RESEARCH ARTICLE

Modelling greenhouse gas emissions from organic and conventional dairy farms

Helmut Frank[1], Harald Schmid[1], Kurt-Jürgen Hülsbergen[1]

HIGHLIGHTS

- Our new greenhouse gas (GHG) accounting model includes all relevant farm-scale GHG flows
- The model is sensitive enough to take into account management changes
- Our new model is able to identify the causes of high GHG emissions
- The dairy farms analysed showed an enormous variability in GHG flows
- GHG reduction in dairy farming requires farm-specific optimisation approaches
- C sequestration and land-use change affect GHG footprints

Abstract

Dairy farming is a major source of greenhouse gas (GHG) emissions in agriculture. There are numerous scientific studies analysing GHG flows and testing GHG reduction methods in dairy farming, yet very few scientific papers cover all the relevant GHG flows. GHG flows that are difficult to quantify, such as C sequestration in soils, the effects of land-use change (LUC) or the energy input used to produce capital equipment, are not always considered.

This paper describes the development and application of a model for energy and GHG accounting in dairy farming. This new model enables all relevant nutrient, energy and GHG flows to be modelled at farm level. This then forms the basis for system analysis and derivation of GHG mitigation strategies. The model was used on 18 organic and 18 conventional farms in Germany. Calculated CO_2-eq emissions per kg of Energy Corrected Milk (ECM) were 995 g on average for organic farms (org) and 1,048 g on average for conventional farms (con). The largest contribution (55 % (org) and 43 % (con)) to total GHG emissions came from enteric methane emissions (549 g CO_2-eq (kg ECM)$^{-1}$ (org) and 449 g CO_2-eq (kg ECM)$^{-1}$ (con)). On the organic dairy farms, there was an increase in soil humus and therefore carbon storage and sequestration in soils, whereas the GHG emissions for the conventional farms included CO_2 emissions from LUC due to soybean usage. The significantly higher energy input in the conventional systems resulted from the production of energy-intensive concentrates, mineral fertilisers and pesticides, and transportation (imported feed).

This study shows that there are many factors that influence GHG emissions in dairy farming, and that these factors often interact with each other. An increase in productivity is one of several optimisation strategies; however, it must not be at the expense of productive lifetime or require an extremely high amount of concentrates. GHG reduction in dairy farming requires farm-specific optimisation approaches due to the heterogeneity of production systems.

1 Introduction[2]

1.1 Problem description and research gap

Dairy farming is a major source of greenhouse gas (GHG) emissions in agriculture, both nationally and globally (FAO, 2006), and is the focus of public debate on the climate impacts of livestock farming, mainly due to methane emissions.

There are numerous scientific studies which analyse GHG flows and test GHG reduction methods in dairy farming (Thomassen et al., 2008; FAO, 2010; Bell et al., 2011;

[1] Technische Universität München, Chair of Organic Farming and Agronomy, Germany

CONTACT sekretariat.oekolandbau@wzw.tum.de

Hörtenhuber et al., 2011; Vellinga et al., 2011; Zehetmeier et al., 2012; Schueler et al., 2018, Grandl et al., 2019). Studies often focus on methane emissions in relation to feed and milk yield (Kirchgeßner et al., 1991; Jentsch et al., 2007). Few scientific papers claim to quantify all relevant GHG flows in dairy farming; most GHG emission calculations are incomplete. For example, the impact of dairy farming on soil C sequestration and the effects of land-use change for soy production have been included in only a few GHG emission calculations for milk production. Although fossil energy use in dairy systems has been analysed (see Refsgaard et al., 1998; Kraatz 2009), the CO_2 emissions associated with energy input have only rarely been included in GHG accounting for dairy farming.

Although there are systemic differences between organic and conventional dairy cattle farming, it is still unclear which system produces milk in a more climate-friendly way, as studies show differing results. Initial comparison studies focused on enteric methane emissions and concluded that organic dairy farming had higher product-related GHG emissions due to lower milk yields. However, this is a rather superficial conclusion and does not take into account important aspects such as differences in the productive lifetime of dairy cows, feed rations and animal husbandry. Many studies comparing the GHG footprints of organic and conventional milk production exist, but the results are contradictory and inconsistent; a valid assessment is not yet possible (Weckenbrock et al., 2019).

The energy and GHG footprints available for dairy farming are usually based on a small number of experimental or model farms (e.g. Refsgaard et al., 1998; Cederberg and Mattson, 2000; Haas et al., 2001; Thomassen and de Boer, 2005; Kraatz, 2009), or have only been calculated for individual cows (Grandl et al., 2019). A systematic investigation of GHG flows in dairy farming has only been carried out on farms with different structures and production intensities to a limited extent, in part due to a lack of suitable models.

1.2 Description and aims of this study

In this study, we describe a model we developed that can be used to analyse the nutrient (nitrogen, phosphorus and potassium), energy and GHG flows of dairy farms. The aim when developing this model was to record all relevant nutrient, energy and GHG flows related to milk production and to merge them into a system analysis. The model is designed to be applicable to organic and conventional dairy cattle farms. It is largely based on available farm data (field records, feed ration balances, livestock management systems, milk yield tests) and therefore relatively little effort is required for data collection on farms.

In order to compare the two systems, our model for calculating nutrient, energy and GHG footprints was used on 18 organic and 18 conventional dairy farms from four agricultural regions in Germany[3]. The goal was to analyse the

individual variability of GHG flows taking into account site conditions, farm structure, feed, milk yield and other determining factors. Ultimately, applying the model should show whether significant GHG reductions are possible at the farm level, which interactions occur and what trade-offs are necessary. We then discuss whether advisory tools based on the model can help to effectively reduce GHG emissions in practice.

2   Material and methods

The calculation of GHG emissions from dairy farming was based on a process analysis comprising the following components and process steps: (1) feed production and feed purchase, (2) feed storage, (3) housing system[4], (4) enteric emissions, (5) milking system, (6) manure storage and (7) heifer production (*Table 3*). All relevant fossil energy inputs in dairy farming related to primary energy usage were included in the calculation of energy balances; solar energy and human labour were not included in the process analysis (*Figure 1*). Each process step is described in a module. The modules are cross-linked, with subsequent modules using input data from previous modules. The CO_2, CH_4 and N_2O flows were quantified, converted into CO_2-eq (CO_2 equivalents)[5] and reported in relation to the products produced (Frank, 2014). The results were then merged into an "Allocation" module; energy and GHG flows were allocated to the products produced (milk, cull cows and calves) according to defined allocation rules based on physical parameters (related to the energy output of the products (calorific value)). The modelling of the individual process steps is described in detail in Frank (2014).

The following GHG flows were included in the model:

- Process-related GHG emissions from the use of fossil energy: Based on a new method for analysing energy fluxes in dairy farming systems (Frank, 2014), GHG emissions from the use of fossil energy on dairy farms (direct emissions) and the production of operating and capital equipment (indirect emissions) were determined.
- GHG emissions related to land use: N_2O emissions were calculated according to IPCC (2006) as a function of nitrogen input using emission factors according to Dämmgen et al. (2007). Using the REPRO model (Hülsbergen, 2003), CO_2 emissions and CO_2 sequestration due to changes in soil humus stocks were calculated based on soil humus and C balances depending on site conditions, crops, cultivation methods, yields and fertilisation. GHG emissions due to land-use change in soybean production were taken into account (FAO, 2010) and values per unit of soybean meal were used according to Hörtenhuber et al. (2011).

---

[4]   "Housing system" includes animal housing (buildings and installations, bedding and manure removal systems) as well as straw used in farmyard manure systems.

[5]   All emissions were converted to CO_2 equivalents [CO_2-eq] using their specific global warming potential (GWP). The GWP index is defined as the cumulative radiative forcing between the present and a selected time in the future, caused by a unit mass of gas emitted now. The GWP (with a time span of 100 years) of CO_2, CH_4 and N_2O is 1, 23 and 296, respectively (IPCC 1997).

Frank et al. (2019) · LANDBAUFORSCH · J Sustainable Organic Agric Syst · 69(1):37–46
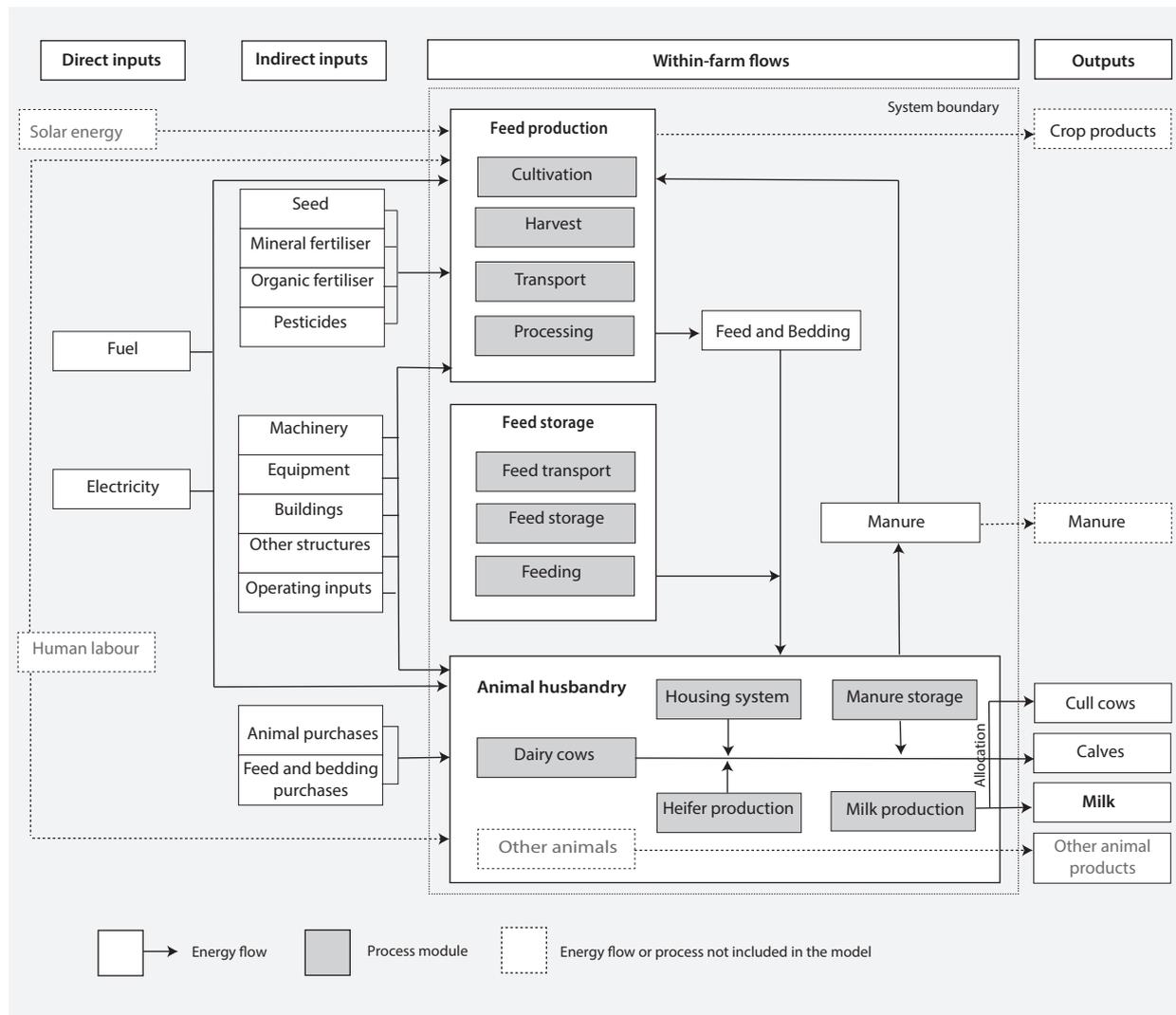
39

FIGURE 1
Model for calculating energy balances in dairy farming, showing the encompassed system boundaries and nutrient and energy flows

- Enteric GHG emissions: Methane emissions from enteric fermentation in the digestive tract of ruminants were calculated according to Ellis et al. (2007) based on the dry matter intake of cattle.
- GHG emissions from manure treatment and storage: An adjusted version of equation 10.23 according to IPCC (2006) was used to calculate these emissions.

The following amounts of embodied energy were used to calculate energy balances (selected inputs, mean values): diesel: 39.60 MJ l^{-1}, biodiesel: 14.10 MJ l^{-1}, electricity: 11.45 MJ kWh^{-1}, machinery: 108 MJ kg^{-1}, maize seed: 14.62 MJ kg^{-1}, mineral N fertiliser: 35.30 MJ (kg N)$^{-1}$, mineral P fertiliser: 36.20 MJ (kg P)$^{-1}$, herbicides: 259 MJ (kg active substance)$^{-1}$, fungicides: 177 MJ (kg active substance)$^{-1}$, insecticides: 237 MJ (kg active substance)$^{-1}$. The following GHG emission factors were used to calculate GHG emissions: diesel: 3.44 kg CO_2-eq l^{-1}, biodiesel: 0.78 kg CO_2-eq MJ l^{-1}, electricity: 0.72 kg CO_2-eq kWh^{-1}, machinery: 7.76 CO_2-eq kg^{-1}, maize

seed: 0.91 CO_2-eq kg^{-1}, mineral N fertiliser: 6.95 CO_2-eq (kg N)$^{-1}$, mineral P fertiliser: 0.70 CO_2-eq (kg P)$^{-1}$, herbicides: 8.33 CO_2-eq (kg active substance)$^{-1}$, fungicides: 5.34 CO_2-eq (kg active substance)$^{-1}$, insecticides: 10.05 CO_2-eq (kg active substance)$^{-1}$. Data sources: Kaltschmitt and Reinhardt (1997), Kalk and Hülsbergen (1996), Hülsbergen (2003), Öko-Institut (2007), Salig and Kölsch (2008), GEMIS (2010), Frank (2014).

In order to quantify energy flows, an energy usage model was developed based on methodology and rules from the REPRO model (Hülsbergen, 2003). A farm is divided into subsystems linked by material and energy flows. In the production process, the output of a subsystem is the input of the following subsystem. To date, only energetic analyses of crop production and/or feed production have been possible using REPRO (Hülsbergen et al., 2001), however, the whole dairy farming system can now be modelled using this new dairy model.

The most important direct energy inputs on dairy farms are fuel and electricity. Indirect energy use includes the

energy input required for the production, maintenance and disposal of inputs and capital equipment[6] (Kalk and Hülsbergen, 1996; Hülsbergen et al., 2001; Frank, 2014). The most important indirect energy inputs are machinery and equipment, animal housing and other buildings or structures, and inputs such as seed, fertilisers and pesticides, as well as the purchase of animals and feed. The outputs of a dairy farm are milk, cull cows, calves and heifers, manure and, if applicable, feed. Energy inputs and outputs are assessed using energy equivalents (Gaillard et al, 1997; Kalk and Hülsbergen, 1996; Hülsbergen et al., 2001; Frank, 2014). The energy equivalents used have been adjusted to represent the latest figures.

Our model was used on 18 organic and 18 conventional dairy farms in southern, western, eastern and northern Germany[7], all forming a pilot farm network. Farm selection was based on the following criteria: affiliation with a study region, good data documentation, willingness to actively participate in the project. Farms were also selected based on location; organic farms were paired with a conventional farm in the immediate vicinity (and vice versa), in order to ensure comparable soil and climatic conditions. The modelled energy balances and GHG emissions were evaluated together with the farmers in the pilot farm network, the causes of high emissions were discussed and options for reducing emissions were derived in regional optimisation workshops.

The farm data presented in *Table 1* are mean values for the study years 2009 to 2012. The farms included in the study represent a wide range of soil and climatic conditions, farm sizes and farm structures. The average milk yield (Energy Corrected Milk[8], ECM) of the organic farms (6,491 kg a^{-1}) was significantly lower than that of the conventional farms (8,555 kg a^{-1}). Dairy cows had a longer productive lifetime on the organic dairy farms. The proportion of roughage and forage from pasture in the feed ration was significantly higher in organic than in conventional dairy farming. There were also differences in manure systems, e.g. higher proportions of solid manure systems and grazing on pasture for cows and heifers in organic dairy farming.

---

[6]   An average useful life for machinery and capital equipment was assumed; the actual useful life on the farms could differ. In order to reduce data collection complexity, buildings and structures (e.g. animal housing and feed storage) were categorised to define storage and housing categories. The cumulative energy input for construction, particularly for producing steel, concrete and other building materials, was determined for each building category, and this cumulative energy input was allotted according to useful life. The animal housing used on the dairy farms was allocated to the appropriate category. This pragmatic approach has proven to be appropriate; collecting more detailed information about the building materials used or the actual useful life of animal housing is not possible in practice. For dairy cattle housing, the energy input was calculated per cubicle according to the values calculated by Kraatz (2009), taking into account a useful life of 25 years (see Kalk and Hülsbergen 1996).

[7]   Scientists, farmers and farm advisors have been collaborating as part of the pilot farm network since 2009.

[8]   Energy Corrected Milk (ECM): values for Energy Corrected Milk (ECM) were determined based on the milk yield and milk constituents in relation to standard milk with 4.0 % fat and 3.4 % protein according to the equation: ECM (kg) = Milk (kg) x [0.38 x (Fat %) + 0.21 x (Protein %) + 1.05] / 3.28

3 Results

Mean CO_2-eq emissions per kg of ECM (delivered milk) calculated using the model were 995 g in the organic farms (org) and 1,048 g in the conventional farms (*Table 2*).

Methane emissions (dairy cows, including replacement calves and heifers) calculated based on milk yield and feed ration made up the largest share of total GHG emissions, with an average of 549 g CO_2-eq (kg ECM)$^{-1}$ (org) and 449 g CO_2-eq (kg ECM)$^{-1}$ (con) (55 % and 43 %, respectively). Methane emissions per kg of ECM from conventional farms were significantly lower than from organic farms, mainly due to higher milk yields and feed rations with a lower proportion of fibre. Methane emissions from manure storage were much lower than emissions from enteric fermentation and did not differ between the two systems (org: 85, con: 77 g CO_2-eq (kg ECM)$^{-1}$).

The N_2O emissions calculated for crop cultivation (soil emissions) and from manure storage are the second most important source of GHG emissions. Emissions were similar for both systems, 253 (org) and 248 (con) g CO_2-eq (kg ECM)$^{-1}$.

There were significant differences in CO_2 fluxes on farms with organic and conventional milk production due to differences in C sequestration and land-use change. According to our calculations, there was C sequestration on the organic farms on average (-57 g CO_2-eq (kg ECM)$^{-1}$) due to an increase in soil humus (attributable to the use of pastures, clover grass leys and fertilisation with farmyard manure). There were also no changes in land use (e.g. no conversion of pasture to arable, no imported soybeans were used). On the conventional dairy farms, on the other hand, CO_2 emissions were calculated as being 82 g CO_2-eq (kg ECM)$^{-1}$) mainly due to LUC, related to the use of soybeans. However, there was mostly no change in humus stocks (*see Table 3*).

GHG emissions from conventional dairy farming associated with the use of fossil energy (192 g CO_2-eq (kg ECM)$^{-1}$) significantly exceeded the GHG emissions from organic dairy farming (165 g CO_2-eq (kg ECM)$^{-1}$). Energy input in milk production was high due to high electricity consumption and the materials needed for milking systems.

Table 3 shows the calculated values for the most important GHG flows for different processes on a dairy farm. The GHG emissions from feed production differed significantly between organic and conventional dairy farming (org: 123 g CO_2-eq (kg ECM)$^{-1}$, con: 308 g CO_2-eq (kg ECM)$^{-1}$), which applies to feed production and feed purchases. The significantly higher energy input in the conventional systems resulted primarily from the use of energy-intensive concentrates (including e.g. soybean or rapeseed meal), as well as from the use of mineral fertilisers and pesticides. On conventional farms, the share of GHG emissions from purchased feed was 11 % (including LUC). There was a higher proportion of energy-efficient pasture (mainly low-input feed production systems) on the organic farms. In addition, ley production (particularly clover grass) was energy efficient. However, the variability of energy utilisation in feed production between individual farms was very high due to the different yield potentials of the various sites and large differences in feed production systems (e.g. harvest frequency

Frank et al. (2019) · LANDBAUFORSCH · J Sustainable Organic Agric Syst · 69(1):37–46

41

TABLE 1

Pilot farm data: mean values for the study years 2009–2012

	Unit	Organic				Conventional				t-test
		Mean	Min	Max	SD	Mean	Min	Max	SD	
Site conditions										
Elevation	m	256	3	780	263	258	1	780	262	n.s.
Annual precipitation	mm	852	536	1,507	247	854	536	1,507	245	n.s.
Mean temperature	°C	8.5	6.9	10.8	1.0	8.5	6.9	10.8	1.0	n.s.
Average soil quality [a]		43	21	54	9	48	31	68	10	n.s.
Farm structure										
Agricultural area	ha	159	30	1,346	300	144	30	973	222	n.s.
Grassland	% FL [b]	46	5	100	30	43	10	100	30	n.s.
Clover grass	% CL [c]	36	0	81	22	10	0	46	12	*
Silage maize	% CL [c]	4	0	19	5	24	0	72	20	*
Grain	% CL [c]	36	0	68	21	40	0	69	22	n.s.
Stocking density	LU ha^{-1}	0.94	0.27	1.56	0.50	1.64	0.74	2.72	0.60	*
Dairy farming										
Dairy cows	No.	52	19	228	47	87	27	452	103	n.s.
Milk yield per cow	kg ECM a^{-1}	6,491	4,236	8,840	1,305	8,555	6,273	10,275	1,142	*
Age at first calving	months	30	27	35	3	29	23	34	3	*
Productive lifetime	months	41	27	81	14	30	25	38	4	*
Calving interval	days	402	368	464	23	406	367	437	19	n.s.
Feed										
Roughage	% DM [d]	90	77	100	7	71	51	93	11	*
Pasture	% DM [d]	26	1	48	15	7	0	34	11	*
Concentrates	% DM [d]	10	0	23	7	29	7	49	11	*
Soybean meal	% DM [d]	0	0	0	0	3	0	9	3	*
Manure system										
Manure	%	44				17				
Slurry	%	56				83				

* significant at level $p \leq 0.05$, t-test

[a] Soil value, determined using the German system of soil evaluation: a soil value of 100 = highest soil quality

[b] % FL: % farmland
[c] % CL: % crop land
[d] % DM: % dry matter

and forage conservation methods such as silage and hay production).

N$_2$O emissions in feed production contributed, with 149 g CO$_2$-eq (kg ECM)$^{-1}$ on the organic farms and 129 g CO$_2$-eq (kg ECM)$^{-1}$ on the conventional farms, to total emissions. The N$_2$O emissions per kg of ECM were dependent on the N input (mineral N, N from organic fertilisers or nitrogen fixation by legumes) per hectare of feed, feed yield, feed ration and milk yield. The conventional farms had a significantly higher fertiliser N input than the organic farms, but due to higher yields this did not result in higher product-related N$_2$O emissions.

With regard to animal housing, the organic farms had a higher product-related energy input due to the high proportion of solid manure systems requiring large amounts of straw. Hence, there were also GHG emissions from straw production. Different requirements in terms of access to pasture and exercise areas also affected GHG emissions.

Although housing on the organic farms often had a lower energy input due to its design, this was offset by the bedding required. There were no differences between the systems in terms of manure removal and fertiliser storage.

Total GHG emissions from raising heifers for herd replacement were comparable in both systems (org: 251 g CO$_2$-eq (kg ECM)$^{-1}$, con: 233 g CO$_2$-eq (kg ECM)$^{-1}$). Raising replacement heifers mainly generated GHG emissions from the use of fossil energys, enteric CH$_4$ emissions and N$_2$O emissions from feed production and fertiliser storage. The heifers raised on organic farms were older at first calving (*Table 1*), but dairy cows had a longer productive lifetime and a higher number of lactations than cows on conventional farms, meaning fewer heifers were needed for herd replacement. The high variability of emissions between farms shows the significant influence farm management and local conditions had and, to some extent, the potential for reductions in GHG emissions.

Process, source	GHG	Organic g CO_2-eq (kg ECM)$^{-1}$				Conventional g CO_2-eq (kg ECM)$^{-1}$				t-test
		Mean	Min	Max	SD	**Mean**	Min	Max	SD	
Energy input [a]	CO_2	**165**	133	218	25	**192**	165	222	19	*
C sequestration, LUC [b]	CO_2	**-57**	-171	38	56	**82**	-71	235	71	*
Crop cultivation [c]	N_2O	**192**	156	263	29	**191**	140	247	30	n.s.
Enteric fermentation [d]	CH_4	**549**	473	706	71	**449**	392	574	46	*
Manure storage [e]	N_2O	**61**	33	95	16	**57**	36	90	13	n.s.
Manure storage [f]	CH_4	**85**	34	151	28	**77**	18	127	30	n.s.
Total GHG emissions	GHG	**995**	835	1,397	149	**1,048**	901	1,269	88	**n.s.**

* significant at level $p \leq 0.05$, t-test

[a] CO_2 emissions from the use of fossil (primary) energy (direct emissions and indirect emissions)

[b] CO_2 emissions due to changes in soil humus stocks and land-use change

[c] N_2O emissions from fertiliser and soils (feed production for cows including heifers)

[d] CH_4 emissions from enteric fermentation (cows including replacement heifers)

[e] N_2O emissions from manure treatment and storage (cows including heifer production)

[f] CH_4 emissions from manure treatment and storage (cows including heifer production)
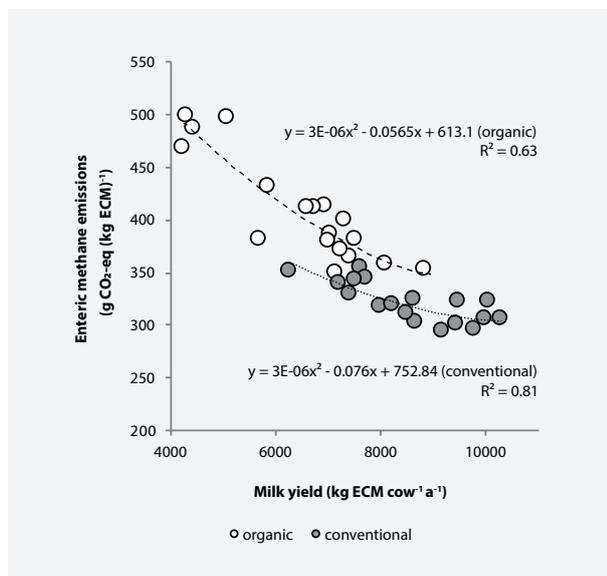
FIGURE 2

Enteric methane emissions of dairy cows in relation to milk yield per cow (without heifer production);
Y = enteric methane emission, x = milk yield

FIGURE 3

Total GHG emissions of milk production in relation to milk yield per cow;
Y = GHG emission, x = milk yield

A key factor influencing the amount of CH_4 emissions and total GHG emissions was milk yield. Enteric CH_4 emissions decreased with higher milk yield (*Figure 2*). For the same milk yield (e.g. 8,000 kg ECM per cow), product-related CH_4 emissions from the organic farms were approximately 50 g CO_2-eq (kg ECM)$^{-1}$ higher than CH_4 emissions from conventional farms.

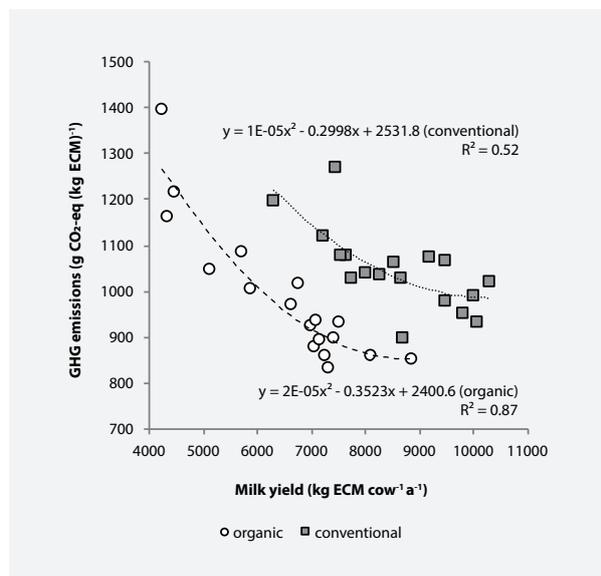As yields increased, total GHG emissions decreased (*Figure 3*). For the same milk yield (e.g. 8,000 kg ECM per cow), product-related GHG emissions from the organic farms are approximately 200 g CO_2-eq (kg ECM)$^{-1}$ lower than from conventional farms (calculated using regression functions). This value is higher than the mean difference of 53 g CO_2-eq (kg ECM)$^{-1}$ for product-related GHG emissions (org: 995 g CO_2-eq (kg ECM)$^{-1}$ vs con: 1,048 g CO_2-eq (kg ECM)$^{-1}$, see *Table 2*) due to the different mean milk yields (org: 6,491 kg ECM per cow, con: 8,555 kg ECM per cow, see *Table 1*).

The slope of the regression curves shows that significant GHG reductions can be achieved by increasing yields if

Frank et al. (2019) · LANDBAUFORSCH · J Sustainable Organic Agric Syst · 69(1):37–46

43

GHG emissions for each process (g CO₂-eq (kg ECM)⁻¹), pilot farms (2009–2012)

No.	Process, source	GHG	Organic g CO₂-eq (kg ECM)⁻¹				Conventional g CO₂-eq (kg ECM)⁻¹				t-test
			Mean	Min	Max	SD	Mean	Min	Max	SD	
1.	**Feed production** [a]	**GHG**	**123**	**52**	**237**	**50**	**308**	**197**	**406**	**59**	*
1.1	**On-farm**	**GHG**	**102**	**14**	**183**	**52**	**196**	**109**	**287**	**49**	*
	Energy input	CO₂	39	18	65	13	59	32	105	22	*
	Fertilisation, soils	N₂O	149	109	193	23	129	77	210	36	*
	C sequestration	CO₂	-86	-199	0	57	8	-89	104	47	*
1.2	**Purchase (off-farm)**	**GHG**	**21**	**1**	**79**	**23**	**112**	**7**	**224**	**59**	*
	Energy input	CO₂	7	2	23	6	30	4	54	15	*
	Fertilisation, soils	N₂O	6	0	33	8	25	0	50	15	*
	C sequestration	CO₂	8	-4	53	14	16	0	60	14	*
	LUC (soy)	CO₂	0	0	0	0	41	0	115	41	*
2.	**Feed storage**	**GHG**	**11**	**3**	**22**	**6**	**13**	**6**	**18**	**3**	n.s.
3.	**Housing system**	**GHG**	**23**	**8**	**54**	**15**	**11**	**5**	**27**	**5**	*
	Energy input	CO₂	15	7	26	7	9	5	21	4	*
	Fertilisation, soils	N₂O	1	0	10	2	2	0	7	2	n.s.
	C sequestration	CO₂	7	-3	28	9	0	-12	3	3	*
4.	**Enteric fermentation**	**CH₄**	**410**	**349**	**498**	**49**	**321**	**294**	**355**	**19**	*
5.	**Milking system**	**CO₂**	**46**	**34**	**60**	**5**	**44**	**42**	**48**	**2**	n.s.
6.	**Manure storage**	**GHG**	**131**	**77**	**227**	**35**	**118**	**47**	**163**	**34**	n.s.
	Energy input	CO₂	14	8	28	6	11	5	16	3	*
	Manure storage	N₂O	35	12	67	12	33	9	48	10	n.s.
	Manure storage	CH₄	82	30	149	28	74	16	124	30	n.s.
7.	**Heifer production**	**GHG**	**251**	**132**	**423**	**73**	**233**	**164**	**437**	**68**	n.s.
	Energy input	CO₂	33	17	56	10	26	18	51	8	*
	Fertilisation, soils	N₂O	36	19	60	10	35	23	69	12	n.s.
	C sequestration	CO₂	14	6	29	6	13	3	35	9	n.s.
	LUC	CO₂	0	0	0	0	4	0	12	3	*
	Enteric emissions	CH₄	139	74	230	40	128	87	224	32	n.s.
	Fertiliser storage	N₂O	26	14	43	7	24	16	42	6	n.s.
	Fertiliser storage	CH₄	3	2	5	1	3	2	5	1	n.s.

* significant at level $p \leq 0.05$, t-test

[a] Feed production and feed purchase for dairy cows

the initial yield level is relatively low. For example, doubling the annual milk yield from 4,000 to 8,000 kg ECM on organic dairy farms would lead to a reduction of about 450 g CO₂-eq (kg ECM)⁻¹ (about 33 %). However, at even higher milk yields, the potential for GHG reductions is much smaller. Further increases in yield require a higher proportion of concentrates in the feed ration (with the associated high energy input and GHG emissions from feed production) and cow productive lifetime decreases (requiring more herd replacement).

The organic farms had the lowest GHG emissions at around 8,000 kg ECM, whereas none of the conventional farms achieved the theoretical minimum of product-related GHG emissions, even at 11,000 kg ECM.

4 Discussion

4.1 Discussion of methods

Our new model for GHG accounting in dairy farming is capable of modelling different types of farms (for example, organic and conventional), farm sizes and site conditions. This is shown by the application of the model on the 36 pilot farms, all with very different production conditions. Model sensitivity is such that changes in management can also be simulated, e.g. in forage production and housing systems. All model calculations are based on the same methodology, namely process analysis, as well as the algorithms and parameters specified in the model, so that the results for different farms are comparable with each other.

Our model is closely linked with the REPRO environmental management model (Hülsbergen, 2003). The REPRO model analyses crop production, i.e. feed production and energy balance in crop production (Hülsbergen et al., 2001), soil humus dynamics (Brock et al., 2012; Leithold et al., 2015) and farm nutrient cycles (Lin et al., 2016). In the REPRO model, feed production processes are analysed for each field and include the use of organic fertiliser along with its resulting GHG flows (NH_3, N_2O and CO_2 emissions, and C sequestration). These results are included in the calculation of GHG emissions for dairy farming (see *Table 3*, process 1.1).

Our dairy model uses relevant data from REPRO, however, the process steps – feed storage, housing system, metabolism, milk production and manure storage – are modelled using the new dairy model. By combining both models, all the relevant GHG flows in dairy farming can be simulated in detail.

Modelling dairy systems is challenging due to the extremely complex and numerous subsystems, processes and interactions in dairy farming. In addition, animal housing and technical systems are highly variable, and are often specially designed for each individual farm. Therefore, simplifications were required to make the model applicable. For example, structures for feed storage and animal housing were grouped into categories, and corresponding parameters were derived for each of these storage and housing categories, such as the energy input and GHG emissions required for production. Buildings and structures on the pilot farms were assigned to these storage and housing categories. Comparable methodological approaches were used by Kraatz (2009) and Dux et al. (2009) to calculate energy input in dairy farming. Defined standard procedures were also used to simplify the analysis of heifer production, whereby a reduction in accuracy was expected. Using exact, farm-specific data would have been extremely complex and fraught with uncertainties.

Modelling the GHG flows in dairy farming requires the collection of operating data from farms, and thus good data documentation and cooperation from farm managers. To minimise the effort required for data acquisition, less significant subprocesses can be simplified and aggregated. However, processes that are critical to the energy and GHG footprints, such as feed production, require detailed modelling. Our model is designed for use on farms and to process operational data. Despite some uncertainties, our model can calculate complete energy and GHG footprints for dairy farms. The model was designed to enable a comparison of results.

Uncertainties and errors in the model result from
- (a) inaccuracies in the collection of production data on the farms. For example, the grassland (pasture) feed yield can only be estimated based on feed intake and checked for feasibility using feed balances
- (b) errors in calculating nutrient and energy balances. For example, energy balances assume average energy equivalents that do not correspond exactly to operational or regional conditions. Due to the complexity of animal husbandry systems (buildings for animal housing and milking systems) and the required model simplifications, farm-specific conditions can only be approximated by the model. The humus balance can only indicate approximate C sequestration values, since only the most important drivers are included
- (c) GHG accounting using GHG emission factors and algorithms that are a drastic simplification of complex conversion processes
- (d) including LUC and the modelling of the associated GHG flows is highly controversial; there are different methodological approaches for the quantification of GHG emissions caused by LUC.

Overall, it should be noted that the new dairy farming model is a compromise between the scientific goal of describing all GHG flows as completely and accurately as possible, and practicality, which necessitates simplifications of complex milk production systems. Sensitivity analyses and error analyses of the individual model components can be found in Hülsbergen (2003) and Frank (2014).

4.2 Discussion of results

The analysis of GHG flows in dairy farming shows that many interacting factors determine GHG emissions. An increase in productivity is one of several optimisation strategies; however, it must not be at the expense of productive lifetime (number of lactations, effort required for herd replacement) or require an extremely high proportion of concentrate in the feed ration. On the farms we analysed, organic farms with milk yields of 7,000 to 9,000 kg ECM a^{-1} had the lowest GHG emissions of 800 to 900 g CO_2-eq (kg ECM)$^{-1}$. On the other hand, conventional farms with an output of 9,000 to 10,500 kg ECM a^{-1} had GHG emissions of 900 to 1,050 g CO_2-eq (kg ECM)$^{-1}$.

As frequently described in the literature (e.g. Flachowsky and Brade, 2007), an increase in milk yield per cow results in a decrease in enteric methane emissions per kg ECM. An increase from 4,000 to 8,000 kg of ECM cow^{-1} a^{-1} resulted in a CH_4 reduction of around 100 g CO_2-eq (kg ECM)$^{-1}$ for the organic pilot farms. For the conventional pilot farms, the potential for reducing CH_4 if output were to be increased from 7,000 to 10,000 kg of ECM cow^{-1} a^{-1} was only around 30 g CO_2-eq (kg ECM)$^{-1}$. Methane emissions can be reduced by changing feed quality and feed composition (Flachowsky and Brade, 2007), however, this may only be possible to a limited extent due to specific site and production conditions (e.g. regions where permanent pasture is dominant), or due to certain requirements in organic farming. However, our research also shows that increasing milk yield is just one of many GHG mitigation strategies and that an increase in performance is neither possible nor plausible for every farm. Among other things, it could conflict with other goals, such as replacing roughage produced in an extensive system with concentrates that require a lot of energy to produce, or negative effects on productive lifetime and animal health. Intensification of feed production and grassland should also not be exaggerated in order to avoid negative environmental effects, such as a reduction in biodiversity. The pilot farms network gives us the opportunity to study the trade-offs between the intensity of milk production systems, product-related GHG emissions, and other environmental effects.

Feed production contributes significantly to energy use and greenhouse gas emissions from milk production (see *Table 3*). Although higher amounts of nitrogen fertiliser are used on conventional than on organic farms (Hülsbergen and Rahmann, 2013), when higher forage yields and milk yields are taken into account, the product-related N_2O emissions from feed production are at about the same level (*Table 3*). The farms studied did not show significant over-fertilisation of feed production areas, which is due in part to moderate stocking rates (livestock farming based on available land area) (see *Table 1*).

There was enormous variability in the GHG flows within individual processes and in the product-related GHG total emissions for the pilot farms. One reason was the wide variety of site conditions and milk production systems on the farms (*Table 1*). Farm management also had a significant impact. Although systemic differences between organic and conventional dairy farming were found in some GHG flows (*Table 2* and *Table 3*), the differences between farms within each system were much greater. In future, system comparisons between organic and conventional agriculture should take this variability in results, as well as uncertainties and possible errors, better into consideration. A simple comparison between organic and conventional farming without taking variability into account could lead to incorrect assessments.

In order to identify the site-specific productivity optimisations necessary to achieve the largest possible reduction in GHG emissions, additional farms and locations need to be analysed and included. Model calculations and sensitivity analyses (Frank, 2014), in which the influencing parameters are varied and a wide range of productivity values are analysed, could supplement the farm analysis, since insignificant and random farm-specific factors are eliminated from the analysis.

5 Conclusion

Our investigations show that a GHG reduction in dairy farming requires farm-specific optimisation approaches due to the heterogeneity of production and operating systems. A one-size-fits-all approach is not particularly effective. Our new model is able to identify the causes of high GHG emissions and to compare farms (see, for example, benchmarking in *Figures 2* and *3*). Within the pilot farm network, measures for reducing GHG emissions were derived during optimisation workshops with the farmers, and their effects on GHG footprints were analysed using the model. It has often been shown that individual measures (for example, increasing milk yield to the maximum) do not solve the problem because they can have a negative impact elsewhere (such as higher concentrate requirements and decreasing cow productive lifetime).

As our study confirms, organic dairy farming can increase soil humus and contribute to soil carbon sequestration. Dairy cattle can use grassland biomass and therefore contribute to the conservation of ecologically valuable grassland. Overall optimisation which takes into account interactions between feed production, animal husbandry, fertilisation, humus and

nutrient management, among others, is required. It should also be emphasised that the assessment and optimisation of environmental sustainability in dairy farming should include other relevant environmental areas, such as soil protection and the preservation of potable water sources and biodiversity, in addition to GHG flows and impacts on the climate.

Our experience with the pilot farms shows that farm managers are increasingly interested in implementing climate change mitigation measures in dairy farming. Our model should therefore be developed further so that it can be used successfully, not only for scientific research, but also by farm advisory services.

Acknowledgements

REFERENCES

Bell MJ, Wall E, Russell G, Simm G, Stott AW (2011) The effect of improving cow productivity, fertility, and longevity on the global warming potential of dairy systems. J Dairy Sci 94(7):3662–3678, doi:10.3168/jds.2010-4023

Brock C, Hoyer U, Leithold G, Hülsbergen KJ (2012) The humus balance model (HU-MOD): a simple tool for the assessment of management change impact on soil organic matter levels in arable soils. Nutr Cycl in Agroecosys 92(3):239–254, doi:10.1007/s10705-012-9487-z

Cederberg A, Mattson B (2000) Life cycle assessment of milk production: A comparison of conventional and organic farming. J Clean Prod 8(1):49–60, doi:10.1016/S0959-6526(99)00311-X

Dämmgen U, Lüttich M, Haenel H-D, Döhler H, Eurich-Menden B, Osterburg B (2007) Berechnungen der Emissionen aus der deutschen Landwirtschaft – Nationaler Emissionsbericht (NIR) 2007 für 2005. In: Dämmgen U (ed) Berechnungen der Emissionen aus der deutschen Landwirtschaft – Nationaler Emissionsbericht (NIR) 2007 für 2005: Einführung, Methoden und Daten (GAS-EM)/Calculations of emissions from German agriculture – National Emission Inventory Report (NIR) 2007 for 2005: introduction, methods and data (GAS-EM). Landbauforsch Volk Agric Res 304(2007), 343 p

Dux D, Alig M, Herzog D (2009) Umweltwirkung von landwirtschaftlichen Gebäuden. Agrarforsch Schweiz 16(8):284–289

Ellis JL, Kebreab E, Odongo NE, McBride BW, Okine EK, France J (2007) Prediction of methane production from dairy and beef cattle. J Dairy Sci 90(7):3456–3466, doi:10.3168/jds.2006-675

FAO (2006) Livestock´s long shadow: environmental issues and options. Rome, FAO

FAO (2010) Greenhouse gas emissions from the dairy sector. A life cycle assessment. Rome, FAO

Flachowsky G, Brade W (2007) Potenziale zur Reduzierung der Methan-Emissionen bei Wiederkäuern. Zuechtungskunde 79(6):417–465

Frank H (2014) Entwicklung und Anwendung eines Modells zur Energie- und Treibhausgasbilanzierung landwirtschaftlicher Betriebssysteme mit Milchviehhaltung. Dissertation, Technische Universität München, Germany, 206 p

Frank H, Schmid H, Hülsbergen K-J (2015): Energie- und Treibhausgasbilanz der Milchviehhaltung – Untersuchungen im Netzwerk der Pilotbetriebe

(Energy and greenhouse gas footprints of dairy farming – Research in the pilot farm network). In: Hülsbergen K-J, Rahmann G (eds) Klimawirkungen und Nachhaltigkeit ökologischer und konventioneller Betriebssysteme – Untersuchungen in einem Netzwerk von Pilotbetrieben. Forschungsergebnisse 2013–2014. Braunschweig: Johann Heinrich von Thünen-Institut, Thünen Rep 29, 25–48, doi:10.3220/REP_29_2015

Gaillard G, Crettaz P, Hausheer J (1997) Umweltinventar der landwirtschaftlichen Inputs im Pflanzenbau. Daten für die Erstellung von Energie- und Ökobilanzen in der Landwirtschaft. Eidgenössische Forschungsanstalt für Agrarwirtschaft und Landtechnik, FAT Schriftenreihe 46(Tech Rep)

Grandl F, Furger M, Kreuzer M, Zehetmeier M (2019) Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. Animal 13(1):198–208, doi:10.1017/S175173111800112X

Haas G, Wetterich F, Köpke U (2001) Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agr Ecosys Environ 83(1–2):43–53, doi:10.1016/S0167-8809(00)00160-2

Hörtenhuber SJ, Lindenthal T, Zollitsch W (2011) Reduction of greenhouse gas emissions from feed supply chains by utilizing regionally produced protein sources: the case of Austrian dairy production. J Sci Food Agric 91(6):1118–1127, doi:10.1002/jsfa.4293

Hülsbergen K-J, Feil B, Biermann S, Rathke GW, Kalk WD, Diepenbrock W (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. Agr Ecosys Environ 86(3):303–321, doi:10.1016/S0167-8809(00)00286-3

Hülsbergen K-J (2003) Entwicklung und Anwendung eines Bilanzierungsmodells zur Bewertung der Nachhaltigkeit landwirtschaftlicher Systeme. Aachen: Shaker-Verlag, 240 p

Hülsbergen K-J, Rahmann G (eds.) (2013) Klimawirkungen und Nachhaltigkeit ökologischer und konventioneller Betriebssysteme – Untersuchungen in einem Netzwerk von Pilotbetrieben (Ecological sustainability and greenhouse gas emissions of organic and conventional farms – analyses in a network of pilot farms). Braunschweig: Johann Heinrich von Thünen-Institut, 412 p, Thünen Rep 8

International Panel on Climate Change (IPCC) (1997) 1996 IPCC Guidelines for National Greenhouse Gas Inventories

International Panel on Climate Change (IPCC) (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Jentsch W, Schweigel M, Weissbach F, Scholze H, Pitroff W, Derno M (2007) Methane production in cattle calculated by the nutrient composition of the diet. Arch of Anim Nutr 61(1):10–19, doi:10.1080/17450390601106580

Kalk WD, Hülsbergen K-J (1996) Methodik zur Einbeziehung des indirekten Energieverbrauchs mit Investitionsgütern in Energiebilanzen von Landwirtschaftsbetrieben. Kühn-Archiv 90:41–56

Kaltschmitt M, Reinhardt GA (Hrsg.) (1997) Nachwachsende Energieträger – Grundlagen, Verfahren, ökologische Bilanzierung. Braunschweig: Vieweg Verlag, 527 p

Kirchgessner M, Windisch W, Müller HL, Kreuzer M (1991) Release of methane and of carbon dioxide by dairy cattle. Agribiol Res (44):91–102

Kraatz S (2009) Ermittlung der Energieeffizienz in der Tierhaltung am Beispiel der Milchviehhaltung. Dissertation, Humboldt-Universität zu Berlin, Germany, doi:10.18452/15940

Leithold G, Hülsbergen K-J, Brock C (2015) Organic matter returns to soils must be higher under organic compared to conventional farming. J Plant Nutr Soil Sc 178(1):4–12, doi:10.1002/jpln.201400133

Lin HC, Huber JA, Gerl G, Hülsbergen K-J (2016) Nitrogen balances and nitrogen-use efficiency of different organic and conventional farming systems. Nutr Cycl in Agroecosys 105:1–23, doi:10.1007/s10705-016-9770-5

Öko-Institut (2010) Globales Emissions-Modell Integrierter Systeme (GEMIS)

Refsgaard K, Halberg N, Kristensen ES (1998) Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agr Syst 57(4):599–630, doi:10.1016/S0308-521X(98)00004-3

Saling P, Kölsch D (2008) Ökobilanzierung: Energieverbräuche und CO$_2$-Emissionen von Pflanzenschutzmitteln. In: Döhler H, Boxberger J, Krötzsch S (eds) Energieeffiziente Landwirtschaft. KTBL-Schrift 463: 65–71

Schüler M, Hansen S, Paulsen HM (2018) Discrimination of milk carbon footprints from different dairy farms when using IPCC Tier 1 methodology for calculation of GHG emissions from managed soils. J Clean Prod 177:899–907, doi:10.1016/j.jclepro.2017.12.227

Thomassen MA, de Boer IJM (2005) Evaluation of indicators to assess the environmental impact of dairy production systems. Agriculture, Ecosystems & Environment 111(1–4):185–199, doi:10.1016/j.agee.2005.06.013

Thomassen MA, van Calker KJ, Smits MCJ, Iepema GL, de Boer IJM (2008) Life cycle assessment of conventional and organic milk production in the Netherlands. Agric Syst 96(1–3):95–107, doi:10.1016/j.agsy.2007.06.001

Vellinga TV, de Haan MHA, Schils RLM, Evers A, van den Pool, van Dasselaar A (2011) Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livest Sci 137(1–3):185–195, doi:10.1016/j.livsci.2010.11.005

Weckenbrock P, Sanchez-Gellert HL, Gattinger A (2019) Klimaschutz. In: Sanders J, Hess J (eds) Leistungen des ökologischen Landbaus für Umwelt und Gesellschaft. Braunschweig: Johann Heinrich von Thünen-Institut, Thünen Rep 65:164–190, doi:10.3220/REP1576488624000

Zehetmeier M, Baudracco J, Hoffmann H, Heissenhuber A (2012) Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. Animal 6(1):154–166, doi:10.1017/S1751731111001467