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Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach

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ABSTRACT

This paper documents and illustrates a model to estimate the greenhouse gas (GHG) emissions and land use on commercial dairy farms. Furthermore, a method of allocating total farm emissions into meat and milk products was developed and, finally, potential mitigation options at farm scale were identified. The GHG emission at farm gate using a Life Cycle Approach (LCA) was estimated based on data from 35 conventional dairy farms with an average 122 cows and 127 ha, and 32 organic dairy farms with an average 115 cows and 178 ha. There was a significant ($p<0.05$) higher emission in kg CO_2-eq. per kg energy corrected milk (ECM) in the organic system (1.27) compared to conventional (1.20) before allocation into milk and meat. In the conventional system 88% was on-farm emission vs. 98% in the organic production system. Based on a mathematical model, an average of 15% of total farm GHG emissions was allocated to meat. This level was low compared with four other methods traditionally used to allocate between milk and meat, with the amounts allocated to meat ranging from 13% for economic value, 18% for protein mass, 23% for system expansion and up to 26% for biological allocation. The allocation method highly influenced the GHG emission per kg meat (3.41 to 7.33 kg CO_2-eq. per kg meat), while the effect on the GHG emission per kg milk was lower (0.90 to 1.10 kg CO_2-eq. per kg ECM). After allocation there was no significant effect of production system on GHG emission per kg ECM. Land requirement, including imported feed, was highest in the organic system at 2.37 m^2 per kg ECM against 1.78 m^2 in the conventional system. Farming strategies based on low stocking rate or with focus on high efficiency in the herd were identified as the most promising for reducing GHG emissions per kg milk at farm gate after allocation between meat and milk. It was concluded that the model can estimate relevant variation in GHG emissions between commercial farms without intensive data registration.

1. Introduction

Agriculture is an important contributor to global emissions of greenhouse gases (GHG), in particular of methane (CH_4) and nitrous oxide (N_2O). Agriculture contributes 10–12% to overall global emissions. Of this, livestock is assumed to be responsible for the largest part at nearly 80% of global agricultural GHG emissions (FAO, 2006). This is particularly due to CH_4 emissions from enteric fermentation in ruminants and manure handling, and due to the intensive nitrogen (N) cycle on livestock farms leading to direct and indirect N_2O emissions (Olesen et al., 2006). With the global demand for animal-sourced foods set to double by 2050, the implications for GHG emissions are profound (FAO, 2006). The already large contribution from agriculture to global GHG emissions will therefore increase in importance unless more effective and climate-friendly systems are adopted. Furthermore, the agricultural contribution to CO_2 emissions from deforestation can only be reduced if the productivity of existing agricultural land is improved. The future challenge within agriculture is therefore three-fold: to adapt to a changing and more variable climate, to increase production and, at the same time, to reduce GHG emissions (Basse et al., 2009).

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This paper will address the last part in relation to dairy production. Olesen et al. (2006) modelled GHG emissions from European dairy production systems and concluded that the GHG emission per kg product was more closely related to N efficiency than to production system, while Schils et al. (2006) found that a reduction in N surplus effectively reduced GHG emissions from Dutch dairy farms. In a model study of different US production systems, Rotz et al. (2010) found that milk yield per cow and the feeding and manure handling strategies were the main factors explaining the variation in emissions between systems. Casey and Holden (2005) in an Irish study found that a combination of high-yielding cows and elimination of non-milking animals was the most effecõtive mitigation strategy. In a Swedish study, Cederberg and Mattsson (2000) found a difference in GHG emissions between organic and conventional milk production based on data from two farms, while Cederberg and Flysjö (2004) in a larger study based on 23 farms in a Swedish region and Thomassen et al. (2008a) based on data from 21 Dutch farms concluded that there was no difference between organic and conventional production systems in terms of GHG emission per kg milk. Within organic farming Müller-Lindenlauf et al. (2010) found that grassland-based farms combined with high milk yield per cow resulted in the lowest emission per kg milk, which is in line with the overall conclusion by FAO (2010), that intensification of farming, in terms of milk yield per cow, creates the lowest GHG emission per kg product. However, no studies have yet set out to verify these suggestions based on empirical farm data, as the very complex structure of the farming system might be an obstacle to identifying the effect of partial changes in a whole-farm perspective (Del Prado et al., 2010).

The purpose of this study was to develop a method based on available data from commercial farms to estimate the impact of dairy farming on GHG emissions at farm gate divided into on-farm (direct or primary) and off-farm (indirect or secondary) emissions and types of GHG, including a method to allocate between milk and meat. Another purpose was to obtain benchmark figures for important parts of total GHG emissions and to highlight areas that have significant impact on these figures and thereby identify possible mitigations options.

2. Materials and methods

Annual data of the production performance, economic turnover and the N budget of specialized dairy farms from the period 2001–2003 were analyzed. The results were expressed either per cow with 365 feeding days, per livestock unit (LSU) equal to 0.75 cow (annual yield 9200 kg ECM with correction for milk yield) or 2.4 heifers of the Holstein Friesian type (Anonymous, 2009a), or per ha of agricultural land, equal to the farmed area including permanent grass and set-aside. These data had been collected as part of other activities in relation to dairy production and N emission to the environment by Nielsen and Kristensen (2005), who also give a more detailed description of the methods used for registration and data collection. We included only farms with (a) at least 90% of the income from dairy activities, (b) registrations of the yearly turnover of animals, feedstuff and manure balanced with the change in on-farm stock, and (c) consistent data on forage production and feed use. Based on these criteria a total of 67 farms, representing both organic ($n = 32$) and conventional ($n = 35$) farms were analyzed. The herds on all organic farms were Holstein Friesian (HF), while on conventional farms nine of the 35 herds were Jersey and the remaining HF. The most dominant manure handling system was slurry, used on 86% of the conventional farms, but only on 53% of the organic farms.

The environmental performance in a cradle-to-farm-gate perspective was evaluated using life cycle assessment (LCA) with focus on the global warming impact category. The LCA was made by the attributional method, where the environmental impact of the production is quantified in a status quo situation (Thomassen et al., 2008b). The global warming potential was estimated for a 100-year time period by converting all GHG to CO_2 equivalents (CO_2-eq.), which on a weight basis gives 1 kg $CH_4 = 25$ and 1 kg N_2O-N = 298 CO_2-eq. (IPCC, 2006).

2.1. System boundary definition

Traditionally the physical farm defines the dairy production system, but in this case the system boundary was extended in order to include also the emissions related to the imported resources such as feed and fertilizer. These latter resources are referred to as off-farm or secondary emissions and the former as direct or primary emissions.

2.2. Production data

We have as far as possible used data from the farm-gate turnover, as also argued by van der Werf et al. (2009), which means that only few data from the internal turnover at the farm are needed. This type of data is often difficult to get and the uncertainty attached to the figures often larger than for the data related to the farm-gate (Kristensen, 2004).

The products from the farms were amounts of milk and meat sold, with meat adjusted for the difference in herd live weight at the start and end of the year and imported animals. The typical Danish dairy farm is a mixed farm based on feed production from its own arable area, where roughage is produced in a rotation with cereals. Often the cereals are used both directly as feed and in exchange for concentrates at the feed manufacturers. This means that the grain production is not a separate enterprise in order to produce a cash crop, but is an integral part of the dairy production system. The amount of cereals produced and its exchange for other types of concentrate at the feed manufacturers is part of the process of giving the herd a balanced diet in terms of energy and crude protein. Therefore we have calculated the net amount of imported feed as the actual import minus exported crops expressed in MJ net energy to lactation (NE) and kg nitrogen (N) based on the amount in kg from the farm accounts, and the nutrient content from either analyses of the feed, information from the feed manufacturer or standard values from feed tables.

The net amount of imported manure was also calculated as the difference between exported and imported manure expressed in kg N. These net calculated sources were treated as input, as they only in a few observations were negative. By calculating the manure and feed sources as net inputs, we did not have to make allocation for manure and crop exported from the farm or to make a subsystem for crop production.

The amount of annual fossil energy used was recorded as a total cost. Based on Danish standard figures it was assumed that the cost was equally distributed between diesel and electricity, and the amount of diesel in litres and energy in kWh was estimated from standard annual prices. The energy cost from the use of contractors was calculated as 12% of the net cost to contractors at each farm, based on a standard use of contractors for the different operations.

2.3. Functional unit and allocation

The functional unit in the study was 1 kg energy corrected milk (ECM) (Sjaunja et al., 1990) calculated from kg milk sold at the farm gate and weekly analyses of fat and protein content.

The method used to divide total farm GHG emissions into meat and milk has significant impact on the estimated emission of the products (Cederberg and Stadig, 2003; Thomassen et al., 2008a). In the present study, a new method of allocation between the two products was developed and compared with four existing methods; the first three of these methods are based on attributional LCA and the last one on consequential LCA. The four methods were:

1) Allocation according to the proportions of milk and meat protein produced, as recommended by FAO (2010)
2) Biological allocation, based on feed energy required to produce the amount of milk and meat at the farm, was made by the empirical relation developed by IDF (2010) from data representing a large variation in type of feed rations, proportion of meat and type of animals
3) Economic allocation based on the amount of milk and meat produced on each farm at standard unit price, which for milk was 0.13 EUR per kg ECM and for meat 0.99 EUR per kg live weight (Anonymous, 2009b) and
4) System expansion where the emissions related to the meat production were subtracted from total emissions, based 50/50 on the emissions from pig meat and beef meat as argued by Nielsen et al. (2003). Emissions from pork are 3.6 kg CO_2-eq. per kg carcass (Dalgaard et al., 2007) and from beef meat 21.7 kg CO_2-eq. per kg carcass calculated as the average of EU suckler cows and intensive steer production (Nguyen et al., 2010), giving 12.65 CO_2-eq. per kg carcass weight, which is equal to 6.33 kg CO_2-eq. per kg live weight.

The allocation method developed in this paper was based on model A, assuming a causal relation between total farm GHG emissions (CO_2-eq.) and the total milk production in kg ECM and total meat production in kg live weight gain.

$$\begin{aligned}\text{Total farm } CO_2\text{−eq.} &= \text{intercept} + \text{ECM (kg)}*\text{a} \\ &\quad + \text{live weight gain (kg)}*\text{b} + \text{error}\end{aligned} \qquad \text{(model A)}$$

The model parameters, a and b, were estimated based on data from the 67 farms in the study and used afterwards to allocate the emissions between milk and meat at each farm.

2.4. Emission factors

Table 1 gives the EF used for calculating the primary emissions of CH_4 and N_2O for each pollutant.

Enteric methane emission was estimated using an EF of 6% (Mikkelsen et al., 2006) and a standard gross energy concentration of 18.45 MJ per kg dry matter (DM) (IPCC, 2006) in combination with the herd-specific annual dry matter intake (DMI) calculated from recordings of daily feed intake (kg and feeding value) at least 12 times during the year. When animals were at pasture, the intake of grass in each subgroup of animals was calculated as the difference between the energy requirement and the recorded intake of supplemented feed. Emission from manure was calculated using the specific EF for the three types of manure systems: slurry, deep litter and pasture (Mikkelsen et al., 2006). The amount of organic matter in manure was estimated from the herd-specific DMI and standard digestion coefficient (72%) and ash content in DM (8%) with a methane formation capacity of 0.22 m^3 CH_4 per kg organic matter (Mikkelsen et al., 2006). The proportion of NE intake from pasture was used to allocate the total amount of manure excreted between pasture and indoors. This amount of indoor-excreted manure was in the deep litter housing system by default allocated with 40% to slurry and 60% to deep litter (Poulsen and Kristensen, 1998). In systems with deep litter the amount of straw used for bedding was added to the organic manure using the standard dry matter content in the straw of 85% and 10% ash content in the dry matter.

The direct and indirect N_2O emissions via NH_3 and NO_3 were calculated from the N flow. N excreted ex animal was calculated as the difference between N in feed intake and N in produced milk and live weight change. Nitrogen in intake was known from recordings of DMI, and the content of crude protein from feed analyses or standard values, converted to nitrogen by dividing by 6.25. The N content in milk was calculated from weekly analyses of milk content, and converted to N by dividing by 6.38. Nitrogen in live weight gain was set to 26 g N per kg live weight (Poulsen and Kristensen, 1998). The emissions of NH_3 in the chain from animal to soil were estimated using the EF related to the Danish standard practice of application (Mikkelsen et al., 2006). The indirect N_2O emission was calculated from the sum of all pathways for NH_3 emission using a common EF of 0.01 (IPCC, 2006).

The type of fertilizer used at each farm was not known so the EF is based on the average amounts and types of fertilizer used in Denmark (Mikkelsen et al., 2006). The emission from crop residues was estimated at farm level by multiplying the area of each type of crop with a standard amount of N in residues (sum of above and below-ground level) per ha for each type of crop. A slightly different grouping of the crops was used to estimate the N_2O emission from mineralization, assuming a C/N ratio of 10 as the change was due to type of crop on farmed land (IPCC, 2006). The N-surplus at farm gate can be divided into losses as shown by Nielsen and Kristensen (2005), but this method is based on detailed information that was not available in this study. A more general method proposed by IPCC (2006) and used at national level in Denmark (Nielsen et al., 2009), which assumes 33% of the N from fertilizer and manure ex storage is lost through leaching, was used instead. Emission from fossil energy use in diesel

Table 1
Emission factors (EF) for estimation of emission from dairy farms.

CH_4, kg	Pollutant	Amount	EF	Source – EF
	Enteric	Herd DMI × 18.45 MJ brutto energi/55.65	0.06	Mikkelsen et al. (2006) IPCC (2006)
	Manure	Non digestible organic DMI + organic matter		Mikkelsen et al. (2006)
	– Slurry	used as bedding; CH_4 formation capacity = 0.22	0.1	
	– Deep litter [a]		0.01	
	– Pasture [b]		0.01	
N_2O-N, kg direct	Stable	N manure ex animal		IPCC (2006)
	– Slurry		0.005	
	– Deep litter [a]		0.01	
	Application	N manure ex storage [c]		IPCC (2006)
	– Slurry		0.01	
	– Deep litter [a]		0.01	
	– Pasture [b]		0.02	
	Fertilizer	N import	0.01	IPCC (2006)
	Crop residues	Crop kg N per ha pr year	0.01	IPCC (2006)
		Grassland, conv. 2 years lay 60 N		Mikkelsen et al. (2006)
		Grassland, organic 3 years lay 47 N		
		Grassland, permanent 5 N		
		Maize, whole crop 25 N		
		Other arable crop 28 N		
	Mineralization	Soil CO_2 change [d]*0.27*0.1	0.01	IPCC (2006)
NH_3-N, kg	Stable	N manure ex animal		Poulsen and Kristensen (1998)
	– Slurry		0.08	Mikkelsen et al. (2006)
	– Deep litter [a]		0.06	
	Storage	N manure ex animal		Mikkelsen et al. (2006)
	– Slurry		0.022	
	– Deep litter [a]		0.25	
	Application	N manure ex storage [c]		Mikkelsen et al. (2006)
	– Slurry		0.12	
	– Deep litter [a]		0.06	
	– Pasture [b]		0.07	
	Fertilizer	N import	0.022	Mikkelsen et al. (2006)
	Crop residues	Ha annual		Gyldenkærne and Albrektsen (2008)
	– Grassland		0.5 kg/ha	
	– Other arable crops		2.0 kg/ha	
N_2O-N, kg indirect	From NH_3	NH_3-N	0.01	IPCC (2006)
	From leaching	NO_3-N = 0.33*(N manure ex storage + N import fertilizer)	0.0075	Nielsen et al. (2009) IPCC (2006)

[a] In deep litter housing system as default 40% of DMI related to slurry and 60% to deep litter.
[b] Amount of manure deposited at pasture estimated from proportion of NE intake from pasture.
[c] N ex animal – NH_3-N emission stable and storage – N manure import – N manure export.
[d] Net soil change kg CO_2 annual per ha: grassland rotation +1900; grassland permanent 0; maize and other arable crops – 3000.

was set at 3.31 kg CO_2-eq. per litre and to 0.654 kg CO_2-eq. per kWh of electricity (Nielsen et al., 2003).

The secondary emission from import of feed and fertilizer is only given in CO_2-eq., but in some cases estimated from CH_4 and N_2O emissions. The secondary emission from imported fertilizer and net import of manure were calculated from total N in fertilizer and from 75% of total N in manure, based on a standard utilization of 75% (Anonymous, 2009a) when applied to the crop, with an emission of 5.44 kg CO_2 per kg N. Assuming that the import of feed energy and N could be met by a combination of barley and soybean meal, the emission related to feed energy and N could be calculated from the emission from barley (0.506 kg CO_2-eq. per kg) and soybean meal (0.632 kg CO_2-eq. per kg) based on Dalgaard et al. (2008) and updated values from Nguyen et al. (2011).

Land use was calculated as the sum of the farmed area and land off-farm for production of imported feed. The calculation for the off-farm area gave values of 20.63 m^2 for 1 kg N imported and 0.23 m^2 per MJ NE imported based on data for the production of soybean and barley (Dalgaard et al., 2008).

Emissions from other production inputs like pesticides, seeds, liming and medicine were not included, as information was missing, and neither were emissions associated with the construction of machinery and buildings or the potential emission from managed organic soil.

2.5. Data analysis

Results are presented by simple means, minima and maxima in order to give as much information as possible about the background for the aggregated results, and the effect of production system was tested by a variance test using PROC GLM in SAS (2009) with production system as the only dependent variable.

The complex relations between the variables used to describe the production at the farms (Table 1) were analyzed with PROC FACTOR (SAS, 2009) by use of the varimax rotation in order to identify the factors, where the dominant variables in each factor are highly correlated and the correlation between the factors is as low as possible (Sharma, 1996). Variables with communality estimates higher than 0.7 and factors with eigenvalues of more than one were maintained in the analysis (Sharma, 1996). Based on the factor pattern each factor was labelled in order to be associated with a farming strategy.

Regression analysis, PROC GLM (SAS, 2009), was used to test the relation between the variation in GHG emission and farming strategy expressed by the factor scores related to each farm and strategy.

3. Results

3.1. Characteristics of conventional and organic production systems

The average milk yield in ECM per cow was 14% higher on conventional farms in this study than on organic farms and almost twice as high per ha, due to a higher stocking rate (Table 2). The young stock was primarily heifers, but some farms also raised some of the male calves as bulls or steers. This, combined with the variation in type of breeds, gave a large variation in the number of young stock per cow and also in live weight gain in the herd expressed per LSU, but without any significant effect of production system. The organic feed ration was based on a larger proportion of roughage, and especially the proportion from pasture was higher on the organic than on conventional farms.

Crop production in NE per ha was highest on conventional farms, while there was no difference in protein (N) yield. This was due to the larger proportion of grassland and much smaller area with maize on the organic farms. The amount of manure (gross N) and fertilizer N applied per ha was 106 kg N higher on conventional farms, while the amount of N input from fixation was estimated at an average of 68 kg per ha on the organic farms and 24 kg N per ha on conventional farms (data not shown).

3.2. Emissions of CH_4, N_2O-N, total GHG and land use

Methane emissions per animal were identical in the conventional and organic production systems with by far the largest contribution (86–88%) from enteric fermentation, of which 89% came from cows and 11% from young stock (Table 3). Although the EF is 10 times higher from slurry than from deep litter, this had only a marginal effect on total emissions within each manure system (119 vs. 114 kg CH_4 per LSU, data not shown). This is due to the emission from the straw used in the deep litter system (3150 kg pr LSU) and to the fact that 40% of the manure in the deep litter system was handled as slurry.

Nitrous oxide emission per ha was significantly lower on the organic farms, both in total and for most of the pollutants (Table 4), except the emission from crop residues, which was identical in the two production systems. The emission from N excreted during grazing was highest in the organic system. Due to the ban on using synthetic fertilizer in the organic system, this source of emissions is only present in the conventional system, contributing 13% to total emissions. Mineralization was 6% of total emissions in the conventional system, while it was slightly negative in the organic production system. The indirect N_2O emission in both systems amounted to 22% of total emissions, but indirect emissions from leaching were in total

Table 2
Farm description – annual number of animals, feeding, production, land use, N application and efficiency in two production systems.

	Conventional $n=35$			Organic $n=32$			P-system
	Mean	Min	Max	Mean	Min	max	
Herd							
Cows, no	122	55	203	115	69	171	ns
Heifers + male calves, no per cow	1.19	0.94	1.69	1.24	0.78	2.03	ns
Milk, kg ECM [a] per cow	8201	6402	10427	7175	6133	8608	***
Live weight gain herd, kg per LSU [b]	179	138	251	174	118	291	ns
Feed intake, kg DM [c] per cow	6593	5514	7761	6618	5903	7472	ns
Roughage, % of DMI – herd	55	39	74	69	54	80	***
Pasture, % of DMI – herd	8	0	23	19	8	28	***
Efficiency, kg ECM per kg DMI – cow	1.25	1.01	1.40	1.08	0.91	1.23	***
Efficiency, kg ECM per kg DMI – herd	0.95	0.78	1.10	0.82	0.68	0.92	***
N efficiency ex animal, %	22	17	25	19	17	22	***
Land							
Area, ha	127	53	308	178	99	236	***
Maize, % of area	17	0	41	3	0	14	***
Grassland in rotation, % of area	24	0	74	45	24	71	***
Grassland permanent, % of area	6	0	31	10	0	23	**
Yield, NE [d] (1000) per ha	50.4	37.9	64.8	37.4	27.0	45.7	***
Yield, kg N per ha	137	93	224	138	78	189	ns
Fertiliser, kg N gross per ha	68	35	106	0	0	0	***
Manure, kg N gross per ha	168	105	291	130	68	181	***
Farm							
Stocking rate, LSU per ha	1.80	1.14	2.92	1.12	0.66	1.40	***
Milk, kg ECM per ha	8701	5135	16171	4780	2623	6676	***
Crop production, % of NE intake	81	43	124	98	62	153	**
Crop production, % of N intake	59	27	93	87	73	104	***

[a] ECM: Energy corrected milk (4.10% fat, 3.30% protein).
[b] LSU: Livestock unit (1 LSU being either 0.75 Holstein Friesian type dairy cow standard yield or 2.4 young stock Holstein Frisian type).
[c] DM: Dry matter.
[d] NE: Net energy lactation.

Table 3
Annual methane emission from the farm production, kg methane (CH_4).

	Conventional			Organic			P-system
	Mean	Min	Max	Mean	Min	max	
Enteric fermentation							
Herd, kg CH_4 per LSU [a]	101	88	110	102	86	113	ns
– Cows, kg CH_4 per animal	131	110	154	132	117	149	ns
– Heifers, kg CH_4 per animal	35	19	48	36	22	48	ns
Manure							
Storage, kg CH_4 per LSU	17	10	21	14	9	19	***
Pasture, kg CH_4 per LSU	0.2	0	0.5	0.4	0.2	0.5	***
Total, kg CH_4 per LSU	119	103	129	116	95	130	ns

[a] LSU: Livestock unit (1 LSU being either 0.75 Holstein Friesian type dairy cow standard yield or 2.4 young stock Holstein Frisian type).

twice as high from the conventional system than from the organic.

The total GHG emission per kg ECM milk at farm gate was lowest (1.20 kg CO_2-eq.) in the conventional production system (Table 5), but the range between farms within system was larger than the difference between the two production systems. The proportion of direct emissions from the farm was highest in the organic system at 96% compared to 81% in the conventional system. Emission from the use of fossil energy was highest per kg ECM in the organic system. There was a large variation between farms in the emission from net imported feed, but the average emission from this pollutant was lowest in the organic system. The ranking of the different internal pollutants based on emission per kg ECM was identical in the two production systems, with the highest contribution from methane, followed by nitrous oxide and fossil energy (Fig. 1).

The total area used for production of 1 kg ECM was 35% higher in the organic system than in the conventional system. The part of this area at the dairy farm was highest in the organic system (96 vs. 73%), whereas a smaller area related to imported feed was used in the organic production system.

3.3. Allocation of emissions between milk and meat

Fig. 2 shows the relation between total emissions (sum of direct and indirect) and, respectively, total milk production and total live weight gain on the 67 farms. Based on the data in Fig. 2, the total GHG emission was modelled using model (A) with the result:

$$CO_2-\text{eq.} = \text{milk} * 1.03(+-0.03) + \text{live weight gain} \\ *4.17(+-1.08) \qquad r^2 = 0.92$$

A model with an intercept was also calculated, but the intercept was not significantly different from zero ($p = 0.54$), and the parameters for milk and meat only changed slightly compared to the parameters in the model without an intercept. The parameter for milk was significant ($p < 0.001$), as it was for meat, although less so ($p = 0.02$).

When using the model parameters from model (A) the GHG emissions after allocation were 1.06 kg CO_2-eq. per kg ECM in the organic and 1.03 kg CO_2-eq. per kg ECM in the conventional system (Table 6). These figures are in the middle of the range (0.90–1.10 kg CO_2-eq. per kg ECM) calculated by the four different allocation methods described earlier.

All methods found a significant effect of production system on the proportion of GHG allocated to meat, which varied from 12 to 22% in the conventional system and from 14 to 29% in the organic system, dependent on the method used for allocation. The allocation method had a larger impact on the range in emission per kg meat than per kg ECM, leading to a variation in emission per kg meat from 3.4 to 6.9 kg CO_2-eq. in the conventional system and from 3.5 to 7.3 kg CO_2 eq. in

Table 4
Annual nitrous oxide emission from the farm production, kg N_2O-N per ha per year.

	Conventional			Organic			P-system
	Mean	Min	Max	Mean	Min	max	
Directly							
Manure							
Storage and stable	0.97	0.57	2.33	0.64	0.47	1.18	***
Application							
○ Manure	1.51	0.94	2.66	1.19	0.63	1.63	***
○ Pasture	0.30	0.94	1.18	0.44	0.20	0.64	*
Fertilizer	0.66	0.30	1.04	0	0	0	***
Crop residues	0.31	0.20	0.51	0.33	0.26	0.40	ns
Mineralization	0.30	−0.25	0.72	−0.02	−0.35	0.17	***
Indirectly							
From NH_3	0.60	0.35	1.17	0.43	0.32	0.58	***
From leaching	0.59	0.41	0.84	0.32	0.17	0.45	***
Total	5.25	3.70	8.43	3.34	2.48	4.28	***

Table 5
Annual emission of green house gasses (kg CO_2-eq.) and land use (m^2) in two dairy production systems per kg ECM.

	Conventional			Organic			P-system
	Mean	Min	Max	Mean	Min	max	
Emission, kg CO_2-eq. per kg ECM							
Internal (farm level)	1.05	0.83	1.22	1.24	0.98	1.67	***
Methane	0.62	0.53	0.73	0.69	0.61	0.85	***
Nitrous oxide	0.29	0.19	0.40	0.35	0.24	0.56	**
Fossil energy	0.14	0.10	0.19	0.20	0.10	0.44	***
External (import)	0.15	−0.03	0.34	0.03	−0.33	0.20	***
Feed	0.10	−0.13	0.30	0.01	−0.33	0.21	**
Manure	0.00	−0.02	0.04	0.02	0.00	0.07	***
Fertilizer	0.05	0.02	0.09	0.00	0.00	0.00	***
Total before allocation	1.20	0.97	1.56	1.27	1.05	1.57	*
Land use, m^2 per kg ECM							
Farm land	1.24	0.62	1.95	2.27	2.50	3.81	***
Import protein	0.18	0.03	0.32	0.07	−0.02	0.14	***
Import feed energy	0.36	−0.46	1.04	0.04	−1.15	0.72	**
Total before allocation	1.78	1.19	2.31	2.37	1.76	3.32	***

the organic production system, while the variation in emission per kg ECM only ranged from 0.90 to 1.10 kg CO_2 eq. per kg ECM across production systems.

3.4. Effect of farming strategy on GHG emissions

There was a large variation in emission per kg ECM between farms within both systems as seen in Fig. 3. The effect of farming strategy on the variation in GHG emission was investigated by a factor analysis followed by a traditional analysis of variance. The hypothesis was that the variables, except farm size and stocking rate, in Table 2, both individually and in a more complex structure were related to the GHG emission. The result of the factor analysis in Table 7 shows that six factors were retained due to an eigenvalue higher than 1.0 and all variables were retained in the model due to communality estimates higher than 0.7. The model separated the variation into factors very well as all variables were represented in one of the factors by loadings higher than 0.6, and only two of these variables, milk yield per cow and N self-sufficiency, were represented in more than one factor by loadings higher than 0.6.

The loadings and the other information presented were used in the interpretation of the factor analyses, leading to these farming strategies behind each factor (Table 7):

Factor1: Grassland-based milk production
Factor2: Feed efficiency in the herd
Factor3: Intensive farming per ha
Factor4: Meat and milk production in combination
Factor5: DMI and milk yield per cow
Factor6: N yield from crop production per ha

Grassland-based milk production (factor 1) was dominated by a high proportion of the area with grass, a low proportion with maize, and a high proportion of feed from pasture and roughage in general (high numeric loadings in Table 7). The proportion of organic farms was also positively related to this

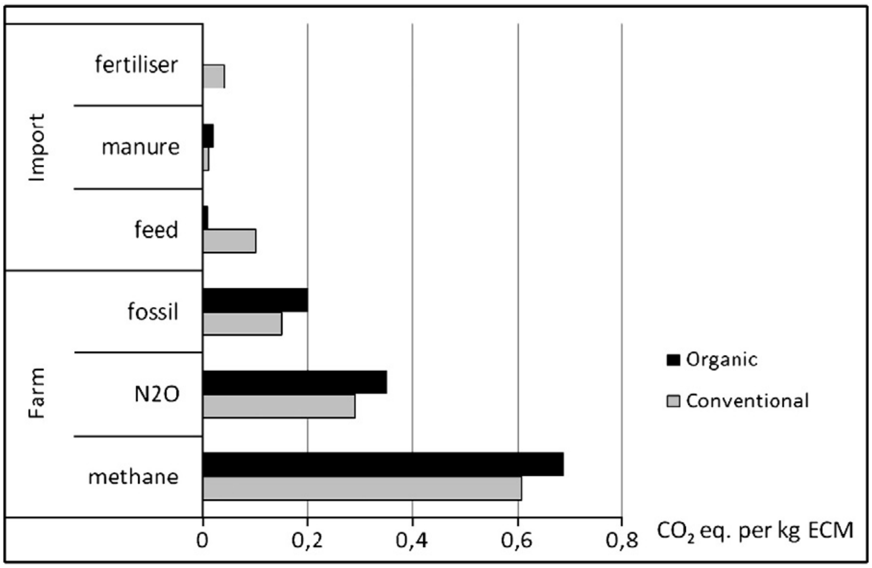

Fig. 1. Contribution of different processes to the greenhouse gas emission at farm gate within two production systems, CO2-eq. per kg ECM before allocation.

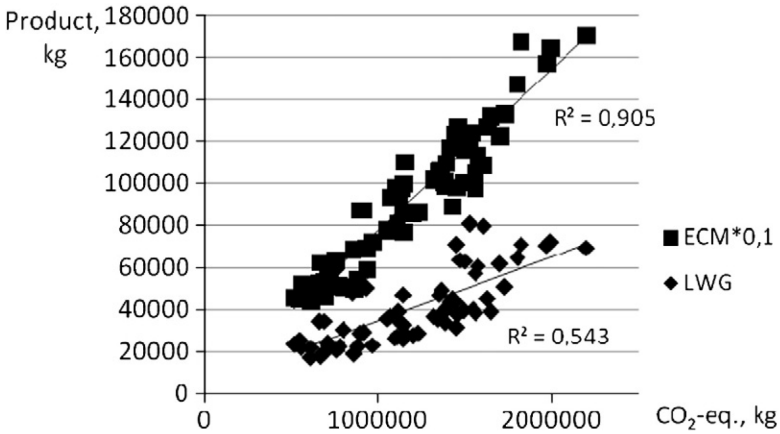

Fig. 2. Production of milk and meat in relation to greenhouse gas emission at farm gate.

strategy. Factors 2 and 5 both have high loadings for milk yield per cow, but factor 2 has a low negative loading for DMI per cow and a high loading for efficiency (ECM per cow and DMI), which was in contrast to factor 5, which had a very high loading for feed intake and low loading for efficiency. Intensive farming (factor 3) was dominated by high milk yield per ha, but a low loading for milk yield per cow, low self-sufficiency in feed (NE and N) and a high input of manure N per ha and represents therefore farming intensity per ha, while factor 5 represents intensity per cow. Factor 4 has a high loading for number of young stock per cow and for live weight gain per LSU, and factor 6 had only one variable, N production per ha, with a numerically high loading.

The effect of farming strategy on GHG emission per kg ECM at three stages – farm, total and after allocation – showed that the factors in total explained 61 to 80% of the variation in GHG emission (Table 8), lowest for emission after allocation and highest for direct emission. The factor that explained most of the variation at all three stages was factor 2, while factor 3 came second. Factor 5 was not significant in relation to the emission at farm level and in total, and factor 4 was not significant in relation to the emission in total per kg ECM.

The quantitative effect of each farming strategy on the GHG emission per kg ECM was calculated by testing the difference between the emissions from the 25% of farms placed highest within each strategy against the emission from the 25% of farms placed lowest. Top and bottom were found from the loadings for each farm within each factor. As shown in Table 8, within each strategy there was in most cases a significant impact of the strategy on GHG emissions for the two groups of farms. After allocation, the largest difference was between the top and bottom group identified by factor 2, “Herd efficiency”, with emissions being 0.13 kg CO_2-eq. per kg ECM lower in the most efficient group compared to the less efficient. This was mainly due a higher conversion of feed to milk of 1.32 vs. 1.06 kg milk per kg DMI, which reduced the CH_4 emission, and to some extent due to the higher milk yield of 8488 vs. 6964 kg ECM per cow, as illustrated in Fig. 4. For

Table 6
Effect on emission per kg products of different methods used for allocation of green house gas emission between milk and meat in two dairy productions systems.

	Conventional			Organic			P-system
	Mean	Min	Max	Mean	Min	max	
Meat CO_2-eq., % of total							
Model (A)	14	10	20	16	10	29	*
Protein mass	17	12	23	19	12	33	*
Biological [a]	24	15	35	29	16	57	*
Economic [b]	12	8	16	14	8	24	*
System expansion [c]	22	15	33	25	16	47	ns
Emission after allocation, kg CO_2-eq. per kg ECM							
Model (A)	1.03	0.86	1.35	1.06	0.92	1.33	ns
Protein mass	0.99	0.83	1.31	1.02	0.86	1.29	ns
Biological	0.91	0.75	1.22	0.90	0.59	1.19	ns
Economic	1.06	0.89	1.39	1.10	0.96	1.37	ns
System expansion	0.94	0.75	1.32	0.96	0.67	1.29	ns
Emission after allocation, kg CO_2-eq per kg meat							
Model (A)	4.17	3.50	5.48	4.29	3.71	5.39	ns
Protein mass	5.05	4.29	6.56	5.08	4.27	6.34	ns
Biological	6.92	5.60	8.99	7.33	6.04	9.04	*
Economic	3.41	2.85	4.47	3.52	3.08	4.41	ns
System expansion	6.35	6.35	6.35	6.35	6.35	6.35	ns

[a] Allocation factor milk = 1–5.771 * (kg live weight gain/kg ECM) from IDF (2010).
[b] 1 kg ECM = 0.31 EUR; 1 kg live weight gain = 0.99 EUR.
[c] 1 kg live weight gain = 6.35 kg CO_2-eq. (LCA for pork and beef meat).

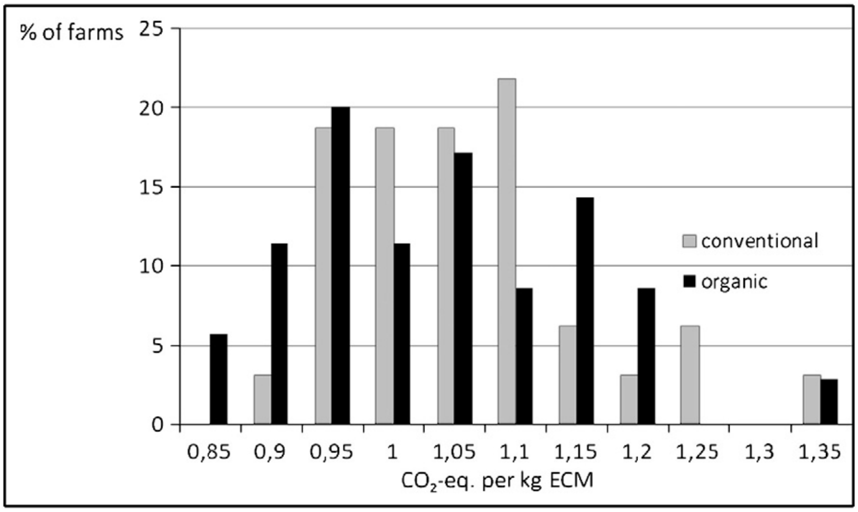

Fig. 3. Distribution between farms of GHG emission per kg ECM within production system.

factor 3, "Intensive farming", the result at farm level showed the lowest emission in the most intensive group of farms, due to the high production of milk per ha, but it changed when the emission was calculated at total level and after allocation. This was caused by a net export of crops in the least intensive group of farms compared to an import of 39% of NE intake and an increase in production to 9705 kg ECM per ha in the intensive group of farms (Fig. 5), while milk yield and DMI per cow were identical for the two groups of farms (data not shown).

4. Discussion

4.1. Conventional and organic production systems

When comparing production systems and not least farming strategies, the number of farms and the accuracy of the data are the critical elements, and for a more general conclusion the representativeness of the farms of the systems in question is also important. We used data from 67

Table 7
Rotated factor pattern after varimax rotation, communalities (h^2), sum of squared loadings (SSL) and SSL as a percentage of common variance (bold values>=60).

Variable	Factor						h^2
	F1 (×100)	F2	F3	F4	F5	F6	
Heifers + male calves, no per cow	−2	−9	−14	**93**	−8	11	91
Milk, kg ECM[a] per cow	−22	**70**	14	−6	**65**	3	98
Live weight gain herd, kg per LSU[b]	16	−1	−9	**91**	−7	1	87
Feed intake, kg DM[c] per cow	7	−12	12	−12	**96**	11	98
Roughage, % of DMI – herd	**68**	−41	−34	−9	8	19	79
Pasture, % of DMI – herd	**77**	−34	−14	14	−17	13	80
Efficiency, kg ECM per kg DMI – cow	−33	**92**	8	3	−3	−4	96
Efficiency, kg ECM per kg DMI – herd	−29	**90**	7	−12	−12	3	94
N efficiency ex animal, %	−34	**69**	20	−41	−7	−22	85
Maize, % of area	**−75**	33	15	−30	−1	3	78
Grassland in rotation, % of area	**77**	−22	−3	−7	16	45	86
Yield, NE[d] (1000) per ha	**−73**	47	4	−2	5	44	95
Yield, kg N per ha	19	−5	33	17	12	**86**	93
Fertiliser, kg N gross per ha	−42	**65**	20	8	12	4	66
Manure, kg N gross per ha	−13	16	**79**	11	22	29	81
Milk, kg ECM per ha	−55	32	**66**	−25	−7	22	95
Crop production, % of NE intake	10	−2	**−89**	36	−6	−4	94
Crop Production, % of N intake	**65**	−31	**−63**	16	−1	8	94
SSL	4.07	3.95	2.66	2.28	1.53	1.41	
SSL, % of common variance	26	25	17	14	9	9	

[a] ECM: Energy corrected milk (4.10% fat, 3.30% protein).
[b] LSU: Livestock unit (1 LSU being either 0.75 Holstein Friesian type dairy cow standard yield or 2.4 young stock Holstein Friesian type).
[c] DM: Dry matter.
[d] NE: Net energy lactation.

Table 8
Variation in green house gas emission at three levels, farm, total, and after allocation between milk and meat, explained by farming strategy and emission from top 25% of farms and bottom 25% of the farms within each strategy, kg CO_2-eq. per kg ECM.

Factor (Table 7)	F1	F2	F3	F4	F5	F6
Farming strategy	Grassland	Herd efficiency	Intensive farming	Meat and milk	Feeding level	N yield crop
Farm emission						
Variance explained, %	10	36	16	14	0	4
Significance	***	***	***	***	ns	**
Top 25% of farms within strategy	1.24	1.04	1.09	1.24	1.17	1.15
Lowest 25% of farms within strategy	1.09	1.30	1.27	1.11	1.15	1.23
Significance of difference	***	***	***	**	ns	*
Total emission						
Variance explained, %	9	36	10	4	0	5
Significance	***	***	***	*	ns	**
Top 25% of farms within strategy	1.32	1.17	1.34	1.29	1.29	1.24
Lowest 25% of farms within strategy	1.20	1.36	1.24	1.25	1.23	1.33
Significance of difference	***	***	**	ns	ns	*
Emission after allocation (model (A))						
Variance explained, %	5	27	17	4	1	7
Significance	**	***	***	*	ns	**
Top 25% of farms within strategy	1.10	1.00	1.14	1.03	1.09	1.05
Lowest 25% of farms within strategy	1.03	1.13	1.04	1.10	1.04	1.12
Significance of difference	*	***	***	*	*	*

commercial farms, representing only two production systems, which is a large number of farms in comparison with earlier studies of production systems (Cederberg & Flysjö, 2004; Thomassen et al., 2008a; van der Werf et al., 2009), and the number of observations is also large in relation to the identification of different farming strategies.

The data from year 2001 to 2003 were from farms focusing on reducing N leaching by lowering N fertilization and improving herd efficiency. Therefore the farms were not representative of Danish dairy farms from that period, and compared to current farming practice in Denmark both within organic and conventional farming, the farms in this paper had a 5% lower milk yield per cow, 10% lower stocking rate and – for the conventional farms – less maize in the feed, but the same level of N fertilization per ha as the modern farm has (Anonymous, 2009b; Anonymous, 2010). In general, the Danish dairy farms are intensive in a global perspective and also compared to organic and most of the conventional farming systems in the EU (Anonymous, 2009b).

The accuracies of the data are often queried when using information from commercial farms (Kristensen, 2004; Oenema et al., 2003). We have used a top–down approach, where the production as far as possible was quantified for a one-year period at farm scale, based on farm-gate turnover. If necessary, we used data from the underlying system elements, like herd DMI, and at crop level annual net production, but not information about the individual animal or field. One of the strengths in this approach is that information from the farm, herd and crop level was checked against each other. As an example, the production of roughage and import of feed has to be equal to the total intake in the herd, and the applied amount of manure N has to be identical to the amount calculated from herd intake and production minus the emission of ammonia

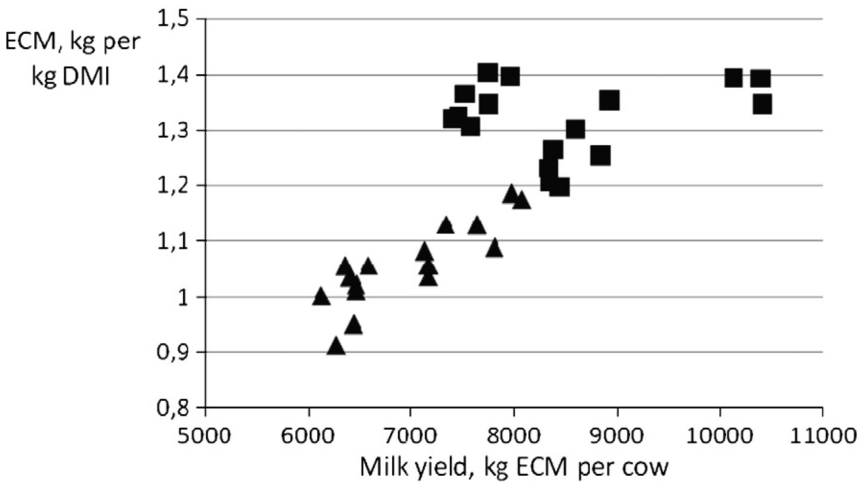

Fig. 4. Effect of factor "Herd efficiency" on annual milk yield per cow and kg milk produced per kg DMI. "■" high efficiency "▲" low efficiency.

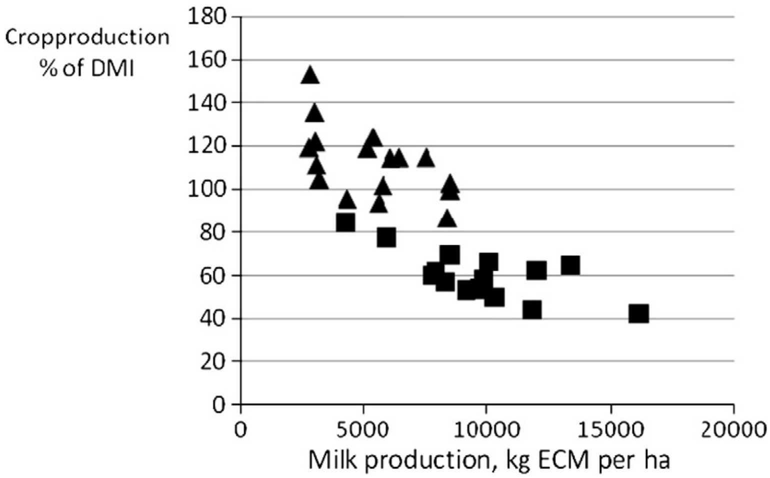

Fig. 5. Effect of factor "Farming intensity" on annual milk production per ha and crop production in percent of herd DMI. "■" high intensity "▲" low intensity.

from housing and during storage. The disadvantages are that time-related aspects are not incorporated, like the effect of storage time and temperature on CH_4 emission, and also the effect of more specific daily management routines, like the timing of manure application, which might affect N_2O emission. The inclusion of this kind of information is possible, but would be time-consuming and decrease the accuracy of the data. These partial effects might be better estimated in whole-farm models rather than based on farm data (Del Prado et al., 2010; Schils et al., 2007).

4.2. Farm GHG calculation method and results from other studies

Which model is used to estimate the GHG emission, including methods of quantification of production, EF and FU, is important when comparing with the results of other studies (De Vries and De Boer, 2010; Van der Werf et al., 2009), as this may significantly affect the level of emission estimated (Rotz et al., 2010; Schils et al., 2005; Thomassen et al., 2008b). With this in mind, our results for kg CO_2-eq. per kg milk are comparable to the level found by Castanheira et al. (2010), Cederberg & Flysjö (2004) and van der Werf et al. (2009), but lower than in Dutch production systems (Thomassen et al., 2008a) and higher than the level in the best scenarios of alternative low GHG production systems estimated by Basset-Mens et al. (2009) and Ogino et al. (2008). In a model study, Rotz et al. (2010) found much lower GHG emissions of 0.60 kg CO_2-eq. per kg milk (3.5% fat and 3.1% protein) in US-based systems. If this result is corrected for the lower content of fat and protein in the milk and a negative CO_2 balance due to higher roughage production than feed intake, the results will be 0.95 kg CO2-eq. per kg ECM in line with our results.

Methane contributed, irrespective of production system, a significant share to total GHG emissions, with more than two thirds of the CH_4 originating from the enteric fermentation in the cows, which is characteristic for more intensive dairy systems (FAO, 2010). Estimation of CH_4 emission was in the present study based on gross energy intake. The use of more detailed models would increase the variation between the herds and might also change the average level of emission (Kristensen, 2009), although DMI and milk production are the main drivers of enteric methane emission as well as energy utilization efficiency (Yan et al., 2010). From experimental data, factors like fat content (Giger-Reverdin et al., 2003), the proportion of roughage dry matter (Mills et al., 2003) and digestibility of the ration (Yan et al., 2000) have been shown to affect the daily CH_4 emission and often also the emission per kg product. Besides an increasing production level, legume-based forage rather than grass, and starch-based concentrates rather than fibre have been found to reduce methane emission by up to 32% (Benchaar et al., 2001). System or management-based effects, like improved feed conversion efficiency, reduced number of young stock or extended lactation (Eckard et al., 2010) are included in our method.

N_2O contributed 22 to 27% to total emissions per kg ECM in the two systems, with the highest contribution from the organic system, but on an area basis the emission in the organic system was only 63% of that in the conventional system. The emission factor in our approach was defined by the system or stage of the emission in the N cycle, with the largest contribution (53 to 69% in the two systems) from manure handling in the period from animal house to application. It is important to stress that the estimate for both the potential N emission as N_2O and the EF is uncertain (IPCC, 2006; Smith et al., 2007). In contrast to CH_4, the emission of N_2O is associated with several pollutants, which means that the total emission is more accurate than the emission from the specific pollutant in the N cycle. The amount of N as N_2O is only around 1.5% of the sum of total gross N in manure ex animal and N imported as fertilizer, and the effect of different management mitigation options during the N cycle will therefore barely be detectable at farm scale. This is supported by the fact that it takes years before the effect of mitigation options like changes in crop rotations or the use of cover crops manifests itself in the production level. The sum of different mitigation options could reduce the N_2O emission by 10 to 20% (Mosier, et al., 1998; Smith et al., 2007). Improved nutrient management generally has an effect, while the effects of most other options like reduced tillage and vegetative cover are inconsistent and not well quantified (Smith et al., 2007). These effects are often related to site-specific conditions (Stewart et al., 2009) and with possible risk of pollution swapping with other forms of N loss from the farm (Del Prado, et al., 2010) and in some cases also with CH_4 emission (Monteny et al., 2006).

4.3. Allocation between milk and live weight gain

Allocation of total GHG emission between milk and live weight gain based on the produced amount of milk and live weight gain on the 67 farms resulted in a lower allocation to meat than estimated by the traditional methods, but not by the economic allocation method. Our method is based directly on the functional units kg ECM and kg meat and therefore follow the overall recommendations for allocation by Cederberg and Stadig (2003) that “allocation should reflect the physical relationship between the environmental burdens and the functions delivered by the system”. Cederberg and Stadig (2003) and FAO (2010) found the same trend for the proportion of GHG allocated to meat depending on allocation method increasing from the method based on mass of milk and meat in kg, to economic value, protein mass of milk and meat over biological allocation and to a large increase using system expansion.

The high proportion allocated to meat by the biological method developed by IDF (2010) of 24 to 29% for the two production systems compared to our method is surprising as the method by IDF (2010) was developed on empirical data representing large variations in the proportion of meat and type of animals and therefore comparable to our method, while others (Basset-Mens et al., 2009; Cederberg and Mattsson, 2000) allocated 15% to meat based on the standard feed requirements to produce milk and meat. On average, the live weight gain at herd level was 335 kg per cow, of which 40 kg came from the cows and the remaining 88% from young stock. Compared to the milk yield the live weight gain was 0.04 kg per kg ECM, which is high compared to the data used by IDF (2010).

Our investigation indicates that the use of economic value to allocate the total GHG is within the range estimated from an empirical model. The problem with economic allocation is that it will depend on place and time. In systems such as those in this paper with only two products, a more direct use of either protein mass or biological methods based on causal relations seems more appropriate. From a product point of view, protein mass represents the demand by consumers for protein (De Vries and De Boer, 2010), while the biological method based on the causal relation between input/output represents the efficiency in energy utilization. Although from a theoretical point of view therefore it seems ideal to use the biological method, there are problems with calculating the feed demand in a system where very different types of farm animals form the basis for the same product (meat, for instance) as the difference between our model and the method by IDF (2010) illustrates. Based on the available information it is not possible to detect the reason for this difference, but an increased contribution of the live weight at herd level from cows combined with a high milk yield per cow will tend to decrease the allocation of NE to meat as the maintenance per kg product decreases.

4.4. Mitigation options at farm level

The non-experimental type of data and the descriptive nature of the statistical method used means that we have identified only structures in the data and not causal relations, but the high degree of explanation (61–80%) of the variation in emissions by the identified strategies illustrates that a whole-farm approach is able to detect the difference between farms. The strength in using non-experimental data from a large number of observations is that it enables the identification of clusters or groups of observations that are significantly different from the rest of the observations, and by identifying the parameters by which they differ it is possible to give general recommendations that have an impact at farm scale (Enevoldsen et al., 1996).

Farming strategies with focus on high efficiency in the herd or on reduced stocking rate and thereby a low import of feed were identified as two of the most promising candidates for reducing GHG emissions. The dominant effect of efficiency in the herd is due to the fact that methane emission accounts for more than half of the total emission at farm level and strategies leading to a low methane emission will therefore also reduce the total emission per kg milk in accordance with Lovett et al. (2008) and the sensitivity analysis by Rotz et al (2010).

The negative relation between farming intensity defined as milk production or LSU per ha and GHG emission was also identified by Basset-Mens et al. (2009). The emission from imported feed in the intensive group of farms was 0.21 kg CO_2-eq. per kg ECM, while there was a net export of 0.07 kg CO_2-eq. per kg milk in the extensive group. The emissions associated with the imported feed compared to the emissions from the farm-produced feed are therefore important for the effect of farming intensity. If the direct farm emissions, except from CH_4, and indirect emissions from import of fertilizer were related to the farm crop production, the emission as an average of the farms was around 0.06 kg CO_2-eq. per MJ NE or 0.45 per kg barley. The imported feed has therefore a higher emission than the home-produced, which is one of the factors behind the effect of farming intensity on GHG emission per kg ECM.

5. Conclusions

We conclude that there are large variations in GHG emissions per kg products between commercial farms within two well-defined production systems, while the difference between the average GHG emissions per kg milk from organic and conventional production was negligible. Across production systems farming strategies based on either low stocking rate or with focus on high efficiency in the herd were identified as the most promising for reducing GHG emissions per kg milk at farm gate after allocation between meat and milk. We further conclude that the model can estimate relevant variations in GHG emissions between commercial farms without intensive data registration.

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