Waste Management 187 (2024) 79–90

Contents lists available at ScienceDirect

Waste Management

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

Research Paper

An integral assessment of the impact of diet and manure management on whole-farm greenhouse gas and nitrogen emissions in dairy cattle production systems using process-based models

Latifa Ouatahar[a,b,c,*], André Bannink[d], Jürgen Zentek[e], Thomas Amon[a,f], Jia Deng[g,h], Sabrina Hempel[f], David Janke[f], Pierre Beukes[i], Tony van der Weerden[j], Dominika Krol[c], Gary J. Lanigan[c], Barbara Amon[b,k]

[a] *Institute for Animal Hygiene and Animal Health, Department of Veterinary Medicine, Freie Universität Berlin, Berlin, Robert-von-Ostertag 7–13, 14163 Berlin, Germany*
[b] *Department of Technology Assessment and Substance Cycles, Leibniz Institute for Agricultural Engineering and Bioeconomy – ATB, Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[c] *Environment, Soils and Land-Use, Teagasc, Johnstown Castle, Co. Wexford. Y35 Y521, Ireland*
[d] *Wageningen Livestock Research, Wageningen University & Research, PO Box 338, 6700AH, Wageningen, Netherlands*
[e] *Institute for Animal Nutrition, Department of Veterinary Medicine, Freie Universität Berlin, Berlin, Königin-Luise-Str. 49, 14195 Berlin, Germany*
[f] *Department of Sensors and Modelling, Leibniz Institute for Agricultural Engineering and Bioeconomy – ATB, Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[g] *Earth Systems Research Center, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH, USA*
[h] *DNDC Applications Research and Training, LLC, Durham, NH, 03824, USA*
[i] *DairyNZ Ltd., Private Bag 3221, Hamilton 3240, New Zealand*
[j] *AgResearch Ltd, Invermay Agricultural Centre, Puddle Alley, Mosgiel 9053, New Zealand*
[k] *Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland*

ARTICLE INFO

Keywords:
Dairy production systems
Feed management
Greenhouse gas emissions
Process-based modeling

ABSTRACT

Feed management decisions are crucial in mitigating greenhouse gas (GHG) and nitrogen (N) emissions from ruminant farming systems. However, assessing the downstream impact of diet on emissions in dairy production systems is complex, due to the multifunctional relationships between a variety of distinct but interconnected sources such as animals, housing, manure storage, and soil. Therefore, there is a need for an integral assessment of the direct and indirect GHG and N emissions that considers the underlying processes of carbon (C), N and their drivers within the system. Here we show the relevance of using a cascade of process-based (PB) models, such as Dutch Tier 3 and (Manure)-DNDC (Denitrification-Decomposition) models, for capturing the downstream influence of diet on whole-farm emissions in two contrasting case study dairy farms: a confinement system in Germany and a pasture-based system in New Zealand. Considerable variation was found in emissions on a per hectare and per head basis, and across different farm components and categories of animals. Moreover, the confinement system had a farm C emission of 1.01 kg CO_2-eq kg^{-1} fat and protein corrected milk (FPCM), and a farm N emission of 0.0300 kg N kg^{-1} FPCM. In contrast, the pasture-based system had a lower farm C and N emission averaging 0.82 kg CO_2-eq kg^{-1} FPCM and 0.006 kg N kg^{-1} FPCM, respectively over the 4-year period. The results demonstrate how inputs and outputs could be made compatible and exchangeable across the PB models for quantifying dietary effects on whole-farm GHG and N emissions.

1. Introduction

Amongst many farm management aspects, feed management decisions are crucial as they strongly affect both greenhouse gas (GHG) and nitrogen (N) emissions from ruminant production systems (David Yáñez-Ruiz et al., 2018) and have major effects on dairy efficiency (de Ondarza and Tricarico, 2017). Dairy production systems are heterogenous, with varying levels of feed intake, composition of the diets, level of milk production achieved, livestock housing and manure management systems, as well as a relatively large contribution to national excreta/

* Corresponding author at: Robert-von-Ostertag 7–13, 14163 Berlin, Germany.
E-mail address: latifati@zedat.fu-berlin.de (L. Ouatahar).

https://doi.org/10.1016/j.wasman.2024.07.007
Received 2 April 2024; Received in revised form 14 June 2024; Accepted 5 July 2024
Available online 11 July 2024

manure-related direct and indirect GHG and N emissions (Rotz et al., 2014). Therefore, quantifying the downstream impact of feeding management decisions on whole-farm emissions is critical when assessing the impact of dietary mitigation options (including tradeoffs and synergies) across the whole-farm system (Jose et al., 2016; Kipling et al., 2014).

In cattle farming systems, non-carbon dioxide (CO_2) emission sources from anthropogenic activities dominate. These comprise methane (CH_4) arising from the process of enteric fermentation, direct emissions of CH_4 and nitrous oxide (N_2O) from housing and manure management, and direct emissions of N_2O from the processes of nitrification and denitrification after dung/urine, manure and fertilizer application in grasslands and other soils (Gerber et al., 2013; IPCC, 2014; Rotz, 2018). In addition to N_2O, ruminant production systems generate other forms of N pollution leading to indirect N_2O emissions, particularly ammonia (NH_3) emitted from housing and manure storage and application, and nitrate leaching (NO_3^-) to groundwater and surface water, and particulate N to surface water (Dijkstra et al., 2013). The CO_2 emitted from livestock or pasture and feed crops is not considered a net source of CO_2 as it involves rapid Carbon (C) cycling of atmospheric CO_2 into plant organic compounds (FAO, 2006).

In both confinement and grazing systems, C and N emissions contribute significantly to the total GHG footprint (Beukes et al., 2020; Joo et al., 2015; Rotz, 2018). An integral assessment approach at the farm scale is necessary to evaluate GHG and N emissions in livestock systems robustly, rather than assessing each emission source in isolation (i.e., animal, housing, manure handling, soil). This is because there is a cascading impact of emissions from each source on subsequent sources (Rotz, 2018; Veltman et al., 2017). However, appropriate measurement protocols, air and water monitoring at the farm level are expensive, time-consuming, and sometimes technically challenging to achieve (Niu et al., 2018). Thus, measurement, reporting and verification (MRV) of the full suite of emissions from individual ruminant production systems, especially in the context of Carbon-Farming schemes, would be prohibitively expensive or even impossible to achieve. Alternatively, mathematical process-based (PB) modelling can play a major role in understanding the interaction between C and N cycling processes and contextualizing empirical observations. Nevertheless, constructing an integral farm C and N budget is a challenge (Vibart et al., 2021) because of a) the lack of data associated with some key ecosystem C and N fluxes such as soil respiration, plant uptake, manure decomposition, nitrogen mineralization, and C sequestration in soil and b) the level of activity data required to populate the models.

Various models have been used to assess GHG and N emissions at the farm scale including approaches ranging from empirical to static mechanistic models, to dynamic mechanistic models (Ouatahar et al., 2021). Process-based models can represent the processes and dynamics of C and N fluxes that are important when assessing spatial strategies or projecting emissions and productivity into the future. This allows for generating a robust whole-farm budget of GHG and N emissions in relation to C and N cycling in the particular system under study (Veltman et al., 2017) (Figure S1). An ensemble modelling approach, whereby a set of PB modeling frameworks are linked for an integral assessment, can be used to quantify downstream impacts associated with dietary changes or alterations to the storage of manures on GHG and N emissions from farm production systems. Despite the promise, such an approach has rarely been utilized (Beukes et al., 2011). Therefore, the objective of this study was to establish a novel comprehensive modelling framework by linking a cascade of PB models. This framework is designed to assess the downstream impact of the dietary factors on manure management chain emissions, including housing, manure storage and handling, and subsequent deposition into soil. This methodology was applied to two case-study dairy cattle farms: a confined system in Germany, where animals are housed indoors and fed a controlled diet, and a pasture-based system in New Zealand, where animals graze outdoors on natural or managed pastures for most or all of the year. As a result, the whole-farm budget of both direct and indirect GHG and N emissions, including C sequestration, along with farm C and N emissions and cycles could be estimated.

2. Materials and methods

2.1. Modeling approach

For this modelling application, four primary components (i.e. animal feed, housing, manure storage, and soil processes) have been linked by building three bridges (Figure S2.). The first bridge simulates the dynamics and processes of C and N in the rumen that generate enteric CH_4 emissions and C and N excreta. The second bridge simulates the flow of C and N in manure management facilities in the barn and storage, and the last bridge models the downstream effect of the incorporation of manure C and N, and additional input (e.g., synthetic fertilizer), into the soil. The integral effect of diet on GHG and N emissions is provided by combining a suite of PB models for capturing the interaction of animals, facilities, and agro-ecosystems. The models link C and N dynamics in the different farm components to show the overall effect on emissions. The approach is demonstrated using two case study farms with accurate monitoring data.

2.2. Process-based modeling frameworks for the implementation of integral assessment approaches

2.2.1. Modeling enteric methane emissions and excretion

For this modeling part, we used the Dutch Tier 3 model for enteric CH_4 emission in dairy cattle (animal model) (Bannink et al., 2018, 2011). This model represents the dynamic aspects of the interaction between feed substrates and micro-organisms in the rumen for assessing the impact of dietary characteristics on enteric CH_4 emissions, feed digestion and excretion in urine and feces. This is a PB model consisting of a set of ordinary differential equations that describe the change in time of pools of the substrate, micro-organisms, and microbial end-product present in the rumen and large intestine. It is driven by inputs related to nutrition, including daily dry matter (DM) intake, the chemical composition of feed and intrinsic degradation characteristics of the starch, crude protein (CP), and cell wall material (structural carbohydrates) as derived for protein evaluation systems for dairy cattle applied in current practice. Besides these degradable fractions, the model also requires inputs on the dietary content of soluble carbohydrates, crude fat, organic acids, ash, and NH_3 (with silages). The model heavily relies on the rumen fermentation model (Dijkstra et al., 1992; Mills et al., 2001) which has been expanded by Dijkstra et al. (2018) to include equations that represent fecal excretion and fecal composition.

2.2.1.1. Modeling housing and manure storage emissions. The ManureDNDC model (Li et al., 2012) used in this study is designed to simulate the biogeochemical cycles of C, N, and phosphorus (P) in dairy farms. It was developed by linking farm components, such as feeding, housing, storage, and treatment, to the biogeochemical model, DNDC (Li et al., 1992b, 1992a). The ManureDNDC model is a PB model comprising several modules, including housing, manure storage, and field application modules. These modules use the current biogeochemical processes to track manure turnover in the farm components. The C and N cycling within the housing module is primarily affected by various factors such as the type of animal, the properties of the manure, the type and properties of bedding material, the scrapping frequency, the cleaning method, and abiotic elements (such as climate) (Deng et al., 2015). The model simulates C, N, P, and water dynamics as well as GHG and N emissions from housing, compost, lagoon/slurry tank storage, digesters, and crop fields including grassland. The model outputs are simulated on a daily as well as an annual basis.

2.2.1.2. Modeling soil emissions. This study utilized the soil module of denitrification decomposition (DNDC) model (v9.5) (Deng et al., 2020; Giltrap et al., 2010; Li et al., 1992b, 1992a). This modified version of DNDC has been optimized for grazed grassland systems (Li et al., 2011; Zimmermann et al., 2018). The DNDC model is a PB model of C and N biogeochemistry in agro-ecosystems. The model consists of two components. The soil climate, crop growth, and decomposition sub-models comprise the first component, which predicts soil temperature, soil moisture, pH, redox potential (Eh), and substrate concentration profiles driven by ecological factors (e.g., climate, soil, vegetation, and anthropogenic activity). The emissions of CO_2, CH_4, NH_3, nitric oxide (NO), N_2O, and dinitrogen (N_2) and changes in soil organic carbon (SOC) from plant-soil systems are predicted by the second component, including the nitrification, denitrification, decomposition and fermentation sub-models.

2.3. Farm case studies: A confinement system in Germany and a pasture-based system in New Zealand

The PB model ensemble described above was applied to two case study farms, representing two contrasting dairy systems (Table 1). The two farm cases were selected because of sufficiently detailed and reliable monitoring data. The first simulated farm was a German dairy farm with 235 Holstein cows and an area of 905 ha, representing a confinement system. The second one was a pasture-based dairy farmlet system in New Zealand with 42 Holstein cows and 19 heifers and an area of 18 ha in total, designed to assess more profitable but lower N leaching farming systems (Beukes et al., 2017). The cases differ significantly in terms of farming intensity, fertilization intensity (kg of N ha^{-1} $year^{-1}$), and feeding intensity (DM intake and milk yield, kg cow^{-1} $year^{-1}$). Hence, they illustrate how PB models may encompass the differences in GHG and N emissions.

2.4. Input data

2.4.0.1. Animal/Feed data

The starting point of the modeling process was inputting detailed dietary information on different rations fed to different categories of animals in the farms. Dietary information includes feed intake, diet composition, and the chemical analysis and intrinsic rumen degradation characteristics of the starch, fiber and protein fraction in feedstuffs. For the confinement system, monthly feed rations for the three categories of cows were obtained from farm recording information for the monitoring period. The rations were inputted with the ingredients composed of roughages, minerals, and concentrates, including compound feed imported outside the farm and single products or purchased by-products. The average diets were generated per animal category. The chemical composition for each ingredient was inputted and includes (g kg DM^{-1}): DM content, CP, NH_3, crude ash, sugars, starch, neutral detergent fiber (NDF), crude fat, and volatile fatty acids. These values were obtained from farm analyses of feedstuffs and feed tables (CVB, 2018).

For the pasture-based system, DMI for cows and heifers was provided based on data from the study conducted by Beukes et al. (2017). Because standard feed data collected in practice does not provide these data, the intrinsic degradation parameters for potentially degradable starch, NDF and CP for all dietary components were estimated (Bannink et al., 2018, 2011). A portion of dietary DM (g kg^{-1} DM) could not be identified (in the order of 10 %), which was calculated as the subtraction of the amount of CP excluding CP originating from NH_3-N, NH_3, crude fat, crude ash, NDF, starch, sugar, and fermentation products from 1000 g kg^{-1} DM. If the amount of dietary starch exceeded the amount of sugar, the unidentified fraction was divided equally between NDF and starch. If the opposite was true, the unidentified fraction was divided equally between NDF and sugars. This method was chosen as a practical way to assign 100 % of DM, including the unidentified portion that contributes to fermentation, microbial growth, digestion, and excretion (Bannink et al., 2011). Table 2 summarizes the feeding information of the two contrasting farm cases.

In the animal model, the body's N (g N d^{-1}) retention was assumed to be zero because it remains very small relatively to animal inflow and outflow of N, and therefore the following equation applies:

$$Nfeed = Nurine + Nmilk + Nfaeces \quad (1)$$

Carbon intake was calculated as follows:

$$C_{intake} = (DMI^*((Carbohydrate + fat + protein)^*Carbon\_content)/1000 \quad (2)$$

Where C_{intake} is carbon intake in g $head^{-1}$ day^{-1}, DMI is DM intake in kg d^{-1}, carbohydrate is the carbohydrate content of the diet in g kg DM^{-1}, fat is the fat content of the diet in g kg DM^{-1}. The molar masses were calculated as 162 g for 1 mol of carbohydrate (assuming an average composition of 6 mol C per mol carbohydrate) and 844 g for 1 mol of fat (assuming an average composition of 50 % C16 and 50 % C18, averaging 17 mol C per mol fat). A standard correction factor of 6.25*N in CP was applied for the protein C content. However, it was necessary to exclude the CP associated with NH_3-N. This portion of CP, excluding NH_3-N, is estimated to contain approximately 0.5 g of C per gram of CP (Rouwenhorst et al., 1991).

FPCM in kg day^{-1} was calculated as follows from reported milk yield (kg day^{-1}), fat (%) and protein (%) content (CVB, 2018):

$$FPCM = (0.337 + 0.116 \times fat + 0.06 \times protein) \times milkyield \quad 3)$$

Milk nitrogen (N_{milk}) in gN day^{-1} is calculated from observed values of milk composition as follows:

$$N_{Milk} = (milk\ yield^*protein\ content(\%)/100)^*1000/6.38 \quad (4)$$

Milk yield is expressed in kg d^{-1}.

2.4.0.2. Housing, manure management, crop and soil data

An overview of climate and farm-related parameters such as outdoor and indoor climate parameters, livestock, housing, manure management, soil, and crop information are shown in Table 3, with the main inputs presented in Appendix A. The inputs included details on temperature, precipitation, wind speed, number of animal heads, housing details, ventilation, manure removal frequency, manure management,

Table 1
General characteristics of two contrasting farm cases of dairy farm management: a confinement system in Germany (Farm 1) and pasture-based system in New Zealand (Farm 2).

Characteristics	Farm 1	Farm 2
Type system	Confinement system/ naturally ventilated	pasture-based farmlet system
Site		
Site name	Groß Kreutz	Waikato
Latitude	52.40	−37.77
Longitude	12.78	175.37
Area (ha)	905	18
monitoring period	2018–2019	2011–2015
Herd		
Cows (head)	235	42 cows + 19 heifers
Race	Holstein	Holstein
Categories animals	High lactating/late lactating/dry cows	Lactating cows/ heifers
Manure management		
Biogas type	anaerobic mesophilic	
Slurry tank capacity (m^3)	two slurry tanks (2000 + 2200)	–
Soil, fertilization		
Soil type	Loam-sandy	silt-loam
Mineral fertilization rate (kg N ha^{-1})	54–130.5	120–146

N: nitrogen, ha: hectare.

Table 2
Summary of inputs used for the animal process-based model, including feed information and milk composition for the two case study farms; the confinement (Farm 1) and pasture-based system (Farm 2).

Item	unit	Farm 1			Farm 2				
category animal name		HL-cows	LL-cows	dry cows	lactating cows	lactating cows	lactating cows	lactating cows	heifers
monitoring period	year	2018–2019	2018–2019	2018–2019	2011–2012	2012–2013	2013–2014	2014–2015	2014–2015
DMI	kg head^{-1} day^{-1}	21.77	18.92	10.65	15.90	13.70	14.61	14.20	9.80
% Concentrate	%	19.8 %	17.5 %	0 %	0 %	0 %	0 %	0 %	0 %
Nitrogen intake	kgN head^{-1} day^{-1}	0.47	0.42	0.24	0.55	0.47	0.50	0.49	0.35
Carbon intake	kgC head^{-1} day^{-1}	10.64	9.25	5.10	8.25	7.10	7.56	7.38	5.12
Crude protein	g kg DMI^{-1}	128.05	135.05	138.18	215.72	215.48	213.05	217.70	222.70
Crude ash	g kg DMI^{-1}	53.22	61.24	87.82	94.46	95.15	94.16	95.39	96.30
Crude fat	g kg DMI^{-1}	28.74	29.20	30.05	39.82	39.94	39.82	39.94	40.00
NDF	g kg DMI^{-1}	399.29	411.72	559.99	473.81	475.46	473.44	475.77	477.30
Milk yield	kg d^{-1}	34.00	26.00	–	13.33	12.82	13.33	13.46	–
FPCM	kg d^{-1}	32.97	26.13	–	13.55	13.03	13.55	13.69	–
Milk fat	%	3.80	4.00	–	4.10	4.10	4.10	4.10	–
Milk protein	%	3.20	3.40	–	3.40	3.40	3.40	3.40	–
Milk nitrogen	g N day^{-1}	170.53	138.56	–	71.06	68.30	71.06	71.75	–
Live Weight	kg head^{-1}	700	700	700	469	469	469	469	425

DMI: dry matter intake, FPCM: fat protein corrected milk, NDF: neutral detergent fiber. Live weight represents the mean of the herd. Farm 1: Germany, one year simulation for different cows; HL-cows: high lactating cows, LL-cows: late lactating cows and dry cows). Farm 2: New Zealand, 4-years simulation for lactating cows and one year for heifers).

Table 3
Overview of inputs used for the manure management and soil/crop process-based models.

parameter	Description
Climate	- Outdoor daily max and min air temperature(°C), precipitation (cm), relative humidity (%) and wind speed (m.s^{-1}).Indoor (inside the barn) daily average temperature(°C), daily relative humidity (%), and daily wind Speed (m.s^{-1})
Livestock	- Number of heads, feed rate (kg DM head^{-1} day^{-1}), CP (%), C and N intake (kg DM head^{-1} day^{-1})
Housing	- Number of housings on the farm Floor area Ventilation type Manure removal frequency (days/removal) Liquid and solid waste fractions removed to slurry tank, digester, field, and/or remaining on site. Digester characteristics
Manure storage and treatment	- Manure removal: frequency, and fraction of manure removed to slurry tank.Slurry tank: capacity (m^3), surface area (m^2), removal frequency Land application: area of field receiving manure
Soil and crop	- soil characteristics: soil texture, bulk density, pH, clay fraction, field capacity, soil organic carbon (SOC) top layer Crop type, areas (ha), planting/harvest dates, crop residue management, crop rotations Tillage application datesFertilization: fertilizer type, application dates, application rate (kg N/ha) application depth, application method Manure amendment: date, rate (kg N ha^{-1}), and application method

soil characteristics, crop details, fertilization, and manure amendment.

2.5. Simulations and general assumptions

The simulations were designed to account for seasonal and annual variations and differences between different cohorts of bovines within the herd (Figure S3.). Therefore, a single year of simulation was conducted for the confinement system by dividing the herd into categories with distinct DMI and milk characteristics, live weights, %CP, DM fraction, and days in milk (DIM) to account for the variation between different animals among the herd. For the pasture-based system, four consecutive years of simulation were conducted with dairy cows, and one year for heifers to capture the interannual variation. For the confinement system, the cows were separated into three groups: high and mid-lactating cows, late-lactating cows, and dry cows. We assumed a lactation period of 305 days (Leon-Velarde et al., 1995), 200 days high and mid lactating, and 105 days late lactating and the remaining 60 days of the year were the dry period. Regarding the pasture-based system, we assumed one average diet was adopted for the whole year for lactating cows and heifers.

For the housing compartment in the confinement system, we assumed the same proportion of each category of cows was housed for the same surface area inside the barn. Dry cows were treated as beef cows in the livestock module. For the pasture-based system, animals were grazed 24 h a day.

Nitrous oxide emissions emerge through two indirect pathways, namely "off-site" N_2O emissions from N volatilization/deposition and N leaching, in addition to the direct emissions of N_2O from managed soils that arise through a direct pathway (i.e., directly from the soils to which N was applied). By assuming all lost N was locally redeposited and using the emission factor (EF) developed for indirect N_2O field emissions, indirect N_2O emissions were calculated from leached N and NH_3 volatilization. These emissions were added to the GHG farm budget by using the EFs from IPCC guidelines (IPCC, 2019, 2006).

$$N_2O_{indirect} - (NH_3) = NH_3 - N \times EF_4 \times \left(\frac{44}{28}\right) \quad (5)$$

$$N_2O_{indirect} - (NO_3{}^-) = NO_3 - N \times EF_5 \times \left(\frac{44}{28}\right) \quad (6)$$

where $N_2O_{indirect}$ – (NH_3) is indirect N_2O emissions from NH_3 volatilization in kg year^{-1}, and $N_2O_{indirect}$ – (NO_3^-) is indirect N_2O emissions from NO_3^- leaching in kg year^{-1}. EF_4 (i.e. 0.01) is EF for N_2O emissions from atmospheric N deposition on soils and water surfaces in kg N_2O-N (kg NH_3-N volatilized)$^{-1}$, and EF_5 (i.e. 0.011) is EF for N_2O emissions from N leaching and runoff in kg N_2O-N (kg N leached and runoff) $^{-1}$.

It is to be noted that a portion of the manure C was released as CH_4 (and burned) as the manure stream was routed through the digester, making it unavailable for soil application. It was, therefore, not simulated in ManureDNDC. However, the CH_4 released by the digester was burned to produce electricity on the farm. The CO_2 produced from burning this CH_4 is considered biogenic, meaning it originates from organic material that absorbed CO_2 during photosynthesis. As such, it is considered carbon–neutral for this accounting, as the amount of CO_2 sequestered during biomass growth is equal to the amount released during combustion (Canadell et al., 2021; FAO, 2006; Pulles et al., 2022). Therefore, CO_2 emissions from the combustion of biogenic fuels are not included in the national emission totals (Pulles et al., 2022).For calculating the net global warming potential (GWP) per farm, the GWP used was as recommended by IPCC Fifth Assessment Report (AR5), without indirect climate forcings (28 times CO_2 equivalent for CH_4 and 265 for N_2O) (IPCC, 2013). To convert the gases from CH_4-C, CO_2-C, N_2O-N into CH_4, CO_2, and N_2O, we multiplied the molar mass of each gas and divided it by the molar mass of C or N (ConvertUnits.com, 2022). Simulations were done on a per hectare basis in the soil model. To generate the net GWP per ha for the whole farm, we used the equivalent in terms of livestock unit coefficient (LUC) per ha for both cows and heifers. The stocking rate for all livestock types was expressed on a livestock unit (LU) basis (i.e. 1.4 LU ha^{-1} for the confinement system and 3 LU ha^{-1} for the pasture-based system (Beukes et al., 2017; EUROSTAT, 2020; Reinsch et al., 2021).

To understand the environmental impact and farm C and N emission of on-farm agricultural practices and farm production, we established system boundaries that encompass the farm gate life cycle stage (Akert et al., 2020). This approach allows for estimating C and N on-farm emission. This means that upstream and downstream emissions related to transportation, processing, packaging, or retailing of the products were not included in the budgets presented here. These emissions only include C and N flows on farm and do not include upstream emissions, such as feed or fertilizer manufacture or downstream sources, such as transport.

Farm C emission can be expressed as follows:

$$Farm\ C\ emission = \Sigma(GHGs\ emitted)/(Amount\ of\ FPCM) \quad (7)$$

where GHGs emitted is the sum of all direct and indirect GHG emissions from the farm gate lifecycle (i.e., CO_2, CH_4, N_2O, NH_3, NO_3^-), and FPCM is the amount of fat protein corrected milk produced.

The equation for calculating the farm N emission can be expressed as follows:

$$Farm\ N\ emission = \Sigma(N\ emissions\ emitted)/(amount\ of\ FPCM) \quad (8)$$

where Σ (N emissions emitted) is the sum of all N-related emissions from the farm gate lifecycle (i.e., N_2O, NH_3, NO_3^-).

3. Results

3.1. Farm carbon and nitrogen emission

The farm gate C and N emissions of the two dairy systems (the confinement system and the pasture-based system) are presented in Table 4. The farm C emission, which represents the total amount of farm-gate GHG (CO_2-eq) divided by total amount of FPCM (kg), of the confinement system was 1.01 kg CO_2-eq kg^{-1} FPCM. The pasture-based system had a lower farm C emission, with values ranging from 0.68 to 0.97 kg CO_2-eq kg^{-1} FPCM, depending on the monitoring year over the four-year simulation period. The farm N emission, which represents farm-gate total N emissions divided by total amount of FPCM (kg), of the confinement system was 0.0300 kg N kg^{-1} FPCM. In contrast, the pasture-based system had a lower farm N emission ranging from 0.0047 to 0.0085 kg N kg^{-1} FPCM over the monitoring period. Methane represented the largest source of emissions with 78 % to 90 % of the GHG farm emission over the 4-year period in the pasture-based system, whilst it represented 63 % in the confinement system. The second major source was N_2O emissions which comprised 32 % in the confinement system and 7–10 % in the pasture-based system.

3.2. Farm carbon and nitrogen cycles

The flows of C and N representing the C and N cycles through different farm components, are in Fig. 1. All the inputs and outputs (in kg C or N per ha per year) for both case study farms were incorporated into the flows. The results indicate that the PB models captured the differences in inputs (e.g., N and C intake, fertilizer N) and variation in outputs from the systems in the form of direct and indirect GHG and N emissions, between the two systems, and across the years in the pasture-based system. In terms of the C cycle, CH_4 emissions in the confinement system comprised 65 % (672.1 kg CH_4-C ha^{-1} $year^{-1}$), while CO_2-C was 34 % (347.7 kg CO_2-C ha^{-1} $year^{-1}$) and ΔSOC was a net sink of −6.6 kg C ha^{-1} $year^{-1}$. For pasture-based system, CH_4-C emissions comprised 31 %-82 % (244.8–278.1 kg CH_4-C ha^{-1} $year^{-1}$), while ΔSOC was 18 %-69 % (−549.5 to 104.1 kg C ha^{-1} $year^{-1}$) depending on the year.

The principal N loss pathway in the confinement system was NO_3^- leaching, which comprised 60 % (61.1 kg N ha^{-1}) of N loss, followed by NH_3 volatilization (37.9 kg N ha^{-1}) which comprised 37 %. In contrast, N_2O emissions only comprised 3 % or 2.8 kg N ha^{-1} of total N loss (Table 4). In the pasture-based system the distribution of emissions changed depending on each year. Nitrate leaching comprised 2 %-6% (1.1– 6.4 kg N ha^{-1}), NH_3 volatilization ranged from 93 % – 96 % (57.5–105.0 kg N ha^{-1}), and N_2O emissions comprised 2 % – 3 % (1.5–2.1 kg N ha^{-1}).

3.3. Whole-farm carbon and nitrogen emissions

The results of the impact of variation in dietary inputs between categories of animals in the confinement system and years in the pasture-based system on predicted direct (i.e., CO_2, CH_4, N_2O, ΔSOC) and indirect (i.e., NH_3, NO_3^-) GHG and N emissions at the farm scale are shown in Table 5. The ΔSOC represents the change in SOC and is calculated from the gross primary production, total ecosystem respiration, leached C, excreta inputs and C consumed/cut from the system. Substantial differences were found in overall emissions between the two

Table 4
farm carbon and nitrogen emission of milk of the case study dairy systems; confinement (Farm 1) and pasture-based system (Farm 2).

Farm		Farm 1	Farm 2			
Monitoring period		2018–2019	2011–2012	2012–2013	2013–2014	2014–2015
Farm carbon emission (kg CO_2-eq kg^{-1} FPCM)						
	CO_2	0.04	0.00	0.00	0.00	0.00
	CH_4 (enteric + manure)	0.65	0.84	0.77	0.78	0.76
	N_2O (direct + indirect)	0.33	0.10	0.07	0.07	0.08
	ΔSOC	−0.01	0.03	−0.16	−0.02	−0.05
	Total	**1.01**	**0.97**	**0.68**	**0.83**	**0.79**
Farm nitrogen emission (kg N kg^{-1} FPCM)						
	NH_3-N	0.0042	0.0079	0.0045	0.0051	0.0051
	N_2O-N	0.0006	0.0002	0.0001	0.0001	0.0002
	Leached NO_3^--N	0.0253	0.0005	0.0001	0.0001	0.0002
	Total	**0.0300**	**0.0085**	**0.0047**	**0.0053**	**0.0055**

FPCM: fat protein corrected milk. CO_2 emissions arise from the barn, digester, and slurry tank. CH_4 emissions arise from enteric fermentation from animals, and manure management (barn, digester and slurry tank), soil emissions represent a sink for CH_4, direct and indirect N_2O emissions arise from the barn and soil, DSOC representing the cumulative change in soil organic carbon.

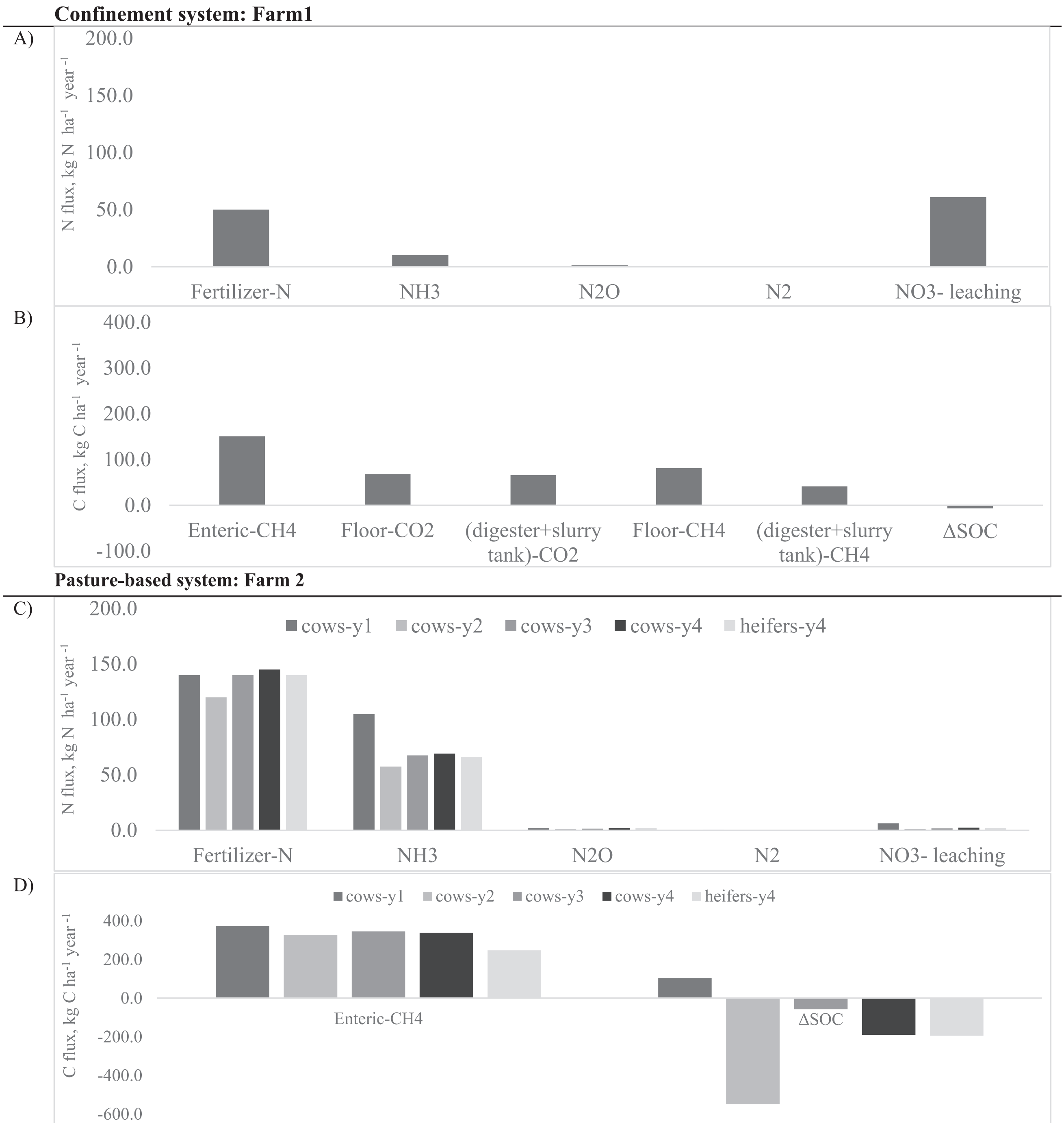

Fig. 1. carbon (C) and nitrogen (N) cycles flows at farm scale (all the N or C inputs and outputs in C or N flux, in kg ha^{-1} year^{-1}) for the confinement (Farm 1) and pasture-based system (Farm 2).

farming systems. This was mainly because there was a large proportion of tillage in the confinement system compared with permanent pasture only for the NZ farm system. The interannual variation in emissions in the pasture-based system, and the variation in emissions in different farm components and different categories of cows in the confinement systems was also noted.

The results indicate that pasture-based systems had lower total emissions per head (Fig. 2) and per ha (Table 5) compared to confinement systems across all years. When comparing emissions per farm component on a ha basis (i.e.. CO_2-eq ha^{-1} year^{-1}) (Table 6), the highest total emissions in both systems were attributed to enteric CH_4. Emissions ranged from between 45 % in the confinement system, to between 76 % to 89 % in the pasture-based system (depending on the years and animal category). Soil emissions constituted the second largest emission source ranging between 14 % to 24 %, respectively. The manure management emissions from the barn were 38 %, whilst digester and slurry tank contributed 14 %, and soil (3 %) of total emissions from the confinement system.

Furthermore, the predicted emissions were consistent across years in the pasture-based system when expressed in terms of CO_2-eq head^{-1} year^{-1} as in Fig. 2. However, the proportions of emissions from each source change slightly. For the confinement system, emissions from animals, barn, manure management, and soil account for 44 %, 37 %, 6 %, and 13 % of the total respectively. For the pasture-based system,

Table 5
Integral assessment of direct and indirect carbon and nitrogen emissions for the confinement (farm 1, one year simulation) and pasture-based system (farm 2, 4-year simulation for cows and one year for heifers).

Farm	monitoring period	category	source	Carbon emissions (kg C ha^{-1} $year^{-1}$)			Nitrogen emissions (kg N ha^{-1} $year^{-1}$)		
				CH_4-C	CO_2-C	ΔSOC-C	N_2O-N	NH_3-N	NO_3^--N
Farm 1	2018–2019	HL-cows	animals	141.7	0.0	0.0	0.0	0.0	0.0
		LL-cows	animals	129.9	0.0	0.0	0.0	0.0	0.0
		dry-cows	animals	69.0	0.0	0.0	0.0	0.0	0.0
		HL-cows	barn	96.0	82.2	0.0	0.6	8.3	0.1
		LL-cows	barn	84.3	70.4	0.0	0.6	8.1	0.1
		dry-cows	barn	63.9	53.7	0.0	0.3	4.4	0.1
			digester	22.0	33.0	0.0	0.0	0.0	0.0
			slurry tank	67.0	108.4	0.0	0.1	8.9	0.0
			soil	−1.7	0.0	−6.6	1.2	8.0	60.8
	Total			**672.1**	**347.7**	**−6.6**	**2.8**	**37.9**	**61.1**
Farm 2	2011—2012	cows	animals	278.4	0.0	0.0	0.0	0.0	0.0
			soil	−0.3	0.0	104.1	2.1	105.0	6.4
	Total			**278.1**	**0.0**	**104.1**	**2.1**	**105.0**	**6.4**
	2012—2013	cows	animals	245.3	0.0	0.0	0.0	0.0	0.0
			soil	−0.6	0.0	−549.5	1.4	57.5	1.1
	Total			**244.8**	**0.0**	**−549.5**	**1.4**	**57.5**	**1.1**
	2013—2014	cows	animals	258.5	0.0	0.0	0.0	0.0	0.0
			soil	−0.4	0.0	−57.4	1.5	67.6	1.8
	Total			**258.1**	**0.0**	**−57.4**	**1.5**	**67.6**	**1.8**
	2014—2015	cows	animals	253.4	0.0	0.0	0.0	0.0	0.0
			soil	−0.4	0.0	−190.0	2.0	69.2	2.3
	Total			**253.0**	**0.0**	**−190.0**	**2.0**	**69.2**	**2.3**
	2014—2015	Heifers	animals	264.5	0.0	0.0	0.0	0.0	0.0
			soil	−0.4	0.0	−194.1	2.1	66.2	2.1
	Total			**264.1**	**0.0**	**−194.1**	**2.1**	**66.2**	**2.1**

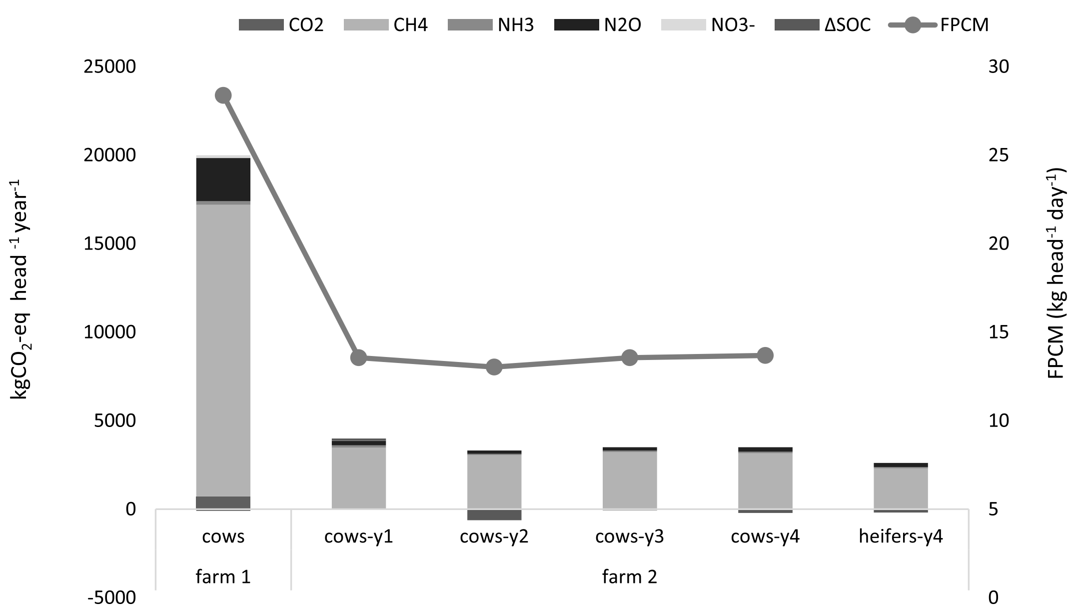

Fig. 2. Comparison of contribution of direct and indirect greenhouse gas emission sources and fat protein corrected milk (FPCM) for confinement (Farm 1) and pasture-based system (Farm 2).

emissions from animals and soil ranged between 77 % to 90 % and 13 % to 23 % of the total, respectively.

Emissions of CO_2, CH_4, NH_3, N_2O, NO_3^- expressed in terms of CO_2-eq $head^{-1}$ $year^{-1}$ are dominated by different farm components as well. Enteric fermentation comprised 54 % of total CH_4 emissions (CO_2-eq $head^{-1}$ $year^{-1}$) for the confinement system. The remainder was produced from the barn (38 %), slurry tank (5 %) and digester (2 %). By contrast, the vast majority of CH_4 arose from enteric fermentation in the pasture-based system. Soil in both systems served as a sink for a small fraction of CH_4 that arose from soil (0.1–1.5 %). The bulk of direct and indirect N_2O emissions from the confinement system emerged from soil, while 100 % arise from the soil in the pasture-based system.

4. Discussion

4.1. Farm carbon and nitrogen emissions

In terms of farm-gate GHG footprint, these results are within the range of the findings of Ledgard et al. (2019) who reported GHG footprints ranging from 0.71 to 0.75 CO_2-eq kg^{-1} FPCM in New Zealand dairy systems using country-specific EF and life cycle assessment models, and 1.2–1.5 kg CO_2-eq kg^{-1} FPCM for German confinement systems, using an LCA approach (Naranjo et al., 2020; Reinsch et al., 2021) and a combination of measured data and IPCC methodology (Robert Kiefer et al., 2015). Simulated values ranging from 0.56 to 1.37

Table 6
Integral assessment of direct and indirect carbon and nitrogen emissions for the confinement (farm1, germany, one year simulation) and pasture-based system (farm 2, new zealand, 4-year simulation for cows and one year for heifers).

Farm	monitoring period	category	source	GWP (kg CO_2-eq ha^{-1} yr^{-1})						Total emissions (kg CO_2-eq ha^{-1} yr^{-1})
				Carbon emissions			Nitrogen emissions			
				CH_4	CO_2	ΔSOC	Direct N_2O	Indirect N_2O–NH_3	Indirect N_2O – NO_3^-	
Farm 1	2018–2019	HL-cows	animals	5299.3	0.0	0.0	0.0	0.0	0.0	5299.3
		LL-cows	animals	4859.6	0.0	0.0	0.0	0.0	0.0	4859.6
		dry-cows	animals	2579.4	0.0	0.0	0.0	0.0	0.0	2579.4
		HL-cows	barn	3591.9	301.3	0.0	230.5	34.7	0.6	4159.0
		LL-cows	barn	3152.2	257.8	0.0	232.2	33.9	0.6	3676.7
		dry-cows	barn	2391.5	196.8	0.0	131.7	18.3	0.3	2738.7
			digester	821.9	120.8	0.0	0.0	0.1	0.0	942.9
			slurry tank	2505.0	397.2	0.0	50.8	37.2	0.0	2990.3
			soil	−64.9	0.0	−24.1	518.5	33.4	278.3	741.2
	Total			**25135.9**	**1274.0**	**−24.1**	**1163.7**	**157.7**	**279.8**	**27987.1**
Farm 2	2011—2012	cows	animals	10413.1	0.0	0.0	0.0	0.0	0.0	10413.1
			soil	−12.0	0.0	381.4	853.5	437.3	29.3	1689.6
	Total			**10401.1**	**0.0**	**381.4**	**853.5**	**437.3**	**29.3**	**12102.7**
	2012—2013	cows	animals	9175.7	0.0	0.0	0.0	0.0	0.0	9175.7
			soil	−21.3	0.0	−2013.5	599.5	239.5	5.1	−1190.7
	Total			**9154.4**	**0.0**	**−2013.5**	**599.5**	**239.5**	**5.1**	**7985.0**
	2013—2014	cows	animals	9668.9	0.0	0.0	0.0	0.0	0.0	9668.9
			soil	−15.3	0.0	−210.2	641.2	281.4	8.1	705.2
	Total			**9653.6**	**0.0**	**−210.2**	**641.2**	**281.4**	**8.1**	**10374.1**
	2014—2015	cows	animals	9477.0	0.0	0.0	0.0	0.0	0.0	9477.0
			soil	−15.3	0.0	−696.3	845.2	287.9	10.7	432.2
	Total			**9461.6**	**0.0**	**−696.3**	**845.2**	**287.9**	**10.7**	**9909.2**
	2014—2015	Heifers	animals	9891.1	0.0	0.0	0.0	0.0	0.0	9891.1
			soil	−13.8	0.0	−711.3	886.8	275.6	9.5	446.8
	Total			**9877.3**	**0.0**	**−711.3**	**886.8**	**275.6**	**9.5**	**10337.9**

HL: high lactating, LL: late lactating, GWP: global warming potential.

kg CO_2-eq l^{-1} milk were reported, using a semi mechanistic model SIMSDairy (Del Prado et al., 2011; Díaz de Otálora et al., 2024). However, if indirect N_2O emissions from NH_3 and NO_3^- were included, the total GHG emissions for the studied dairy systems increased by approximately 0.15 to 0.19 kg CO_2-eq l^{-1} milk. Lower values for farm-to-gate C footprint ranging from 0.37 to 0.69 CO_2-eq kg^{-1} FPCM were reported in confined, dry lot and grazing dairy systems using DairyGHG model Rotz et al. (2010), while values ranging from 0.75 to 1.21 CO_2-eq kg^{-1} FPCM were reported using the Integrated Farm System Model (Rotz, 2018).

The farm N emission for the pasture-based system was lower, with an average of 0.006 (i.e., average of the four years) kg N kg^{-1} FPCM compared to 0.03 kg N kg^{-1} FPCM for the confinement system. Previous studies for feedlot systems have ranged from 0.012 kg N kg^{-1} FPCM to 0.02 kg N kg^{-1} FPCM (Rotz et al., 2021; Veltman et al., 2018) and from 0.008 to 0.06 kg N kg^{-1} FPCM (Ledgard et al., 2019; Mu et al., 2016). Including ΔSOC into the budget of emissions resulted in either a reduction of 3 % in emissions or increase of 2 %–23 % when ΔSOC was negative (a sink) or positive (a source) respectively in a specific year in the pasture-based system. This agrees with the trend of other studies that show that SOC sequestration may significantly impact and contributes to reducing C footprint in livestock systems, depending on land-use (Idrissou et al., 2024). Furthermore, the comparatively large land area in the confinement system, which was 905 ha, amplified the proportional contribution of direct and indirect N_2O emissions into the total GHG farm emission (32 %), which is lower (between 20 % to 25 %) in previous studies (Del Prado et al., 2013; Rotz, 2018). Therefore, capturing fluctuations and variability in farm C and N emissions across farming systems and between the years in this study highlights the need for case specific assessments taking into consideration feed and chemical information data and all the biotic and abiotic factors affecting the general budget of on-farm emissions. This means these factors have to be taken into account when making decisions on how to reduce on-farm C and N emissions.

4.2. Impact of production system and choice of metrics on GHG and N emissions

Comparing total emissions in terms of CO_2-eq per ha or per head resulted in the German feedlot farm having the highest total emissions due to the emissions coming from the barn and to a lesser extent from the slurry tank and digester. This difference ranges from 1.3 to 2.5 times more emissions from the confinement system compared to the pasture-based system when expressed on a per unit area basis, to 4.0–6.4 times when expressed on a per head basis, and 1.2–1.5 times when expressed on a per FPCM basis. This indicates that stocking rates assumed, production per cow and number of animals significantly impacted the metric used to express and compare total emissions between different production systems.

The type of production system also affects the breakdown and level of CH_4, N_2O and CO_2, NO_3, NH_3 emissions and C sequestration. Direct and indirect GHG emissions are enhanced by high intensity farming that requires high levels of applied manure and fertilizer (Ibarra et al., 2019). For this reason, climatic conditions and the type of dairy production system must be considered while exploring different mitigation measures at the farm level. For example, a higher risk of excessive emissions to the environment through leaching could be related to intensifying livestock production under extremely humid conditions. The PB models may be best suited to assess the downstream impact of the management and biotic and abiotic factors on GHG and N emissions at the farm level.

4.3. Capturing the downstream impact of diet on whole-farm GHG and N emissions

The integral on-farm GHG and N emissions were generated by exchanging the outputs-inputs between the dynamic and mechanistic models at the different stages of the manure management chain. The direct and indirect GHG emissions sources including C sequestration/accumulation (ΔSOC) were included in this study's global farm GHG budget. The simulations examined the transformations of C and N flows in the digestive systems of dairy cattle, as well as the downstream effects on C and N dynamics, throughout the manure management chain. Additionally, the consequences of excretion on C and N dynamics in housing and stored manure were considered, along with the emissions of NH_3 and NO_3^- in soil. These processes are of great importance, as they contribute to indirect N_2O emissions from manure and its deposition into ecosystems and are to be an integral part of any farm system assessment.

The combining of various mechanistic modeling frameworks into a comprehensive model has been tackled by other studies (Veltman et al., 2018), but not for the whole-farm budget that includes direct and indirect emission sources and SOC. For example, Hempel et al. (2022) investigated the coupling of different mechanistic modelling techniques into a whole barn-scale NH_3 emission model, including the dietary and chemical composition data, in naturally ventilated dairy housing systems, and Rotz et al., (2014) also developed a whole PB farm model for NH_3 emission from dairy farms. At the farm scale, whole-farm models are generally adopted to quantify emissions in grassland and confinement systems. However, these farm-scale models rely heavily on EFs and empirical relationships to estimate emissions and are mainly based on IPCC Tier 2 EFs (Del Prado et al., 2013; Rotz, 2018). Nonetheless, this approach does not always capture the detailed underlying processes and variations in the drivers that impact emissions. For example, whilst dietary effects on enteric CH_4 could be considered as well controlled and reproducible, with the ruminant host closely regulating rumen fermentation conditions with continuous inflow and outflow, N_2O emissions and possibly C sequestration are influenced by high variability of climate on soil conditions and vegetation. As a result, the timing of field operations and the extent (amount) of an activity have fundamental influences on the latter's emissions rate.

Enteric CH_4 in this study is modelled depending on the lactation stage for the confinement system with values ranging from (kg head^{-1} year^{-1}) 65.80 for dry cows, 123.97 for late lactating cows and 135.19 for high lactating cows. These findings align with the results found in the literature (Dämmgen et al., 2012). Besides, different levels of feed intake and CP content have been associated with variations in N emissions (Hoekstra et al., 2020), which was captured in this study by taking the level of feed intake and CP levels for each category of animals into account. The variation in concentrates levels between the different animal categories with distinct levels of lactation was also captured in this study, which was reported to have an impact on enteric CH_4 production (Duthie et al., 2017; van Wyngaard et al., 2018).

Dietary composition not only influences enteric CH_4 emissions but also directly impacts the composition and quantity of cattle excreta (Bougouin et al., 2022; Hilgert et al., 2023), which impacts downstream housing and manure management practices, and subsequent field emissions. The modelled CH_4 emission for the housing facility was between 61.01 to 91.63 kg CH_4 head^{-1} year^{-1} for dry cows and high lactating cows respectively, which shows the impact of the level of feed intake on excretion and emissions. Different excreta released by different categories of cows have different capacities to produce CH_4 during storage due to variability in the amount and composition (Cárdenas et al., 2021). These values were rather low in this study, due to a very low residence time of the manure in manure pit prior to anaerobic digestion or slurry tank storage (3–4 days). systems. The values fall within the range reported in a *meta*-analysis by Çinar et al. (2023). Comparable values were found in tie stall slurry based systems (Amon et al., 2001; Sajeev et al., 2018), and higher values were reported by Jayasundara et al. (2016) in freestall confinement systems.

For soil emissions from the pasture-based system, the PB model appears to be able to capture inter-annual variation in emissions. Nitrous oxide emission arising from soil were slightly lower in the pasture-based system (1.4–2.1 kg N_2O–N ha^{-1} year^{-1}) compared to the confinement system (2.8 kg N_2O–N ha^{-1} year^{-1}). These emissions from both systems were generally higher than the values reported by Kasper et al. (2019) using DNDC model, that were ranging from 0.15 to 1.29 kg N_2O–N ha^{-1} year^{-1}. In the confinement system the relatively high NO_3^- leaching (61.1 kg NO_3^--N ha^{-1} year^{-1}) compared to the pasture-based system was probably due to heavy rainfall events during the monitoring period, the sandy soil texture and the use of nitrate-based fertilizers. Nevertheless, higher values reaching 149.3 kg NO_3^-–N ha^{-1} year^{-1} were reported by the same study (Kasper et al., 2019). However, indirect N_2O emissions resulting from NH_3 volatilization were higher in the pasture-based system due, in part, to the use of urea-based fertilizer compared to ammonium nitrate in the confinement systems (57.5—105.0 NH_3–N ha^{-1} year^{-1}). These differences in emissions are principally driven by soil moisture content, the climate conditions, fertilizer applications, and manure that is deposited during grazing into soil. Indeed, findings indicate that maximizing the efficiency of cow manure utilization as fertilizer can result in substantial environmental advantages (Zhang et al., 2023).

The whole farm budget of emissions (in t CO_2-eq ha^{-1}) was 28.0 tCO_2-eq ha^{-1} for the confinement system and ranged between 8.0 and 12.1 tCO_2-eq ha^{-1} for the pasture-based system. Lower results were observed in a study by Del Prado et al. (2013), where emissions of 13.2 t CO_2-eq ha^{-1}, 11.4 t CO_2-eq ha^{-1}, and 16.1 t CO_2-eq ha^{-1} were reported for the confinement, partial grazing, and extended grazing systems, respectively, using a whole farm modeling approach. In terms of whole fam emissions in tCO_2-eq head^{-1}, Rotz (2018) reported total farm emissions ranging from 8.1 tCO_2-eq head^{-1} to 8.3 tCO_2-eq head^{-1} in grazing systems in New Zealand and Ireland, and emissions of 9.3 tCO_2-eq head^{-1} to 12.5 tCO_2-eq head^{-1} in confinement systems in USA using a whole farm system model. The results from the pasture-based system that ranges between 2.7 and 4.0 tCO_2-eq head^{-1} are lower than these reported values. However, the confinement system had higher emissions (19.9 tCO_2-eq head^{-1}). In New Zealand context, values ranging between 10.8 and 20.6 tCO_2-eq ha^{-1} year^{-1} were reported using a combination of mechanistic and IPCC based approach (Beukes et al., 2011; van der Weerden et al., 2018), which are in the range of the findings of the present study. However, the values of the present study varied between the years and included ΔSOC, which shows that using a cascade of mechanistic models captures inter-annual variations within the system that an IPCC based approach may not take into account.

These findings indicate that different livestock production systems have different emissions profils across years depending on the levels of feed intake, the chemical composition of the diets, and the management and climate aspects. However, as the PB models account for differences in climate and soil type, these differences can magnify or reduce different cohorts of emissions. This is particularly evident in the leached losses from the German farm due to its sandy soils and the inter-annual variation in direct N_2O emissions from the NZ farm, which were partly climate driven. Therefore, use of PB models to evaluate management strategies may be a tailored application to minimize their environmental impact in contrast to generic equations and static farm-level models that fall short in capturing the dynamics of C and N biogeochemical cycling within the farm. In this regard, inputs and outputs could be compatible and exchangeable across the models, which could communicate, so there aren't any major limitations on the combined use of the models.

Nevertheless, PB models have considerable drawbacks, including complexity, computing needs, and reliance on substantial and precise data. These models need rigorous calibration and validation since they can increase uncertainty owing to assumptions and simplifications. Data gaps, overfitting, and scaling issues may also impact their effectiveness.

Additionally, PB model accessibility could be constrained, and it's still difficult to effectively capture complicated interactions and feedback. Multidisciplinary efforts, improved data collecting, and continual model improvement are required to address these shortcomings to increase the models' validity and application.

5. Conclusions

This study used a novel PB modeling framework to evaluate the downstream impact of feeding management on whole farm GHG and N emissions in a confinement and a pasture-based case study dairy cattle farm. The results indicate that this approach effectively capture variations across different farm components, years, and categories of animals under diverse climate conditions. Confinement systems tend to have higher emissions due to intensive feed and manure management practices, whereas pasture-based systems may have lower emissions but could be affected by soil and vegetation management. Developing a PB modeling framework for different farm components and levels of manure management chain, enhances our understanding of how ruminant diets affect GHG and N emissions, as well as the mechanisms by which farm management and the dairy sector may influence C and N cycles. This understanding can guide future policies and management practices aimed at reducing whole-farm emissions. However, research efforts are needed to improve the accuracy and calibration of the PB models based on local conditions, to evaluate the effectiveness of mitigation strategies, and understanding the interaction between feeding strategies and climate change on whole-farm emissions. Future studies should focus on comparing farms of similar sizes and datasets to further validate the PB model's applicability across diverse farming systems. The PB models or the PB modelling framework should be open access and well-documented to facilitate further development, adoption and calibration by the community of users. These models should also be evaluated against independent measurements and farming conditions.

CRediT authorship contribution statement

Latifa Ouatahar: Writing – original draft, Visualization, Investigation. **André Bannink:** Writing – review & editing, Methodology, Conceptualization. **Jürgen Zentek:** Writing – review & editing. **Thomas Amon:** Conceptualization. **Jia Deng:** Writing – review & editing, Methodology. **Sabrina Hempel:** Writing – review & editing, Validation. **David Janke:** Writing – review & editing, Validation. **Pierre Beukes:** Writing – review & editing, Investigation. **Tony van der Weerden:** Writing – review & editing. **Dominika Krol:** Conceptualization. **Gary J. Lanigan:** Writing – review & editing, Supervision, Methodology. **Barbara Amon:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This article was produced as part of the Capturing Effects of Diet on Emissions from Ruminant Systems (CEDERS) project, a FACCE ERA-GAS-funded project. The lead author is supported by the Teagasc Walsh Scholarship Fund and The Leibniz Institute for Agricultural Engineering and Bioeconomy-ATB Potsdam. The participant of Jia Deng was supported by California Air Resource Board (contract number: 21RD019). The contribution of Pierre Beukes was supported by New Zealand dairy farmers. We thank Detlef May and Kathleen Biscoff for their assistance in data collection. We further acknowledge fruitful discussions with Sebastian Vogel and his assistance on the soil data collection. We further thank Mario Fernandez and Ben Marmont for revising the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.07.007.

References

Akert, F.S., Dorn, K., Frey, H., Hofstetter, P., Berard, J., Kreuzer, M., Reidy, B., 2020. Farm-gate nutrient balances of grassland-based milk production systems with full- or part-time grazing and fresh herbage indoor feeding at variable concentrate levels. Nutr. Cycl. Agroecosystems 383–400. https://doi.org/10.1007/s10705-020-10072-y.

Amon, B., Amon, T., Boxberger, J., Alt, C., 2001. Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr. Cycl. Agroecosystems 60, 103–113. https://doi.org/10.1023/A:1012649028772.

Bannink, A., van Schijndel, M.W., Dijkstra, J., 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the dutch national inventory report using the IPCC Tier 3 approach. Anim. Feed Sci. Technol. 166–167, 603–618. https://doi.org/10.1016/j.anifeedsci.2011.04.043.

Bannink, A., Spek, W.J., Dijkstra, J., Šebek, L.B.J., 2018. A tier 3 method for enteric methane in dairy cows applied for fecal N digestibility in the ammonia inventory. Front. Sustain. Food Syst. 2 https://doi.org/10.3389/fsufs.2018.00066.

Beukes, P.C., Gregorini, P., Romera, A.J., 2011. Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. Anim. Feed Sci. Technol. 166–167, 708–720. https://doi.org/10.1016/j.anifeedsci.2011.04.050.

Beukes, P.C., Romera, A.J., Gregorini, P., Macdonald, K.A., Glassey, C.B., Shepherd, M. A., 2017. The performance of an efficient dairy system using a combination of nitrogen leaching mitigation strategies in a variable climate. Sci. Total Environ. 599–600, 1791–1801. https://doi.org/10.1016/j.scitotenv.2017.05.104.

Beukes, P.C., Gregorini, P., Cameron, K., Attwood, G.T., 2020. Farm-scale carbon and nitrogen fluxes in pastoral dairy production systems using different nitrogen fertilizer regimes. Nutr. Cycl. Agroecosystems 117, 1–12. https://doi.org/10.1007/s10705-020-10052-2.

Bougouin, A., Hristov, A., Dijkstra, J., Aguerre, M.J., Ahvenjärvi, S., Arndt, C., Bannink, A., Bayat, A.R., Benchaar, C., Boland, T., Brown, W.E., Crompton, L.A., Dehareng, F., Dufrasne, I., Eugène, M., Froidmont, E., van Gastelen, S., Garnsworthy, P.C., Halmemies-Beauchet-Filleau, A., Herremans, S., Huhtanen, P., Johansen, M., Kidane, A., Kreuzer, M., Kuhla, B., Lessire, F., Lund, P., Minnée, E.M. K., Muñoz, C., Niu, M., Nozière, P., Pacheco, D., Prestløkken, E., Reynolds, C.K., Schwarm, A., Spek, J.W., Terranova, M., Vanhatalo, A., Wattiaux, M.A., Weisbjerg, M.R., Yáñez-Ruiz, D.R., Yu, Z., Kebreab, E., 2022. Prediction of nitrogen excretion from data on dairy cows fed a wide range of diets compiled in an intercontinental database: a meta-analysis. J. Dairy Sci. 105, 7462–7481. https://doi.org/10.3168/jds.2021-20885.

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cunha, L.C. da, Cox, P.M., Eliseev, A.V., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P.K., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S., Zickfeld, K., (2021). Global Carbon and Other Biogeochemical Cycles and Feedbacks, in: Climate Change 2021 – The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816. DOI: 10.1017/9781009157896.007.

Cárdenas, A., Ammon, C., Schumacher, B., Stinner, W., Herrmann, C., Schneider, M., Weinrich, S., Fischer, P., Amon, T., Amon, B., 2021. Methane emissions from the storage of liquid dairy manure: influences of season, temperature and storage duration. Waste Manag. 121, 393–402. https://doi.org/10.1016/j.wasman.2020.12.026.

Çinar, G., Dragoni, F., Ammon, C., Belik, V., van der Weerden, T.J., Noble, A., Hassouna, M., Amon, B., 2023. Effects of environmental and housing system factors on ammonia and greenhouse gas emissions from cattle barns: a meta-analysis of a global data collation. Waste Manag. 172, 60–70. https://doi.org/10.1016/j.wasman.2023.09.007.

ConvertUnits.com, 2022. Molecular weights [WWW Document]. ConvertUnits. URL https://www.convertunits.com/molarmass/N2O (accessed 9.20.22).

CVB, 2018. CVB Feed Table 2019 Chemical composition and nutritional values of feedstuffs, Livestock Research Wageningen UR.

Dämmgen, U., Rösemann, C., Haenel, H.-D., Hutchings, N.J., 2012. Enteric methane emissions from German dairy cows. Landbauforsch. Volkenrode 62, 21–31.

David Yáñez-Ruiz, A.R., Morgavi, D., Misselbrook, T., Melle, M., Dreijere, S., Aes, O., Sekowski, M., (2018). Mini-paper: Feeding strategies to reduce methane and ammonia emissions.

de Ondarza, M.B., Tricarico, J.M., 2017. REVIEW: advantages and limitations of dairy efficiency measures and the effects of nutrition and feeding management interventions. Prof. Anim. Sci. 33, 393–400. https://doi.org/10.15232/pas.2017-01624.

Del Prado, A., Misselbrook, T., Chadwick, D., Hopkins, A., Dewhurst, R.J., Davison, P., Butler, A., Schröder, J., Scholefield, D., 2011. SIMS DAIRY : a modelling framework to identify sustainable dairy farms in the UK. Framework description and test for organic systems and N fertiliser optimisation. Sci. Total Environ. 409, 3993–4009. https://doi.org/10.1016/j.scitotenv.2011.05.050.

Del Prado, A., Crosson, P., Olesen, J.E., Rotz, C.A., 2013. Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems. Animal 7 (Suppl 2), 373–385. https://doi.org/10.1017/S1751731113000748.

Deng, J., Li, C., Wang, Y., 2015. Modeling ammonia emissions from dairy production systems in the United States. Atmos. Environ. 114, 8–18. https://doi.org/10.1016/j.atmosenv.2015.05.018.

Deng, J., Xiao, J., Ouimette, A., Zhang, Y., Sanders-DeMott, R., Frolking, S., Li, C., 2020. Improving a biogeochemical model to simulate surface energy, greenhouse gas fluxes, and radiative forcing for different land use types in northeastern United States. Global Biogeochem. Cycles 34. https://doi.org/10.1029/2019GB006520.

Díaz de Otálora, X., Amon, B., Balaine, L., Dragoni, F., Estellés, F., Ragaglini, G., Kieronczyk, M., Jørgensen, G.H.M., del Prado, A., 2024. Influence of farm diversity on nitrogen and greenhouse gas emission sources from key European dairy cattle systems: a step towards emission mitigation and nutrient circularity. Agric. Syst. 216 https://doi.org/10.1016/j.agsy.2024.103902.

Dijkstra, J., DSrC MEAL, H., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J. Nutr 122, 2239–2256. https://doi.org/10.1093/jn/122.11.2239.

Dijkstra, J., Oenema, O., van Groenigen, J.W., Spek, J.W., van Vuuren, A.M., Bannink, A., 2013. Diet effects on urine composition of cattle and N2O emissions. Animal 7 (Suppl 2), 292–302. https://doi.org/10.1017/S1751731113000578.

Dijkstra, J., Bannink, A., Bosma, P.M., Lantinga, E.A., Reijs, J.W., 2018. Modeling the effect of nutritional strategies for dairy cows on the composition of excreta nitrogen. Front. Sustain. Food Syst. 2 https://doi.org/10.3389/fsufs.2018.00063.

Duthie, C.A., Haskell, M., Hyslop, J.J., Waterhouse, A., Wallace, R.J., Roehe, R., Rooke, J.A., 2017. The impact of divergent breed types and diets on methane emissions, rumen characteristics and performance of finishing beef cattle. Animal 11, 1762–1771. https://doi.org/10.1017/S1751731117000301.

EUROSTAT, 2020. Livestock unit coefficients 2.

FAO, 2006. Livestock's long shadow: environmental issues and options. Rome, Italy.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Giltrap, D.L., Li, C., Saggar, S., 2010. DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. Agric. Ecosyst. Environ. 136, 292–300. https://doi.org/10.1016/j.agee.2009.06.014.

Hempel, S., Ouatahar, L., Janke, D., Doumbia, E.M., Willink, D., Amon, B., Bannink, A., Amon, T., 2022. Ammonia emission prediction for dairy cattle housing from reaction kinetic modeling to the barn scale. Comput. Electron. Agric. 199, 107168 https://doi.org/10.1016/j.compag.2022.107168.

Hilgert, J.E., Herrmann, C., Petersen, S.O., Dragoni, F., Amon, T., Belik, V., Ammon, C., Amon, B., 2023. Assessment of the biochemical methane potential of in-house and outdoor stored pig and dairy cow manure by evaluating chemical composition and storage conditions. Waste Manag. 168, 14–24. https://doi.org/10.1016/j.wasman.2023.05.031.

Hoekstra, N.J., Schulte, R.P.O., Forrestal, P.J., Hennessy, D., Krol, D.J., Lanigan, G.J., Müller, C., Shalloo, L., Wall, D.P., Richards, K.G., 2020. Scenarios to limit environmental nitrogen losses from dairy expansion. Sci. Total Environ. 707, 134606 https://doi.org/10.1016/j.scitotenv.2019.134606.

Ibarra, a., Merino, P., Mijangos, I., Pinto, M., Garbisu, C., Albizu, I., 2019. Effect of fertilizer source on N 2 O emissions from grasslands. J. Environ. Manage. 250, 811–813.

Idrissou, Y., Vall, E., Blanfort, V., Blanchard, M., Alkoiret Traoré, I., Lecomte, P., 2024. Integrated crop-livestock effects on soil carbon sequestration in Benin. West Africa. Heliyon 10. https://doi.org/10.1016/j.heliyon.2024.e28748.

IPCC, 2006. vol 4. Agriculture, Forestry and Other Land Use, in: IPCC Guidelines for National Greenhouse Inventories. Hayama, Japan.

IPCC, 2013. Anthropogenic and Natural Radiative Forcing: In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Jacob, D., Ravishankara, A.R., Shine, K. (Eds.), IPCC AR5 The Physical Basis. pp. 659–740. DOI: 10.1017/ CBO9781107415324.018.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (CUP), Cambridge, United Kingdom and New York, NY, USA. DOI: https://research.wur.nl/en/publications/deliverable-83-second-version-of-estimates-of-mitigation-and-adap.

IPCC, 2019. Chapter 11: N2O emissions from managed soils, and CO2 emissions from lime and urea application, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. pp. 11.1-11.54.

Jayasundara, S., Ranga Niroshan Appuhamy, J.A.D., Kebreab, E., Wagner-Riddle, C., 2016. Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: an updated review. Can. J. Anim. Sci. 96, 306–331. https://doi.org/10.1139/cjas-2015-0111.

Joo, H.S., Ndegwa, P.M., Heber, A.J., Ni, J.Q., Bogan, B.W., Ramirez-Dorronsoro, J.C., Cortus, E., 2015. Greenhouse gas emissions from naturally ventilated freestall dairy barns. Atmos. Environ. 102, 384–392. https://doi.org/10.1016/j.atmosenv.2014.11.067.

Jose, V.S., Sejian, V., Bagath, M., Ratnakaran, A.P., Lees, A.M., Al-Hosni, Y.A.S., Sullivan, M., Bhatta, R., Gaughan, J.B., 2016. Modeling of greenhouse gas emission from livestock. Front. Environ. Sci. 4, 27. https://doi.org/10.3389/fenvs.2016.00027.

Kasper, M., Foldal, C., Kitzler, B., Haas, E., Strauss, P., Eder, A., Zechmeister-Boltenstern, S., Amon, B., 2019. N 2 O emissions and NO 3− leaching from two contrasting regions in Austria and influence of soil, crops and climate: a modelling approach. Nutr. Cycl. Agroecosystems 113, 95–111. https://doi.org/10.1007/s10705-018-9965-z.

Kipling, R.P., Scollan, N.D., Bartley, D., Bellocchi, G., Hutchings, N.J., Dalgaard, T., Dasselaar, A.V. den P., (2014). Modelling livestock and grassland systems under climate change, in: EGF at 50: The Future of European Grassland. Proceedings of the 25th General Meeting of the European Grassland Federation. Aberystwyth, Wales, 7-11 September 2014. pp. 97–99.

Ledgard, S.F., Wei, S., Wang, X., Falconer, S., Zhang, N., Zhang, X., Ma, L., 2019. Nitrogen and carbon footprints of dairy farm systems in China and New Zealand, as influenced by productivity, feed sources and mitigations. Agric. Water Manag. 213, 155–163. https://doi.org/10.1016/j.agwat.2018.10.009.

Leon-Velarde, C.U., McMillan, I., Gentry, R.D., Wilton, J.W., 1995. Models for estimating typical lactation curves in dairy cattle. J. Anim. Breed. Genet. 112, 333–340. https://doi.org/10.1111/j.1439-0388.1995.tb00575.x.

Li, C., (2011). Mitigating Greenhouse Gas Emissions from Agroecosystems : Scientific Basis and Modeling, in: Guo L et al. (Ed.), Understanding Greenhouse Gas Emissions from Agricultural Management. ACS Symposium Series , American Chemical Societ, Washington, DC, p. Chapter 16pp 299-330. DOI: 10.1021/bk-2011-1072.ch016.

Li, C., Frolking, S., Frolking, T.A., 1992a. A model of nitrous oxide evolution from soil driven by rainfall events' 1. Model structure and sensitivity. J. Geophys. Res. 97, 9777–9783. https://doi.org/10.1029/92jd00510.

Li, C., Frolking, S., Frolking, T.A., Li, C., Frolking, S., Frolking, T.A., 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model Applications. J. Geophys. Res. 97, 9777–9783. https://doi.org/10.1029/92jd00510.

Li, C., Salas, W., Zhang, R., Krauter, C., Rotz, A., Mitloehner, F., 2012. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosystems 93, 163–200. https://doi.org/10.1007/s10705-012-9507-z.

Mills, J.A., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E., France, J., 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: model development, evaluation, and application. J. Anim. Sci. 79, 1584–1597. https://doi.org/10.2527/2001.7961584x.

Mu, W., Van Middelaar, C.E., Bloemhof, J.M., Oenema, J., De Boer, I.J.M., 2016. Nutrient balance at chain level: a valuable approach to benchmark nutrient losses of milk production systems. J. Clean. Prod. 112, 2419–2428. https://doi.org/10.1016/j.jclepro.2015.09.116.

Naranjo, A., Johnson, A., Rossow, H., Kebreab, E., 2020. Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. J. Dairy Sci. 103, 3760–3773. https://doi.org/10.3168/jds.2019-16576.

Niu, M., Kebreab, E., Hristov, A.N., Oh, J., Arndt, C., Bannink, A., Bayat, A.R., Brito, A.F., Boland, T., Casper, D., Crompton, L.A., Dijkstra, J., Eugène, M.A., Garnsworthy, P.C., Haque, M.N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., McClelland, S.C., McGee, M., Moate, P.J., Muetzel, S., Muñoz, C., O'Kiely, P., Peiren, N., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yáñez-Ruiz, D.R., Yu, Z., 2018. Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. Glob. Chang. Biol. 24, 3368–3389. https://doi.org/10.1111/gcb.14094.

Ouatahar, L., Bannink, A., Lanigan, G., Amon, B., 2021. Modelling the effect of feeding management on greenhouse gas and nitrogen emissions in cattle farming systems. Sci. Total Environ. 776, 145932 https://doi.org/10.1016/j.scitotenv.2021.145932.

Pulles, T., Gillenwater, M., Radunsky, K., 2022. CO2 emissions from biomass combustion accounting of CO2 emissions from biomass under the UNFCCC. Carbon Manag. 13, 181–189. https://doi.org/10.1080/17583004.2022.2067456.

Reinsch, T., Loza, C., Malisch, C.S., Vogeler, I., Kluß, C., Loges, R., Taube, F., 2021. Toward specialized or integrated systems in northwest europe: on-farm eco-efficiency of dairy farming in germany. Front. Sustain. Food Syst. 5, 1–20. https://doi.org/10.3389/fsufs.2021.614348.

Robert Kiefer, L., Menzel, F., Bahrs, E., 2015. Integration of ecosystem services into the carbon footprint of milk of South German dairy farms. J. Environ. Manage. 152, 11–18. https://doi.org/10.1016/j.jenvman.2015.01.017.

Rotz, C.A., 2018. Symposium review: modeling greenhouse gas emissions from dairy farms. J. Dairy Sci. 101, 6675–6690. https://doi.org/10.3168/jds.2017-13272.

Rotz, C.A., Montes, F., Chianese, D.S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93, 1266–1282. https://doi.org/10.3168/jds.2009-2162.

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43, 1143. https://doi.org/10.2134/jeq2013.04.0121.

Rotz, A., Stout, R., Leytem, A., Feyereisen, G., Waldrip, H., Thoma, G., Holly, M., Bjorneberg, D., Baker, J., Vadas, P., Kleinman, P., 2021. Environmental assessment of United States dairy farms. J. Clean. Prod. 315, 128153 https://doi.org/10.1016/j.jclepro.2021.128153.

Rouwenhorst, R.J., Frank Jzn, J., Scheffers, W.A., van Dijken, J.P., 1991. Determination of protein concentration by total organic carbon analysis. J. Biochem. Biophys. Methods 22, 119–128. https://doi.org/10.1016/0165-022X(91)90024-Q.

Sajeev, E.P.M., Amon, B., Ammon, C., Zollitsch, W., Winiwarter, W., 2018. Evaluating the potential of dietary crude protein manipulation in reducing ammonia emissions from cattle and pig manure: a meta-analysis. Nutr. Cycl. Agroecosystems 110, 161–175. https://doi.org/10.1007/s10705-017-9893-3.

van der Weerden, T., Beukes, P., de Klein, C., Hutchinson, K., Farrell, L., Stormink, T., Romera, A., Dalley, D., Monaghan, R., Chapman, D., Macdonald, K., Dynes, R., 2018. The effects of system changes in grazed dairy farmlet trials on greenhouse gas emissions. Animals 8, 1–20. https://doi.org/10.3390/ani8120234.

van Wyngaard, J.D.V., Meeske, R., Erasmus, L.J., 2018. Effect of concentrate feeding level on methane emissions, production performance and rumen fermentation of Jersey cows grazing ryegrass pasture during spring. Anim. Feed Sci. Technol. 241, 121–132. https://doi.org/10.1016/j.anifeedsci.2018.04.025.

Veltman, K., Jones, C.D., Gaillard, R., Cela, S., Chase, L., Duval, B.D., Izaurralde, R.C., Ketterings, Q.M., Li, C., Matlock, M., Reddy, A., Rotz, A., Salas, W., Vadas, P., Jolliet, O., 2017. Comparison of process-based models to quantify nutrient flows and greenhouse gas emissions associated with milk production. Agric. Ecosyst. Environ. 237, 31–44. https://doi.org/10.1016/j.agee.2016.12.018.

Veltman, K., Rotz, C.A., Chase, L., Cooper, J., Ingraham, P., Izaurralde, R.C., Jones, C.D., Gaillard, R., Larson, R.A., Ruark, M., Salas, W., Thoma, G., Jolliet, O., 2018. A quantitative assessment of beneficial management practices to reduce carbon and reactive nitrogen footprints and phosphorus losses on dairy farms in the US great lakes region. Agric. Syst. 166, 10–25. https://doi.org/10.1016/j.agsy.2018.07.005.

Vibart, R., Klein, C. De, Jonker, A., Weerden, T. Van Der, Bannink, A., Bayat, A.R., Crompton, L., Durand, A., Eugène, M., Klumpp, K., Kuhla, B., Lanigan, G., Lund, P., Ramin, M., Salazar, F., (2021). Challenges and opportunities to capture dietary effects in on-farm greenhouse gas emissions models of ruminant systems. Sci. Total Environ. 769, 144989. DOI: 10.1016/j.scitotenv.2021.144989.

Zhang, T., Bai, Y., Zhou, X., Li, Z., Cheng, Z., Hong, J., 2023. Towards sustainability: an integrated life cycle environmental-economic insight into cow manure management. Waste Manag. 172, 256–266. https://doi.org/10.1016/j.wasman.2023.10.038.

Zimmermann, J., Carolan, R., Forrestal, P., Harty, M., Lanigan, G., Richards, K.G., Roche, L., Whitfield, M.G., Jones, M.B., 2018. Assessing the performance of three frequently used biogeochemical models when simulating N2O emissions from a range of soil types and fertiliser treatments. Geoderma 331, 53–69. https://doi.org/10.1016/j.geoderma.2018.06.004.