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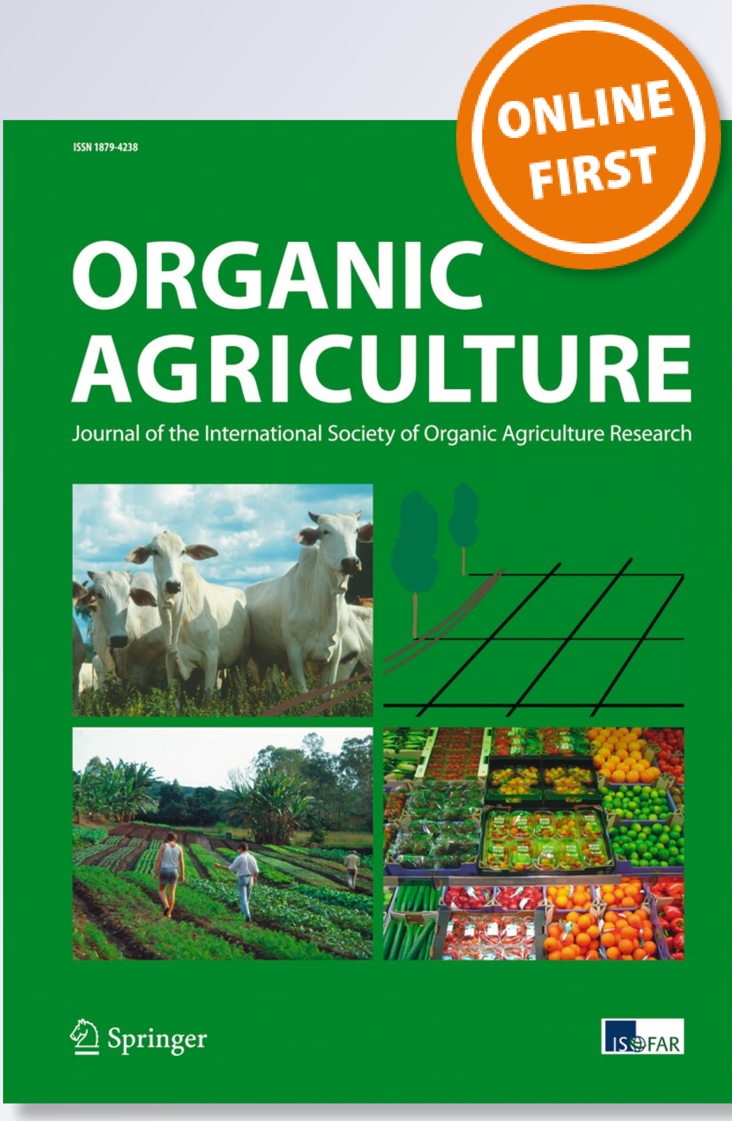

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Greenhouse gas emissions from enteric fermentation and manure on organic and conventional dairy farms—an analysis based on farm network data

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Abstract Feed and manure composition and qualities in an organic and conventional dairy farm network in Germany (22 farm pairs) were analysed. Related greenhouse gas (GHG) emissions from enteric fermentation and from animal excretions were calculated by using two methods each. Feeding and feedstuff quality were farm specific. On average, organic dairy cows received significantly less concentrates, maize silage and straw and significantly more pasture and hay than conventional dairy cows. No differences were found for feeding grass silage. Results for methane (CH_4) emissions from enteric fermentation depended strongly on the calculation methodology. They were higher when feed quality was considered as an input parameter (average GHG emissions 3822 and 3759 kg CO_2-eq. cow^{-1} a^{-1} on organic and conventional farms) as opposed to when only feed intake was considered (2852 and 3112 kg CO_2-eq. cow^{-1} a^{-1}). Differences between the methods were particularly prominent when high amounts of fibre-rich feedstuff were used and, with regard to product-related emissions, at lower milk yields. GHG emissions from manure are also directly connected with feed intake and quality. Manure qualities and storage conditions on the farms were highly variable. On average, the related GHG emission potential was similar in liquid and solid manures (32 kg CO_2-eq. t^{-1} fresh matter). Since feed quality management on farms influences milk yield, enteric CH_4 emissions and manure composition, it should be part of advisory concepts that aim at reducing GHG emissions in milk production. Technical changes in manure storage and handling offer an additional GHG reduction potential.

Keywords Methane · Diet · Feed quality · Manure · Calculation methods · Greenhouse gas

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Introduction

In 2012, agriculture contributed 7.4 % or 69,490 Gg CO_2 equivalents (CO_2-eq.; without considering process energy) to Germany's overall greenhouse gas (GHG) emissions (NIR 2014). They consist of 59 % of nitrous oxide (N_2O) emissions from nitrogen (N) fertiliser application to soils, 30 % of methane (CH_4) emissions from enteric fermentation of ruminants and 7 % of CH_4 and 4 % of N_2O from manure management. Approximately 57 % of the total CH_4 emissions from enteric fermentation and 35 % of the total emissions from manure can be attributed to dairy cows (Haenel et al. 2014).

Feeding influences CH_4 production in the rumen as well as the excretion of substances in livestock manures that are relevant for GHG emissions. Organic and conventional feeding practices of dairy cattle differ due to specific regulations that are in place for organic farming. For example, dairy cows

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must have access to pasture, while soybean extract, a very common concentrate in conventional dairy feeding, may not be fed to organic animals (EC 2007, 2008; EU 2012). Impacts of different feeding regimes on GHG emissions from enteric fermentation can be expected. However, it is unknown how the actual practices in feeding and manure handling are in organic farming in comparison to conventional farming and how this affects CH_4 emissions from enteric fermentation and manure.

This article focuses on the main GHG (CH_4, N_2O and $N_2O_{indirect}$ from ammonia (NH_3) deposition on soils) in a dairy farm network with organic and conventional farms. Feeding practices, feed qualities, manure management and manure qualities on the individual farms are depicted. Related GHG emissions from enteric fermentation and from animal excretions, calculated by using two methods each, are presented. A view on limits of modelling approaches based on practical farm data is given. Recommendations for farm management to produce milk with lower CO_2 emissions are concluded.

Material and methods

A total of 44 dairy farms (22 organic and conventional each) in four German regions were analysed for their GHG emissions as part of the project 'Climate Effects and Sustainability of Organic and Conventional Farming Systems' (Kassow et al. 2010; Hülsbergen and Rahmann 2013). All feedstuffs were sampled and analysed on the pilot farms of the network in 2009 (in early spring for feedstuffs produced in 2008 and in autumn for feedstuffs produced in 2009) and in 2010 (in autumn for feedstuffs produced in 2010). Feedstuffs were characterised for their crude nutrient contents by Weende analysis. Contents of energy and usable crude protein were calculated according to GfE (2001). The digestibility of organic matter of the feeds was taken from DLG (1997). The average diets fed to the lactating and dry cows, including estimations of feed intake, were collected via interviews with the farmers. The diets were then calculated from the animals' energy demands while considering the average winter and summer diets, feed qualities from the laboratory analysis, average milk yields from milk recordings and cow weights. The duration the animals spent in the stable, in the milking parlour and on pasture was also recorded from the interviews with the farmers. Energy-corrected milk (ECM) yield per cow and year was calculated according to GfE (2001) [kg ECM cow^{-1} a^{-1}].

CH_4 emissions from enteric fermentation of the dairy cows were estimated in two ways: (a) based on the results of the feedstuff analysis and dry matter intake (formula: CH_4 [g day^{-1}]=(63+79 CF+10 NfE+26 CP−212 CL) [kg day^{-1}] (Kirchgeßner et al. 1995, with the means of the ranges of the multipliers in the original equation)) and (b) based on dry matter intake alone (CH_4 [MJ day^{-1}]= 3.23+0.809 DM [kg day^{-1}] (Ellis et al. 2007, equation 2d); conversion of [MJ] to [g] was done according to the energy content of methane of 55.56 MJ kg^{-1}).

Three steps were carried out to estimate GHG emissions from manure. In the first step, the components in the cows' excretions that are relevant for GHG emissions (N_{total}, NH_4–N=total ammoniacal nitrogen (TAN) and organic matter=volatile solids (VS)) were determined (a) in a 'manure analysis' approach and (b) in a 'feed analysis' approach. In the second step, the results from the first step were multiplied by emission factors (IPCC 1996, 2006) that were chosen according to the average annual temperatures and storage conditions of the manures on the different farms. In the last step, the results of enteric and manure emissions were multiplied by their global warming potential (GWP100).

For the manure analysis approach, all manures in the different storage facilities of the farms were sampled and N_{total}, NH_4–N and organic matter were analysed according to the methods described in VDLUFA (1995). For the feed analysis approach, the excretions of N_{total}, TAN and VS were calculated according to the procedures used for the German National Greenhouse Gas Report (Haenel et al. 2012) by using the analysed feedstuff composition and feed demand of the dairy cows. These procedures are based on C and N flow models. GHG emissions from excreta dropped on pastures and in the stable and during manure storage were calculated under consideration of the time the cows spent there. Manure management was assessed via interviews with the farmers (input data detailed by Warnecke et al. 2013).

Only the rather narrow range of milk production of the average dairy cow and of its annual milk yield was analysed. Pre-chain emissions or credits (e.g. emissions from feed production by energy use or soil carbon gains) and emissions from manure application are not included in the following results. However, the droppings on pasture belong to two parts of the farm system: to 'cow keeping and manure storage' and to 'manure application' (in this case to pasture). The emissions from straw used as litter are included in the emissions from cow keeping and manure storage while the emissions from straw left in the field are not subject of this calculation.

Results

As expected, the average diets of the dairy cows differed between organic and conventional dairy farms (Table 1). On average, organic farms used less ($p \leq 0.001$; Table 1) concentrates (13.9 % of the total diet on a dry matter (DM) basis) than conventional farms (24.1 %). Nevertheless, individual organic farms fed as much as 31.5 % concentrates (Fig. 2). Organic dairy cows were fed significantly less maize silage than conventional cows, while organic cows received far more ($p \leq 0.001$) pasture than conventional ones. On a total of 13 conventional farms, dairy cows had no access to pasture at all (Schulz et al. 2013). No difference was found between the average use of grass silage in organic and conventional production. The other roughages and feedstuffs used were not fed in a significantly different percentage on organic and conventional farms either.

Figure 1 shows the regional comparison of the feeding regime between organic and conventional farms. Organic farms with low milk yields and a high percentage of hay in the diet were found in the East and South Germany. Those were large farms that did not use advisory services for dairy feeding. The low percentage of concentrates in dairy rations is typical for the organic farms in the alpine region. The conventional farms in that area feed more hay than conventional farms in the other regions, and the use of maize silage is of lower importance than in other regions. In all regions, the share of feed intake by grazing was significantly higher on the organic compared to the conventional farms. In the coastal area of North Germany, grazing was of higher importance in conventional farming than in conventional farming in the other parts of Germany. Due to the small number of farm pairs analysed (5–7 pairs per region), these means are highly influenced by the individual farm management. However, a more variable diet composition in organic farms is obvious in all regions (Fig. 1).

The feedstuff qualities varied more or less, but no statistically significant difference of the means was found between those of organic and conventional origin (Kassow et al. 2011) or of feedstuffs between regions (data not shown). For this reason, Table 2 summarises mean feedstuff qualities for all farms. As expected, typical relations of quality parameters in the different feedstuffs were found: Hay and straw had the lowest energy (NEL) and the highest crude fibre (CF) contents. In comparison to grass silage, maize silage displayed lower CF contents and only half the crude protein (CP) contents at slightly higher NEL contents. Pasture and maize silage had comparable CF contents, but CP contents were far higher in pasture samples than in maize silage.

The highest share of GHG emissions per kilogram ECM results from CH_4 emissions from enteric fermentation, followed by the emissions from animal excreta (Fig. 2). With only one exception, the results for enteric

Table 1 Average diets of the dairy cows (including both lactation and dry period) on the organic (n=22) and conventional (n=22) pilot farms (mean and minimal and maximal values as averages of the years 2008–2010)

	Milk yield (ECM) [kg cow^{-1} a^{-1}]	No. of years analysed [n]	Concentrates [% of DM]	Maize silage	Other roughage and feedstuffs	Hay	Straw	Grass silage	Pasture
Organic dairy farms									
Mean	6382a	1.9	13.9a	7.2a	7.9	11.8a	0.8a	28.9	29.5a
Min-Max	3881–9135	1–3	0–31.5	0–33.9	0–59.6	0–60.3	0–8.5	0–53.6	6.3–53.2
Conventional dairy farms									
Mean	8660b	1.9	24.1b	30.9b	5.5	3.1b	3.2b	28.4	5.0b
Min-Max	6393–10278	1–3	8.2–34.1	0–44.0	0–28.6	0–12.0	0–20.8	12.9–54.1	0–37.6

Other roughage and feedstuffs consist of spent grains, maize cobs, chicory, freshly cut feedstuffs such as rape or grass, whole plant silage, haylage, potatoes, carrots, wet pulp and soybean pulp. Means that are significantly different (t test; $p \leq 0.05$) have different letters

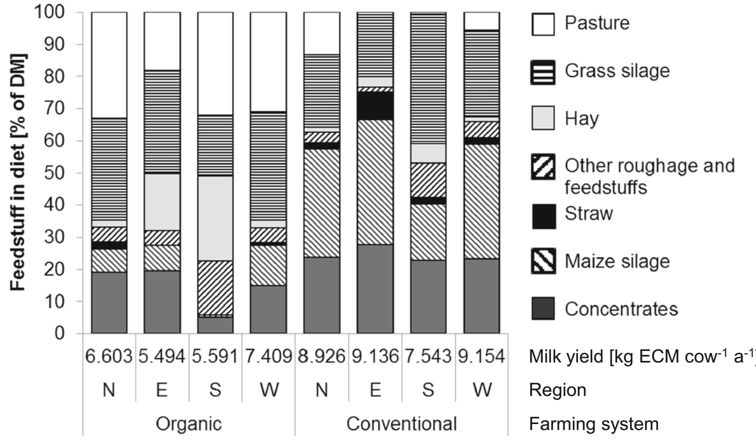

Fig. 1 Means (2008–2010) of the average annual diets of the dairy cows (including both lactation and dry period) and milk yields on the organic (n=22) and conventional (n=22) pilot farms by region (north, east, south, west; Table 1 details the feedstuffs summarised in category 'Other roughage and feedstuffs')

CH_4 emissions from the formula of Kirchgeßner et al. (1995) (using feedstuff quality and dry matter intake as input parameters) were higher than those from the formula of Ellis et al. (2007) (using dry matter intake as the only input parameter). Differences between the results of the two methods were particularly pronounced on farms with lower milk yields and high amounts of hay (up to 60 %) or straw in the diet. These were largely organic farms which also fed a low share of concentrates. Another example for a large difference in the results between the methods is a conventional farm that fed 21 % straw in the average diet. If highly digestible feedstuffs are used, lower differences between the calculation methods occurred even at lower milk yields. This can be seen in the results from the farm indicated in Fig. 2: It used feedstuff with low fibre contents (fresh grass, concentrates, maize silage and high quality grass silage) and had a relatively low milk yield (6393 kg ECM cow^{-1} a^{-1}). The higher the milk yields and the higher the contents of concentrate and maize in the diets, the lower the product-related differences between the results of the calculation methods.

GHG emissions from manure in stables, storage and during grazing on pasture were dependent on the type of manure (solid or liquid), on the time the cows spent in the stable, on the grazing duration and on manure storage conditions on farms. A farm with solid manure only (farm with 5285 kg ECM cow^{-1} a^{-1} in Fig. 2) showed the highest product-related emissions from this source. This results from the comparatively high amount of straw used (2555 kg cow^{-1} a^{-1} as opposed to an average of 1565 kg cow^{-1} a^{-1} on the 38 farms that had any kind of straw input into the stable), from the high emission factors for N_2O and CH_4 used for solid manure (IPCC 1996) and from the low milk yield of this farm. In the two farms with biogas plants, the GHG emissions from stable and storage were reduced considerably (Fig. 2) because the largest part of VS in the manure is turned into biogas. Also, the largest part of N is kept in the closed biogas system, while the NH_3 emissions that occur immediately after excretion were accounted for these two farms.

In all farms, the GHG emissions from manure in the milking parlour were negligible because (a) only NH_3 emissions were considered here (the rest of the emissions of the excreta that were excreted in the milking parlour occurred in the manure storage) and because (b) the animals spent a comparatively small amount of time here. For the product-related GHG emissions, there was a strong negative correlation of milk yield for all evaluated emission sources and locations, except for the emissions in the milking parlour (Table 3).

Only small differences between organic and conventional farms were found in the measured mean concentrations of VS, N_{total} and TAN in the manures, in the resulting potential to emit GHG (called 'potential greenhouse effect' in the following) and in the storage conditions. In both systems, storage of solid manure and storage of liquid manure had comparable potential emissions of approximately 32 kg t^{-1} CO_2-eq. based on fresh matter (FM). Based on dry matter (DM), the mean potential greenhouse effect of stored solid manures was higher than that from liquid manures. CH_4 was the most relevant source for emissions in liquid manures, whereas N_2O and CH_4 were equally relevant in solid manures (Table 4). The mean values show high standard deviations. This reflects (a) the wide range of manure composition, (b) the effects of the individual

Table 2 Feed qualities (means of all farms and of the years 2008–2010)

Feedstuff	No. of samples analysed per feedstuff [n]	CF [g kg^{-1} DM]	NfE	CP	CL	NEL [MJ kg^{-1} DM]
Hay	119	308	486	112	16.4	5.55
Straw	60	476	435	30	10.7	4.01
Pasture	19	216	478	185	33.4	6.90
Grass silage	237	268	445	154	26.9	6.21
Maize silage	100	214	641	78	28.6	6.45
Concentrates	252	98	588	220	43.5	7.90

CF crude fibre, *NfE* nitrogen-free extracts, *CP* crude protein, *CL* crude fat, *NEL* net energy lactation

storage conditions on the farms and (c) the setting of emission factors for solid manure, liquid manure and storage systems. The latter influences results and complicates interpretation and adequate management reactions (Paulsen et al. 2013).

Discussion

Readily degradable feed components reduce enteric CH_4 production per kilogram fermentable organic matter, while fibre-rich feedstuffs increase it (Johnson and Johnson 1995; Piatkowski et al. 2010). Kirchgeßner et al. (1995) take crude nutrients into account while calculating CH_4 emissions from enteric fermentation. Using this formula for the mean feedstuff qualities of all farms given in Table 2 yields the following results: Hay 91.6, straw 103.5, pasture 82.6, grass silage 86.9, maize silage 82.2 and concentrates 73.1 g CH_4 kg^{-1} DM intake. The diets were quite different with respect to the share of pasture and maize silage respectively. However, no overall difference between organic and conventional

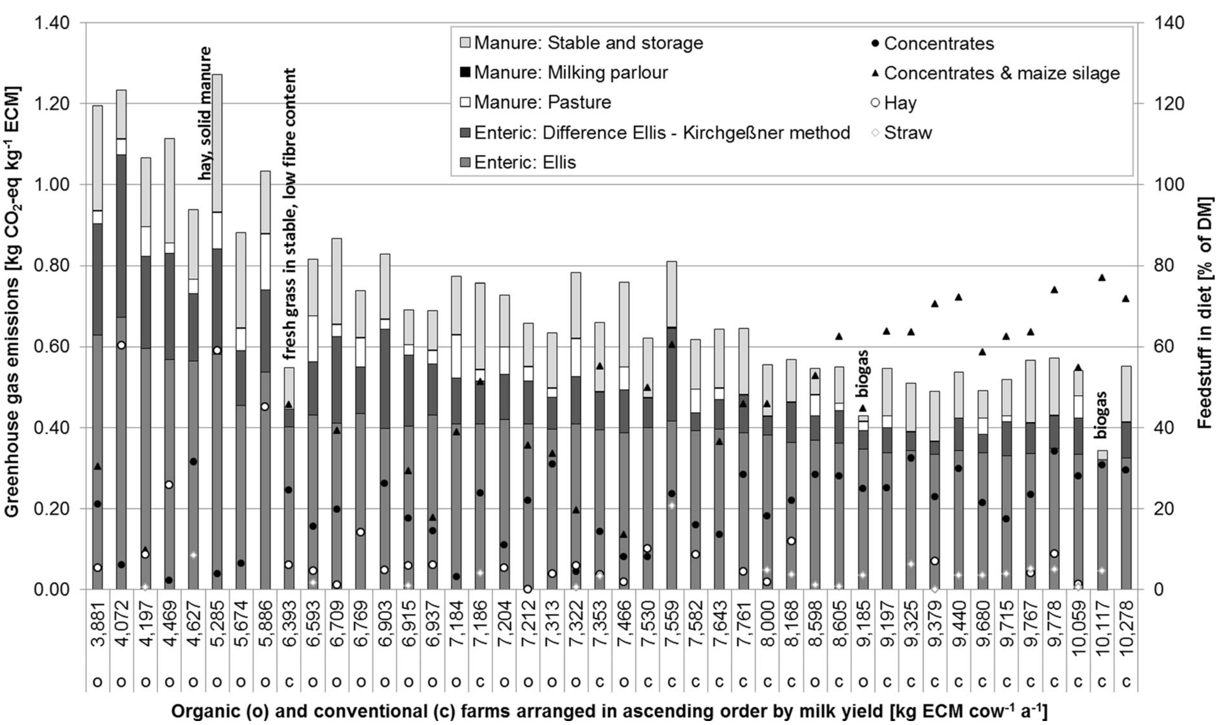

Fig. 2 Product-related GHG emissions of milk production from enteric fermentation and from manure in stable, storage and pasture and share of selected feed components in the average annual diets of dairy cows on 44 organic and conventional farms in Germany

Table 3 Pearson correlation matrix for the interrelationship of the sources of product-related GHG emissions in milk production

	Enteric fermentation (EF) according to Kirchgeßner/Ellis	Stable and storage	Milking parlour	Pasture	Sum
Milk yield [kg ECM a^{-1}]	−0.89***/ −0.93***	−0.62***	−0.08***	−0.42***	−0.68***
EF Kirchgeßner et al. (1995)	− / 0.96***	0.60***	0.23***	0.38***	0.65***
EF Ellis et al. (2007)		0.58***	0.13***	0.42***	0.65***
Stable and storage			0.10***	0.22***	0.90***
Milking parlour				0.07***	0.12***
Pasture					0.63***

*0.05≥p<0.01; **0.01≥p<0.001; ***p≤0.001 (significance of correlation)

CH_4 output from enteric fermentation can be expected from pasture and maize silage since CH_4 emission per kilogram feedstuff is very similar. On average, organic dairy cows received more fibre-rich hay (which produces more CH_4 per kg of DM) and conventional dairy cows were fed more readily degradable concentrates (which produce less CH_4 per kilogram of DM; Figs. 1 and 2). Hence, it could be expected from the combination of diet and feed quality that on average, organic dairy cows produced slightly more CH_4 from enteric fermentation per kilogram feed consumed (DM) than conventional dairy cows.

CH_4 emission from enteric fermentation of dairy cows was the most important on-farm source of GHG emissions in dairy farming in this study, independent of the estimation method used (Fig. 2). However, the choice of methodology to calculate these CH_4 emissions is highly relevant for the level of both the animal-related and the product-related GHG emissions of milk. Enteric CH_4 emissions according to the crude nutrients approach by Kirchgeßner et al. (1995) were 3822 and 3759 kg CO_2-eq. cow^{-1} a^{-1} on organic and conventional farms, respectively, while it was 2852 and 3112 kg cow^{-1} a^{-1} for the DM intake approach by Ellis et al. (2007). In comparison to the formula of Ellis et al. (2007), the formula of Kirchgeßner et al. (1995) increased the level of GHG emissions from enteric fermentation in almost all cases with an average difference between the methods of 808 kg CO_2-eq. cow^{-1} a^{-1} (>25 %).

Just like CH_4 emissions from enteric fermentation, emissions from manure are also directly connected with

Table 4 Mean concentration of VS, TAN and N_{total} as analysed from the manure samples and calculated potential GHG effects from those manures as dependent on the storage conditions in 44 dairy farms in Germany based on dry matter (DM) and fresh matter (FM) (means of the manure samples from all farms in 2009–2011)

		Solid manure (n=36)		Liquid manure (n=38)	
		[kg t^{-1} DM]	[kg t^{-1} FM]	[kg t^{-1} DM]	[kg t^{-1} FM]
VS		778±121A	208±43a	727±65B	40±21b
N_{total}		20.0±3.7B	5.3±1.1a	63.7±39A	2.7±1.6b
TAN		3.1±1.58B	0.81±0.4b	36.5±28A	1.3±0.7a
CO_2-eq. from	CH_4	62.6±9.8B	16.7±3.4a	526±47A	27.5±16.5b
	N_2O	46.8±8.6B	12.4±2.5a	113±102A	4.5±3.1b
	$N_2O_{(indirect)}$ [a]	8.85±4.46	2.27±1.1a	6.83±6.16	0.25±0.15b
	Total	118±16B	31.4±5.2	646±11A	32.2±18.3

Results of comparison of the mean of solid and liquid manures (t test, p≤0.05) in different capital or small letters are indicating significant differences in the dry or fresh matter content, respectively

[a] Resulting from NH_3 deposition

feed intake and feed quality. Hence, milk yield and product-related GHG emissions from enteric fermentation were strongly negatively correlated. The medium correlation found for GHG emissions from manure in stable and storage and on pasture with milk yield (Table 3) can be hypothesised to be influenced by parameters that are determined by farm management (type of manure and duration of grazing). The sum of the product-related GHG emissions and those from manure in stable and storage showed a strong positive correlation (90 %). This reflects interrelationship in calculation between digestibility of feed, milk yield and amount of manure. On the other hand, this reveals a GHG reduction potential by technique and management on the farms, e.g. increasing digestibility of feed or optimising manure storage. Therefore, feed quality data should be included in management recommendations aiming at reducing GHG emissions from enteric fermentation and excreta in milk production. Also, technical changes in manure storage and handling (e.g. managing liquid manure in a way that allows formation of a natural crust as opposed to daily manure stirring or integrating a slurry based biogas plant) offer a considerable GHG reduction potential in dairy farming (Fig. 2; Weiske et al. 2006; Novak and Fiorelli 2010).

In this study of the rather narrow range of milk production, on average, organic dairy cows produced more CO_2-eq.kg^{-1} ECM a^{-1} from enteric fermentation than conventional ones and no differences of the potential greenhouse effect of manures were found between organic and conventional farms. However, the differences in feeding regime that were observed on the individual farms also affect the primary energy use for feed production. For a subset of 24 farms of the dairy farm network described in this study, Frank et al. (2013) used a whole-farm model to determine energy balances and CO_2 balances. They showed that farms with a high share of roughage in the diet had a lower energy input at a similar energy output per kilogram ECM. This effect was most pronounced in farms where dairy cows were able to graze as opposed to farms where dairy cows were fed conserved roughage. Hence, it was most pronounced on the organic farms in this study. Another factor closely linked to feeding is the organic carbon content of the soils where the animals' feeds are produced. Frank et al. (2013) found farms that sequestrated as much carbon as to compensate for a considerable share of the enteric emissions. The extent of estimated soil carbon loss or gain depends on the methodology and coefficients used in the modelling. For that reason, soil carbon gain or loss should always be reported separately and in detail in whole-farm CO_2 balances.

For the farms of this study, Blank et al. (2013) enlarged the view beyond the time frame of a year. They found that average herd life (months between first day in lactation to end of productive life) was higher on the organic (39 months, n=19) than on the conventional farms (27 months, n=16). Average lifetime efficiencies (kg ECM per day from birth to end of productive life) on the farms increased with milk yield and with decreasing age at first calving (organic/conventional 31/28 months, n=19/17) and, despite of the higher average herd life, was lower in organic (10.3 kg ECM day^{-1}, n=19) than in conventional farms (12.0 kg ECM day^{-1}, n=17). Integration of these aspects into estimations of GHG emission of milk production will paint a more diverse picture of the matter.

Additional factors beyond the topics and boundaries described in this study increase or decrease GHG emissions in dairying. One of them is the allocation of emissions from offspring to milk, to meat, or maybe even to another farm that is specialised in fattening (Cederberg and Stadig 2003; Nguyen et al. 2013). Another factor is animal health and welfare, e.g. the use of medicinal products which can lead to discarding of milk, thus increasing the burden of emissions per kilogram milk sold.

On the long run, aspects like these have to be integrated into calculations of GHG emissions to come up with further relevant advice on the rather complex optimisation approaches necessary for a climate-friendly milk production.

Conclusion

On average, the product-related enteric CH_4 emissions of the conventional dairy cows were lower than those of the organic dairy cows. This could largely be attributed to their higher annual milk yields and to the lower ratio of fibre-rich feedstuff in their diet. No systematic differences were found between the two systems with respect to emissions from manure. Differences between the individual farms were higher than between the systems and were particularly pronounced between the organic farms.

If farms or farming systems are compared with respect to overall or partial GHG emissions, it is important to use the same methodology for generating the results. The choice of methodology to estimate enteric CH_4 emissions of dairy cows proved highly relevant for the level of both the animal-related and the product-related CH_4 emissions. Feed quality management plays a key role on dairy farms since it impacts on milk yield, enteric CH_4 emissions and manure composition. Hence, systematically optimising feedstuff quality and feeding regime serve to increase milk yields while simultaneously reducing GHG emissions from enteric fermentation and manure in dairy farming.

Differences in feeding regime on dairy farms have consequences for the primary energy use for feed production and for the organic carbon pool in soils where the feed is produced. The system boundaries and the allocation of emissions to products or to parts of the agricultural system impact on the overall results of GHG emissions from milk production. These aspects should be clearly addressed by whole-farm assessments to conclude over GHG emissions in organic and conventional dairy farms. They should be part of advisory concepts that aim at reducing GHG emissions in milk production. Technical changes in manure storage and handling offer an additional GHG reduction potential.

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