ emissions are highly sensitive to shallow WTDs where anaerobic conditions prevail and facilitate CH₄ production. For N₂O no significant relationship between emissions and WTD was found, thus average EFs based on observed fluxes for different LU categories were used.

To provide so-called "implied EFs" (aggregated GHG EFs) as shown in Table 3, the site-specific emission estimates derived from these non-linear response functions and average N₂O factors are aggregated across all organic soils in Germany. This comprehensive aggregation process incorporates the frequency distribution of WTD within each LU category, accounts for the uncertainty of the response functions, and includes further GHG sources like CH₄ from drainage ditches (for which IPCC default EFs were used) (Tiemeyer et al. 2020). The result is a single, nationally representative "implied EF" for each LU category, integrating all complex calculations and sources, which can then be directly multiplied by the total area of the respective LU

Table 4 Coefficients of the fitted Gompertz function for LU category grassland (Tiemeyer et al. 2020)

Coefficients	CO ₂ -C _{min} (t C ha ⁻¹ yr ⁻¹)	CO ₂ -C _{diff} (t C ha ⁻¹ yr ⁻¹)	a	b(m ⁻¹)
Grassland	-0.93	11.00	7.52	12.97

category to determine total national emissions (Table 3) (Tiemeyer et al. 2020).

c) Water table dependent response functions by Tiemeyer et al. (2020)

In the methodology developed by Tiemeyer et al. (2020), the estimation of GHG emissions from drained peatlands is improved by incorporating regional WTDs into the response functions (Tiemeyer et al. 2020). WTDs are crucial in determining CO₂ and CH₄ emissions, as they influence soil aeration, the decomposition of organic matter, and are particularly relevant for CH₄, the development of anaerobic conditions (Tiemeyer et al. 2020). To achieve more accurate GHG estimations, regional WTD data are integrated into non-linear response functions for both CO₂ and CH₄ emissions. This approach allows emissions to be estimated based on site-specific conditions rather than relying on default EFs, providing more precise calculations tailored to each region's characteristics (Tiemeyer et al. 2020).

The response functions developed by Tiemeyer et al. (2020) are used to estimate GHG emissions from drained peatlands under grassland LU, considering the mean annual region-specific WTD. For CO₂ emissions, the Gompertz function is applied:

$$\text{CO}_2 - \text{C}(\text{WT}) = \text{CO}_2 - \text{C}_{\text{min}} + \text{CO}_2 - \text{C}_{\text{diff}} e^{-ae^{b\text{WT}}}$$

Where:

- CO₂-C_{min} is the lower asymptote for CO₂ emissions (t C ha⁻¹ yr⁻¹),
- CO₂-C_{diff} is the difference between the upper and lower asymptote (t C ha⁻¹ yr⁻¹)
- a and b are fitting parameters related to the displacement along the x-axis and growth rate, respectively
- WTD is the mean annual water table depth (m)

The following table shows the coefficients of the fitted Gompertz function for on-site CO₂-C emissions from organic soils for the LU category of grassland that were used together with the respective WTD (Table 4).

For CH₄ emissions, an exponential function by Tiemeyer et al. (2020) is used:

$$\text{CH}_4(\text{WT}) = \text{CH}_{4\text{min}} + ce^{-d\text{WT}}$$

Where:

- CH₄_{min} is the lower asymptote for CH₄ emissions (kg CH₄ ha⁻¹ yr⁻¹),

- c and d are fitting parameters
- WTD is the mean annual water table depth (m)

Table 5 shows the coefficients for the CH₄ response functions for land emissions from organic soils under grassland use that were applied with the respective WTD (Table 5).

The above-described functions allow for more accurate GHG estimates by incorporating region- or even farm-specific WTD values, providing better emissions predictions for grassland areas on drained peatlands. To achieve a high degree of site-specificity, the mean annual WTD for each individual farm is required. As no direct WTD measurements are available for the farms, the necessary annual mean WTD values for the year 2020 were obtained from a high spatial resolution modeling approach for peatland water levels developed by Friedrich (2025). This model uses gradient boosting regression (GBR), an artificial intelligence (AI) method, to regionalize point-based WTD measurements across peatlands in Bavaria, resulting in annual mean WTD values (Friedrich 2025). GBR is an ensemble learning technique that minimizes prediction errors, enabling highly accurate, spatially explicit estimates (Friedman, 2001; Friedrich 2025). These farm-specific WTD values were then used as the primary input (WTD) in the Tiemeyer et al. (2020) response functions to calculate the site-specific EFs for CO₂ and CH₄ for each farm.

This approach significantly improves the spatial resolution of estimations compared to broad regional averages, thus enabling the precise application of the WTD-dependent response functions.

The new EFs obtained for WTD-dependent CO₂ and CH₄ emissions (Table 6) were applied for the specific farms for CF calculations in the respective LCAs. As for N₂O no significant relationship between emissions and WTD was found, average EFs based on observed fluxes for different LU categories were used (Table 6).

d) Consideration of baseline emissions from intact peatlands.

To ensure the LCA only accounts for emissions linked to farming, a reference scenario representing the natural GHG fluxes from intact peatlands was established. The fluxes from this natural baseline were subtracted from the total emissions of the drained peatlands to determine the net anthropogenic impact of the agricultural activity. While intact peatlands are widely considered climate-neutral or climate-cooling in the long-term, particularly for CO₂ due to balanced uptake and release over long time scales, they naturally emit CH₄ due to anaerobic conditions (Drösler 2024; Drösler et al. 2008; Frohling and Roulet 2007; Tanneberger et al. 2021b). Given the absence of specific, nationally representative measured baseline EFs for intact peatlands in Germany, annual GHG emissions for this reference scenario were calculated using the WTD-response functions by

Table 5 Coefficients of the CH₄land response functions for LU category grassland (Tiemeyer et al. 2020)

Coefficients	CH ₄ min (kg CH ₄ ha ⁻¹ yr ⁻¹)	c (-)	d(m ⁻¹)
Grassland	3.5	17,055	-42.3
Rewetted unutilized organic soils	1.3	292	-5.6

Table 6 Mean annual water table depths and WTD-dependent EFs for the respective farms in 2020

Specific EFs based on water table depth (WTD)	Farm 1	Farm 2	Farm 3
Mean annual WTD (m)	-0.370	-0.336	-0.344
CO ₂ -C _{organic} (t C ha ⁻¹ yr ⁻¹)	9.41	9.06	9.15
CH ₄ organic (kg CH ₄ ha ⁻¹ yr ⁻¹)	3.5	3.5	3.5
N ₂ O-N _{organic} (kg N ha ⁻¹ yr ⁻¹)	4.2	4.2	4.2

Table 7 WTD-dependent EFs for the near-natural-state peatland scenario as baseline emissions

Specific EFs based on water table depth (WTD)	Intact peatland scenario
Mean annual WTD (m)	-0.10
CO ₂ -C _{organic} (t C ha ⁻¹ yr ⁻¹)	0.48
CH ₄ organic (kg CH ₄ ha ⁻¹ yr ⁻¹)	168.09
N ₂ O-N _{organic} (kg N ha ⁻¹ yr ⁻¹)	4.20

Tiemeyer et al. (2020). This methodology was selected as it is tailored to German conditions and allows for the estimation of emissions based on specific WTDs.

For this calculation, a mean annual WTD of -0.10 m was assumed, representing a wet, near-natural state characteristic of relatively intact peatlands (Drösler 2024). Based on this WTD, CO₂ and CH₄ emissions for the reference scenario were calculated using the Gompertz and exponential functions (as described in Sect. 2.2.3.) with the respective grassland coefficients by Tiemeyer et al. (2020) (Table 4+5). The calculated EFs for the intact peatland scenarios are shown in Table 7.

The EFs obtained for WTD-dependent CO₂ and CH₄ emissions for near-natural state peatlands were applied for the specific farms and the respective peatland area for CF calculations (Table 7).

This approach provides an adjusted CF that isolates the additional GHG emissions specifically attributable to the drainage and subsequent agricultural management, relative to a natural, undisturbed state.

It is important to note that the primary results presented in the main body of this study reflect the total emissions originating from the managed agricultural land without this subtraction. CFs adjusted to natural background emissions are described in the Supplementary Material.

2.2.4 Impact assessment and characterization

The IPCC 2021 methodology was used to evaluate the climate change impact, incorporating the GWP factors for a

100-year time horizon (GWP100) (Intergovernmental Panel on Climate, 2023). Emissions of CO₂, CH₄, and N₂O were converted into CO₂-equivalents (CO₂-eq) using the following conversion factors: 1 for 1 kg of CO₂, 27.2 for 1 kg of biogenic CH₄, and 273 for 1 kg of N₂O. The calculations were performed using SimaPro 9.1 LCA software (Sustainability 2020).

3 Results

The CF of milk production was determined for three different dairy farms, both with and without considering peatland-derived GHG emissions. Table 8 presents total emissions in kg CO₂-eq per kg of FPCM for each farm, using three different methodological approaches as described in Chap. 2.2.3. A supplementary analysis, where the calculated baseline emissions of a near-natural state peatland reference scenario were subtracted, is shown in Table S1 of the Supplementary Material.

3.1 Carbon footprint of milk (without emissions from drained peatlands)

When peatland emissions were excluded from the LCA, the CF of milk production averaged 0.85 kg CO₂-eq/kg FPCM across the three farms (Table 8). Although the three farms show different characteristics in their management and structure, emissions originating from CH₄ of enteric fermentation are found as strong contributors to CFs in all of them. In farm 1 (58.1%) and 2 (55.6%) enteric fermentation even makes up for over 50% of the total CF, while the CF of farm 3 also displays emissions from enteric fermentation with a share of 43% of the total CF as a strong contributor (Fig. 2). Considering farm 1 (18.3%) and farm 2 (19.6%), manure management is the second-largest source of emissions. In

contrast, the CF of farm 3 reveals only little contribution of emissions originating from manure management (1%), as anaerobic digestion is used. However, the results show that concentrate feed plays a relevant role in farm 3 as second-greatest emission source (19.2%). This finding aligns with the CF of farm 2, showing a great share of emissions from concentrates, too (18.3%), whereas farm 1 is not using concentrates at all. In addition, grass production is found to be another relevant source of emissions, substantially contributing to each CF of all farms analyzed (Fig. 2). Other sources such as electricity, fertilizer use, bedding, external forages, diesel and crop production slightly vary in their exact proportion between the three farms but play a rather minor or even negligible role in general (Fig. 2).

3.2 Including emissions from drained peatlands in the carbon footprint of milk

The inclusion of peatland-derived emissions in the LCA significantly increased the CF of milk production. Moreover, the magnitude of the CF's increase grew with increasing complexity of the methodology.

Figure 3 summarizes the calculated CFs for each farm, showing the impact of including and excluding peatland-derived emissions within the LCA as well as the effect of methods applied for calculating emissions from drained peatlands.

Applying the IPCC Tier 1 approach, the CF of milk production increased notably across all three farms, with the total CF rising by 48.4% to 134.4% (Table 8). As this approach uses EFs that are not farm-specific, it rather represents a basic estimation of peatland emissions. Utilizing the implied EFs developed by Tiemeyer et al. (2020) as a second estimation approach, the CFs increased further, showing a range of 58.2% to 172.7% (Table 8). The implied EFs stem from regional data and represent a more refined assessment than the IPCC Tier 1 approach, resulting in more accurate and generally higher estimates of peatland emissions.

Finally, the use of WTD-dependent response functions from Tiemeyer et al. (2020) resulted in the highest CF values in all of the three farms with increases ranging from 67.0% to 190.9% relative to the scenario excluding peatland emissions (Table 8). This confirms that incorporating site-specific WTD information is essential for the most robust estimation of GHG emissions.

Figure 4 illustrates the relationship between the share of drained peatland area (relative to the total farm area) and the resulting total CF for each farm based on the WTD-dependent approach. It shows that the total CF rises consistently with an increasing share of drained peatland area across all farms. Notably, farm 1 exhibits the steepest gradient in CF increase relative to the share of drained peatland

Table 8 Overview of carbon footprints of milk for the three farms analyzed excluding and including peatland emissions

Carbon footprint milk (kg CO ₂ -eq per kg FPCM)			
Excluding peatland emissions	Farm 1	Farm 2	Farm 3
	0.91	0.99	0.66
Including peatland emissions by different approaches			
<i>IPCC Tier 1 approach</i>	1.38	2.49	1.05
<i>Implied EFs by Tiemeyer et al. 2020</i>	1.44	2.70	1.10
<i>WTD dependent response functions by Tiemeyer et al. 2020</i>	1.52	2.88	1.15
Increase of CFs relative to baseline excluding peatland emissions (%)			
<i>IPCC Tier 1 approach</i>	51	152	59
<i>Implied EFs by Tiemeyer et al. 2020</i>	58	128	67
<i>WTD dependent response functions by Tiemeyer et al. 2020</i>	67	191	74

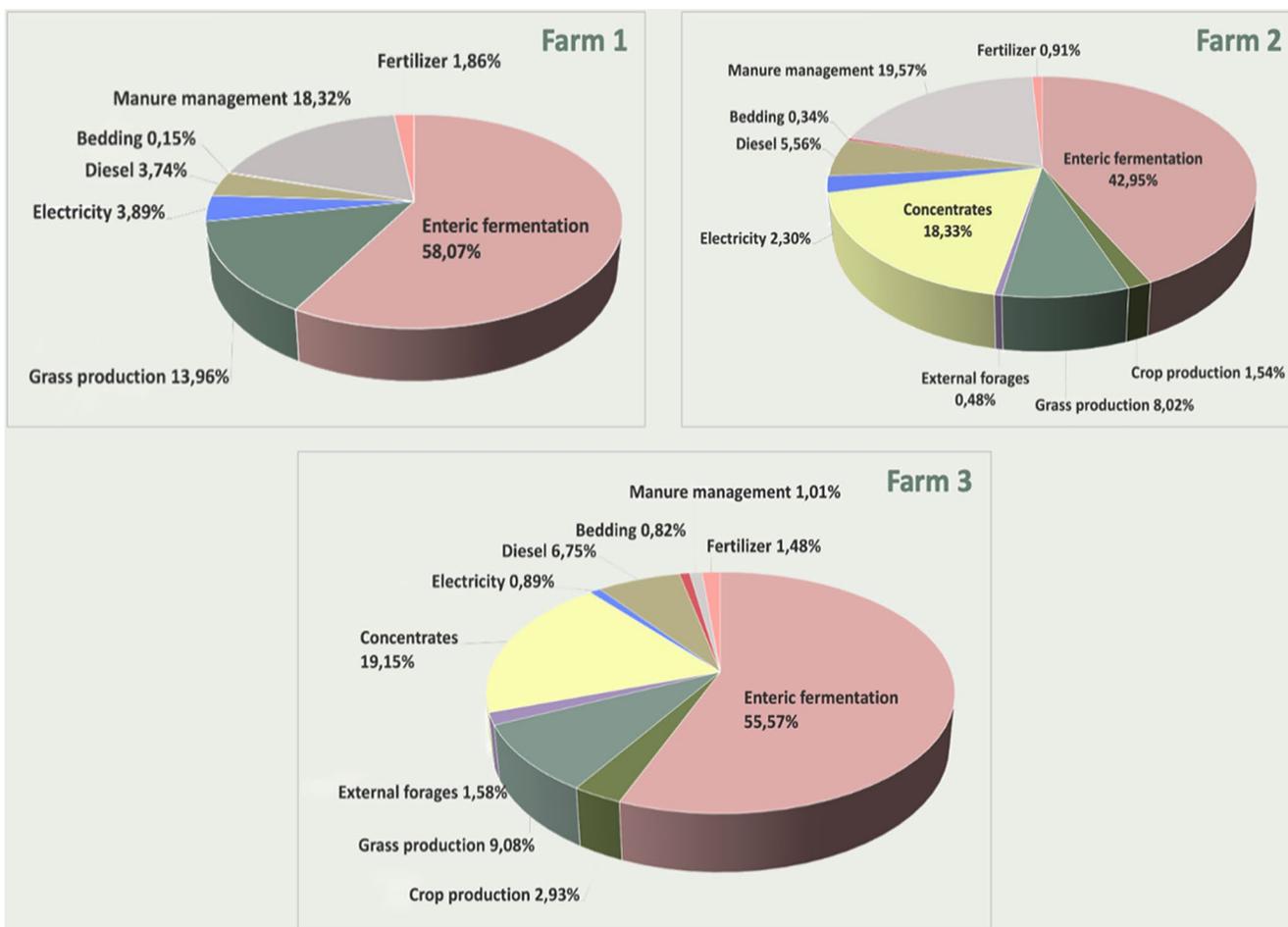
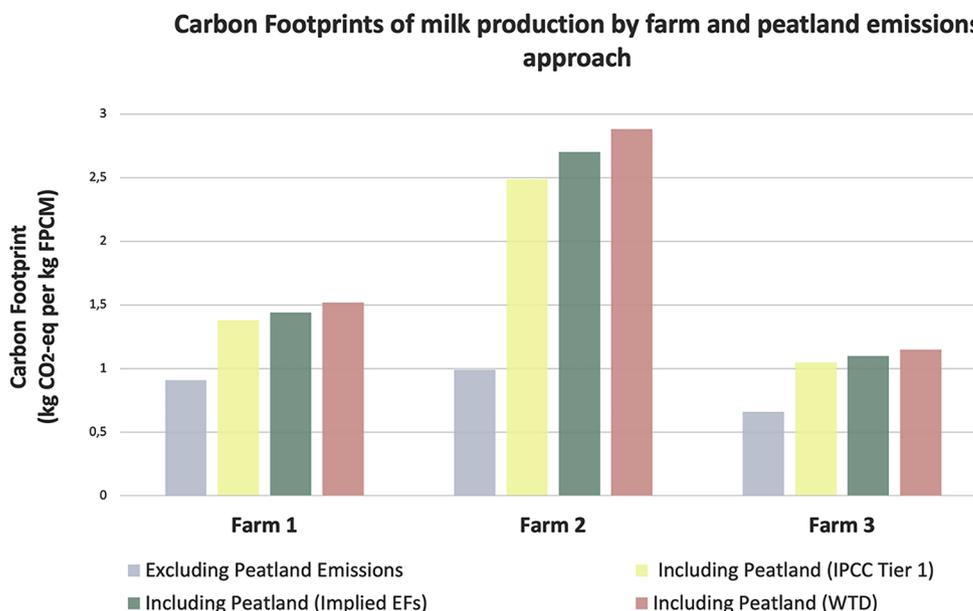


Fig. 2 Contribution to the carbon footprints from different sources excluding emissions from drained peatlands expressed as percentage of the total CF for the three farms analyzed

Fig. 3 Carbon footprints of milk production (kg CO₂-eq per kg FPCM) for the three dairy farms, shown for scenarios excluding and including peatland emissions using different methodological approaches



Relationship between drained peatland area and total carbon footprint across farms

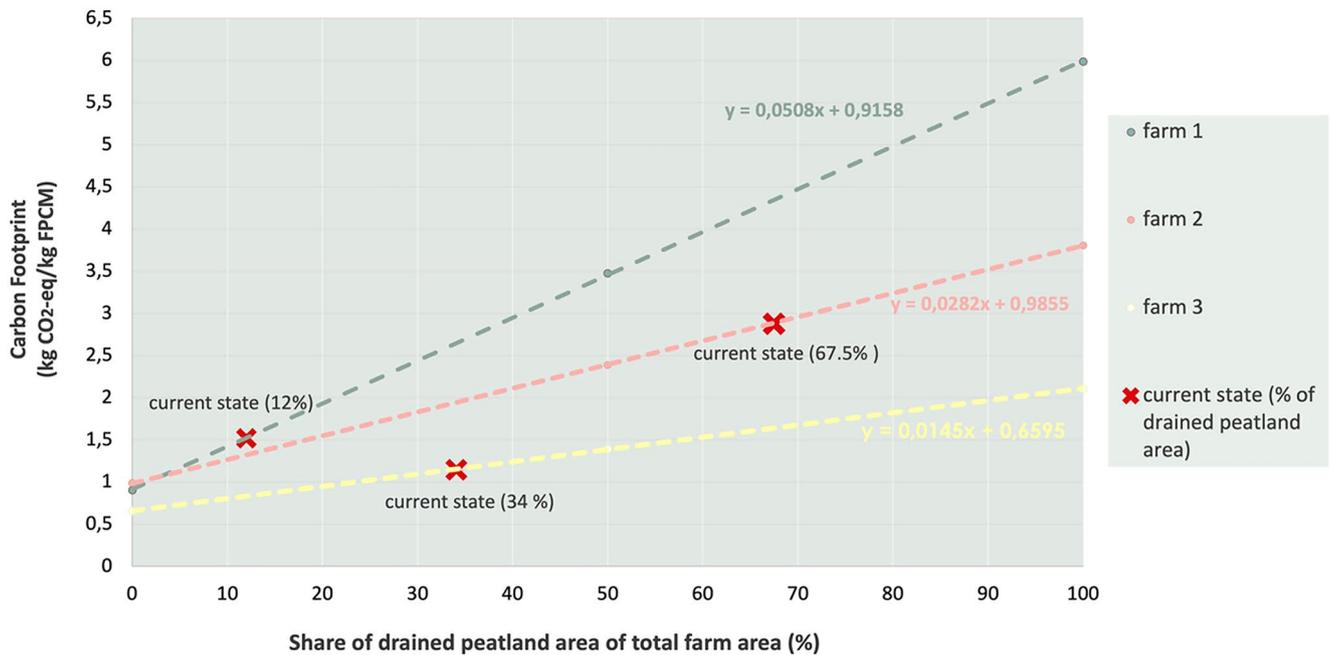


Fig. 4 Relationship between the share of drained peatland area (of total farm area) and the total CF (kg CO₂-eq/kg FPCM), based on the WT-dependent response functions for all three farms, including their current state

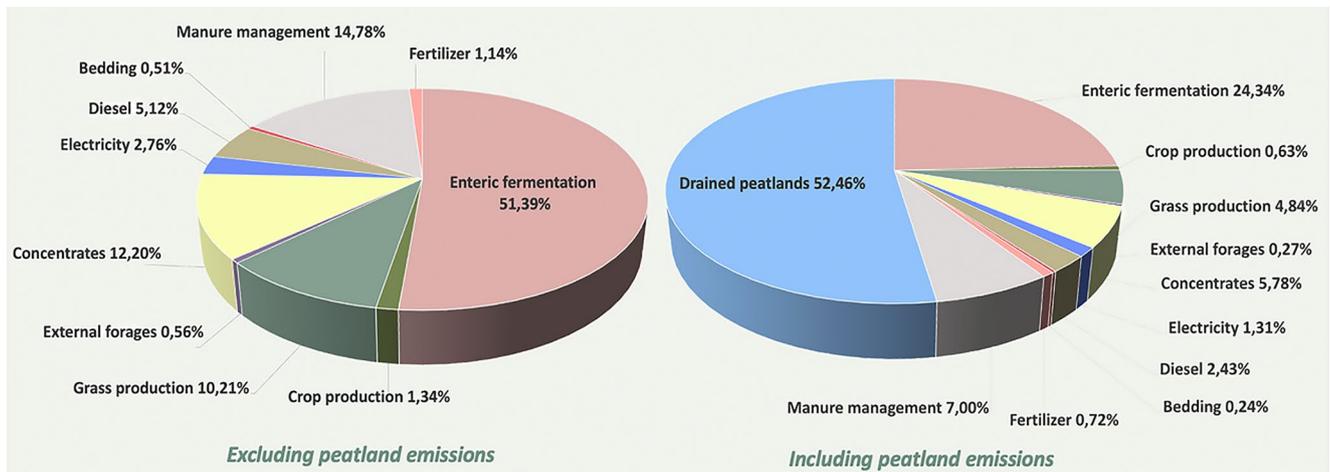


Fig. 5 Comparison of the average CF of the three farms excluding (left) and including peatland-derived emissions using the WTD-approach (right)

area, indicating a significantly higher sensitivity to drainage compared to farm 2 and farm 3. Farm 2 also shows a substantial rise, whereas farm 3 demonstrates a comparatively less pronounced increase (Fig. 4). The current state of each farm’s drained peatland share with the corresponding CF is also highlighted within the figure (Fig. 4).

Overall, the choice of methodology for accounting for peatland emissions showed a substantial impact on the calculated CFs: The WTD-dependent response function developed by Tiemeyer et al. (2020) consistently yielded in the

highest CF values, followed by the implied EFs from Tiemeyer et al. (2020), and the IPCC Tier 1 approach displaying the lowest values.

However, independently of the method chosen, when peatland emissions are included, they become the dominant source, highlighting their importance in the overall CF. Notably, the greatest emission source can be attributed to the drained peatland area, representing an average amount of approximately 52.5% of the total CF (Fig. 5).

4 Discussion

The results show that the CFs estimated from all of the three farms excluding peatland emissions, range from 0.66 to 0.99 kg CO₂-eq/kg FPCM. This places them in lower range compared to other LCA studies, showing typically report CFs of approximately 0.8 to 1.5 kg CO₂-eq/kg FPCM in European countries (De Jong 2013; Fantin et al. 2012; Koesling et al. 2025; Sevenster and de Jong 2008; Wattiaux et al. 2019).

This is low range is primarily due to several factors: high milk yields (ranging from 7,299.24 kg FPCM/cow/yr to 10,296.66 kg FPCM/cow/yr), low consumption of concentrates as well as the use of European soybeans to avoid LUC emissions. Additionally, farm 3 benefits from advanced manure management (anaerobic digestion).

The results of this study demonstrate that peatland emissions are a highly significant contributor to the CF of milk production, increasing it on average by more than twofold and changing the relative emission share such that peatland emissions become the dominant source on all farms. This finding highlights the importance of including emissions from drained peatlands within LCAs of agricultural production to provide a complete picture of the CF of the milk in regions where peatlands are commonly drained.

Also, the choice of methodology used to estimate peatland emissions has been shown to have a significant impact on the calculated CFs. The third methodological approach utilized farm-specific WTD information to model peatland GHG emissions. These emission estimates are considered the most accurate within this study because the WTD approach accounts for spatial variability in emissions driven by the hydrological conditions across individual farms. These hydrological conditions are recognized as the primary factor influencing the extent of the resulting emissions (Tiemeyer et al. 2020).

However, model uncertainty in the WT estimation must also be taken into account. The current WT-model used in this approach demonstrated good performance, including in independent validation tests. With an R² of 0.52 and a root mean square error (RMSE) of 0.17 m, the model meets the criteria for satisfactory performance when calculating monthly mean water levels, as suggested by Moriasi et al. (2007)(Friedrich 2025; Moriasi et al. 2007). Given the high sensitivity of GHG emissions to changes in WT, model uncertainty can lead to increased uncertainty in emission estimates, as derived by the WTD-dependent response functions that were used for calculations (2.2.3.). While this approach allows for annual or even monthly emission calculations, what can significantly reduce overall uncertainty compared to static methods, it also faces a crucial limitation with its reliance on a single mean annual WTD value. Given

that the relationship between WTD and CO₂ and CH₄ emissions is non-linear, using a mean annual value results in an averaging error compared to calculations based on a time-series of shorter intervals (e.g., monthly or daily WTD). Thus, future LCA refinements should prioritize the integration of monthly or seasonal WTD data where available, as this is essential to better capture the non-linearity of emissions driven by short-term water table fluctuations.

Notwithstanding the defined model uncertainty in WTD estimation, the resulting GHG flux from peatland soils represents a magnitude of emission that establishes it as the dominant determinant of the overall CF result. While established LCA uncertainty analyses often identify enteric CH₄ and N₂O emissions from mineral soils as primary drivers of uncertainty (Basset-Mens et al. 2009; Thomassen et al., 2008; Wolf et al. 2017), the calculated peatland emissions in this study, which at least double the total CF, are likely to remain the single largest and most sensitive contributor to the CF result. Thus, we emphasize that the core finding, namely the dominance of peatland emissions, is robust across typical uncertainty ranges observed in dairy LCAs. Future research efforts should therefore focus on reducing the model uncertainty in WTD estimation, as this directly translates into the most significant potential reduction of the overall environmental impact of these dairy systems.

For this study, the reference year 2020 was used, which represents an average year in terms of precipitation in the pre-alpine region as discussed in the study of Friedrich et al. (2024) (Friedrich et al. 2024). However, years with significantly higher or lower precipitation totals as well as differing patterns of potential evapotranspiration could substantially alter the emission estimates, as stated before.

All calculated CFs exhibit an overall increase in their values, correlating with the higher peatland emission estimates generated by the increasingly accurate calculation methodology employed. This highlights the importance of accurate quantification of peatland emissions to reflect the inherent spatial dynamics of these complex environments, as well as the availability of high-resolution and region-specific data, such as WTD. Utilizing even the least detailed but scientifically sound approach is a substantial improvement over complete omission, as it provides a more complete and environmentally relevant picture of the carbon footprint.

Furthermore, a supplementary analysis was conducted to account for potential baseline emissions from an intact, near-natural-state peatland reference scenario. As described in the Supplementary Material (Table S1), even after subtracting these calculated baseline emissions (derived from the Tiemeyer et al. (2020) response functions at a mean annual water table depth of -0.10 m), the overall CFs of milk production remained largely consistent in their magnitude and relative differences across farms and methodologies.

This indicates that the substantial increase in CFs observed when incorporating peatland emissions is mostly driven by the additional emissions resulting from peatland drainage and agricultural management, rather than being significantly offset by natural background fluxes. Thus, the conclusion regarding the critical role of drained peatlands as a dominant emission source remains robust.

Furthermore, the data reveal that farm 2, possessing the largest area of drained peatland (81 ha) of the three farms, consistently yields the highest CFs across all scenarios including peatland emissions. This observation is a direct consequence of its dominant proportion of drained peatland, which also results in the highest increase in GHG emissions (up to 190.9%) relative to the other farms with lower shares of drained peatland area.

The relationships presented in Fig. 4 show that while an increased share of drained peatland invariably leads to a higher CF, the steepness of this increase varies significantly between farms. This gradient illustrates different systematic sensitivities to the peatland GHG burden, which are determined by the farm's structure, mitigation efforts and productivity. Farm 1 exhibits the steepest rise because its production system is intensely linked to the local grassland feed base, and the resulting GHG burden is distributed over its specific milk yield, leading to a high CF sensitivity per kg FPCM. In contrast, farm 3 shows the least pronounced increase due to a combination of a lower initial CF, partly buffered by different mitigation measures (e.g., anaerobic digestion of manure), a more diversified feed procurement as well as higher productivity, helping to distribute the peatland GHG burden over a larger FPCM output.

These findings emphasize the substantial influence of drained peatlands on the overall CF of milk production, highlighting that an increased share of drained peatland area will contribute to increased emissions and reinforcing the need for site-specific assessments and tailored management strategies on dairy farms to mitigate their environmental impact.

A comprehensive assessment is crucial because existing milk production LCAs have largely overlooked the significant GHG emissions from drained peatlands, potentially leading to a substantial underestimation of the dairy sector's CF in regions with these soil types. To the best of our knowledge, this research represents the first study to systematically integrate peatland-specific EFs, derived from established methodologies like that of Tiemeyer et al. (Tiemeyer et al. 2020) into the LCA framework for German milk production. Our findings demonstrate a considerable impact of drained peatland areas on the calculated CF, revealing a potential maximum increase by a factor of 3 to 6.5. This maximum would apply if the entire farm's feed production area was located on drained peat soil. Previous

estimates of peatland emissions in the context of dairy farming have pre-dominantly originated from grey literature and extrapolations from broader LU- studies (Couwenberg, 2023). By applying different approaches to account for these previously overlooked impacts, this study provides transparent assessment of emissions and new insights into the environmental footprints of milk production in the pre-alpine region of Germany. Especially, with the approach using WT-specific response functions, the consistent relationship of WTD and CO₂ emissions from organic soils is highlighted, as established in the broader literature, describing carbon emissions to increase with a decreasing WTD (Chen et al. 2021; Evans et al. 2021; Koch et al. 2023; Tanneberger et al. 2021a; Tiemeyer et al. 2020, 2024; Tuohy et al. 2023; Wilson et al. 2016). Moreover, the strong correlation observed in our study between the proportion of drained peatland area and the resulting CF further underscores the potential of raising the WT as key strategy to reduce carbon emissions from milk production.

Therefore, transitioning to land management practices that support higher WTs offers dairy farms on drained peatlands a relevant pathway to significantly lower their CF. However, the widespread success of rewetting strongly depends on policy frameworks that ensure farmer's long-term economic viability (Tanneberger et al. 2021b; Zehetmeier et al. 2012). This necessitates a shift in agricultural subsidies and support mechanisms to actively incentivize rewetting initiatives as well as the adoption of paludiculture or other alternative land uses (Jurasinski et al. 2020; Tanneberger et al. 2020, 2021b; Wichtmann et al. 2016). Furthermore, any strategy should guarantee that the issue is not displaced. For instance, increasing external feed consumption as a substitute for grass could transfer LUC emissions (e.g. land-based GHG emissions) to a supplying region.

The accurate quantification of the current impact, as provided by this study, is a crucial first step in evaluating the potential effectiveness of such rewetting strategies and informing policy decisions aimed at reducing the climate impact of agriculture on peatlands (Tanneberger et al. 2021b). Thus, further research should also focus on the long-term effects and economic feasibility of these mitigation measures for dairy farming in Germany. Furthermore, the availability and accessibility of region-specific data, such as detailed WT measurements, are essential for refining emission estimates and improving the accuracy of future assessments of mitigation effectiveness.

5 Conclusion

Our findings underscore the substantial climate impact of dairy on organic soils and demonstrate that peatland decomposition becomes the dominant GHG source in milk production. This result establishes the urgent need to include accurate, site-specific peatland emissions in standard LCAs to reflect the true environmental burden. Consequently, rewetting represents a key mitigation strategy, though its success requires supportive policies that address farmer profitability. In light of these findings, enhanced accessibility to high-resolution data, particularly continuous water table measurements, is crucial for refining emission estimates and developing effective climate change mitigation solutions in this sector.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-026-02599-z>.

Acknowledgements CircAgric-GHG Proposal ID 52 under the Joint Call 2021 on Circularity in mixed crop and livestock farming systems with emphasis on greenhouse gas mitigation. The study was funded through the partners of the Joint Call of the Cofund ERA-Nets SusCrop (Grant No. 771134), FACCE ERA-GAS (Grant No. 696356), ICT-AGRI-FOOD (Grant No. 862665) and SusAn (Grant No. 696231). The funder played no role in study design, data collection, analysis and interpretation of data, or the writing of this manuscript.

Author contributions A.M. contributed to conceptualization, investigation, formal analysis, methodology, visualization, and writing, including original draft preparation and review. G.P. contributed to formal analysis, methodology, data curation, resources as well as to writing and editing. S.F. was responsible for resources as well as review. R.K. contributed to review, editing and supervision. C.S. contributed to review, editing, supervision, conceptualization, and project administration. All authors have read and approved the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability The data used in the study will be made available upon request.

Declarations

Competing interests All authors declare no competing financial or personal interests.

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