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Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy

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ABSTRACT

The environmental impact of 12 dairy farms in Denmark, Germany and Italy was evaluated using an LCA approach and the most important parameters influencing their environmental sustainability were identified. The farms represent different production methods (organic vs. conventional), summer feeding systems (confinement vs. pasture) and annual production levels (6275–10,964 kg ECM cow^{-1}). There was large variability in stocking rates (1.1–11.0 LU ha^{-1}) among farms, which has a major impact on the production per unit area of farmland, on feed self-sufficiency and on farm surplus of nitrogen. The proportion of grassland on farmland used for forage production or pasture varied from 0 to 100%. The lowest global warming potential (GWP), acidification, eutrophication and non-renewable energy use were achieved by the German pasture-based system, followed by the Danish organic dairy system and the very intensive Italian farming system with very similar environmental impact values. However, a sensitivity analysis showed that when emissions relating to direct land use change of soybean production were included in the assessment, the GWP changed considerably for the conventional farms due to the inclusion of conventional soymeal in the feed concentrate. There were strong and positive correlations between the four impact categories, and overall the results indicate that improving greenhouse gas emissions would improve the general environmental sustainability of the dairy farm. The land occupation was lowest in the farms with the highest stocking rate. The organic Danish farms had the lowest impact on biodiversity loss, which in general was positively influenced by the share of grassland in the system. A high proportion of grassland also had a significant positive effect on GWP, acidification and energy use. The other feature that mainly improved the environmental impact was the feed efficiency of the dairy cows, which was negatively correlated with GWP, acidification and eutrophication. We found no relation between the environmental impact and the milk production per cow or the stocking rate at the farm. However, due to the limited number of observations (only 12 farms were assessed), the results of the correlation analyses should be handled with care. There was also large variation in the relative contributions from on- and off-farm activities among farms and for the different impact categories, showing the importance of a holistic approach and the difficulties in evaluating a farming system both in a product and area-based perspective.

1. Introduction

Production of milk is an example of an agricultural activity that causes adverse environmental side effects, such as emission of greenhouse gases and nutrient enrichment in surface water (Thomassen et al., 2008). In the future, dairy producers will have to meet tighter environmental regulations including limits on greenhouse gas (GHG) emissions and noxious gaseous emissions such as ammonia (NH_3), and stricter nutrient management regulations to control diffuse pollution from nitrate (NO_3) leaching and phosphate (PO_4^{3-}) run-off (O'Brien et al., 2012). Milk production systems vary across Europe, ranging from lowland to highland-based and from extensive to intensive. Increased intensification has exacerbated environmental impacts and the planned removal of the European Union (EU) milk quota system in 2015 (Yan et al., 2011) is expected to result in an increase in milk output and

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decline in milk price, which presumably will lead to an acceleration of the processes of intensification and specialization (O'Brien et al., 2012). In situations where land availability is a major impediment, producers may decide to adopt alternative production strategies such as confinement systems using a Total Mixed Ration (TMR). In order to be able to devise the best strategy to cope with the new demands, the most efficient and environmentally friendly dairy systems and the parameters affecting these need to be identified. In the last ten years the Life Cycle Assessment (LCA) method has been used in several studies to assess the environmental impact of different milk production systems across Europe, especially for the comparison of organic and conventional systems (Cederberg and Mattsson, 2000; de Boer, 2003; Thomassen et al., 2008) or simply to evaluate the environmental performance of milk production on a typical dairy farm (Castanheira et al., 2010; Müller-Lindenlauf et al., 2010; O'Brian et al., 2012). Not least when discussing the effect of intensification and change in land use is it important to use methods that go beyond the dairy farm and include the off-farm activities, as illustrated by Kristensen et al. (2011). In a strategic perspective it is important to estimate the environmental impact for several categories and also to address the correlation between these categories and the different management choices of the dairy production systems. Therefore the aim of the present paper was to evaluate the environmental impact of different dairy farming systems across Europe and identify the parameters that most strongly affect the environmental performances for six impact categories of strategic importance for the dairy farmer.

2. Materials and methods

2.1. Life cycle assessment

Life Cycle Assessment (LCA) is a compilation and appraisal of the inputs, outputs and environmental impacts of a production system throughout its life cycle (Guinee et al., 2002). According to ISO standards (ISO, 2006a,b), an LCA consists of four distinct phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation.

2.1.1. Goal and scope definition

The goal of this study was to assess the environmental impact of milk production of different farming systems and to identify the weaknesses and the strengths of the different farming choices and strategies with the purpose of mitigating the environmental pressure.

The analysis included the life cycle required for the production of raw milk from the production stage of inputs to the products leaving the farm gate, i.e. excluding transport or processing of raw milk. For each dairy farm, a "cradle-to-farm-gate" LCA was performed. All the processes related to the on-farm activity (i.e. forages and crop production, energy use, fuel and electricity use, manure and livestock management) and related emissions were taken into account. Emissions and energy consumption from off-farm activities like production of fertilizer and pesticides, fodders and bedding materials, feed concentrate, electricity and fuel, and breeding of replacement animals were included in the estimation. Transport associated with the production of purchased feed (both commercial feed and roughages) and bedding material was included.

The functional unit used was kg energy corrected milk (ECM) (Sjaunja et al., 1990): kg ECM = kg milk*(0.25 + 0.122 * Fat% + 0.077 * Protein%) delivered to the dairy at the farm gate.

For the dairy farm the main focus is on milk production, while the meat generated from surplus calves and culled dairy cows is an important co-product (IDF, 2010). When analysing multifunctional processes the choice of allocation method is a required step in order to partition the environmental impact into the co-products generated by the system. A biological allocation, based on the feed energy required to produce the amount of milk and meat at the farm and developed by IDF (2010) was used.

2.1.2. Inventory analysis

The inventory comprised annual data from 12 dairy farms: five from Denmark (DK), two from Germany (GER) and five from Italy (IT). The farms were chosen as being representative for different milk yields and stocking rates, expressed in livestock units (LU) per unit area of farmland. Two of the five Danish (DK-1 and DK-2) farms were organic. The two German farms differed in their summer feeding systems (confinement vs. pasture), while all Italian farms used confinement feeding. The data for the Danish farms were based on intensive registration, while the data used for the GER and IT systems were collected from interviews with the farmers.

Total on-farm estimated emissions included fuel combustion, enteric fermentation from the cows, manure management (storage and handling including field application) and emissions that occur during the application of chemical fertilizers and urine/faecal deposition during grazing. The methods applied and the emission factors used are shown in Table 1.

Carbon dioxide (CO_2) emissions related to energy consumption (combustion of fossil fuels and electricity use) were estimated on the basis of the amount of diesel (litres) and electricity (kWh) used for farm operations. Emissions from livestock respiration are part of a rapidly cycling biological system, where the plant matter consumed is itself created through the conversion of atmospheric CO_2 into organic compounds. Since the emitted and the absorbed quantities are considered to be equivalent, livestock respiration is not considered a net source under the Kyoto Protocol (Steinfeld et al., 2006). Methane (CH_4) emissions from enteric fermentation were calculated according to the Tier 2 IPCC (2006a) method that is based on the dry matter intake (DMI) of the herd. CH_4 emissions from stored manure were calculated on the basis of IPCC guidelines following the Tier 2 method (IPCC, 2006a). The amount of manure handled within a system is based on the daily number of LU housed in each system and on pasture. Methane is also released from manure deposited by animals on pasture and this was estimated using the IPCC (2006a) method. Calculations for direct nitrous oxide (N_2O) emissions from manure storage were based on excretion of nitrogen (N) given as the difference between total N intake (calculated as the dietary dry matter intake and the N content of the diet) and the N output in products (meat, milk). The emission factors used are those proposed by IPCC (2006a) for solid manure and liquid slurry storage systems. Indirect emissions of N_2O from manure storages, which are mainly due to volatilisation of ammonia (NH_3), were estimated using the EF value according to IPCC (2006a).

Direct and indirect N_2O emissions occur also at field level after the application of fertilizer in organic and inorganic forms. Direct N_2O emissions were estimated from the inputs of nitrogen in the form of mineral and organic fertilizers, crop residues and N mineralization as suggested by the IPCC (2006b) Tier 1 method. The IPCC methodology was also used to compute the direct N_2O emissions that occur during the grazing period and likewise were the indirect N_2O emissions.

Nitrogen emissions from manure storage were estimated by multiplying the amount of nitrogen excreted by the emission factors proposed by IPCC (2006a), and in accordance with Castanheira et al. (2010) they took entirely the form of NH_3 volatilization. The volatilization of nitrogen in the forms of NH_3 and NO_x that occur during the application of organic and mineral fertilizers was estimated using the default emission factors indicated by Tier 1 in the EEA (2009) guidebook. The two main N inputs to agricultural land

Table 1
Equations and emission factors for the estimation of emissions at dairy farm level.

Pollutant	Source	Amount	Emission factor	Reference
kg CH_4	Enteric	CH_4 = kg DMI herd^{-1} * 18.45 (Gross Energy MJ kg^{-1} DMI) * Ym%/55.65	Ym (6.5% ± 1.0%)	IPCC (2006a)
	Storage	CH_4 = VS *B_0 * 0.67 * MCF/100 * MS	MCF solid storage: 4 MCF liquid slurry: 17 MCF pit storage: 27	IPCC (2006a)
	Pasture	CH_4 = VS *B_0 * 0.67 * MCF/100 * MS	MCF pasture: 1.5	IPCC (2006b)
kg N_2O direct	Storage	N_2O = Nex (conf. syst.) * MS * EF * 44/28	EF solid storage: 0.005 (0.0027–0.01) EF liquid slurry: 0.005 EF pit storage: 0.002	IPCC (2006a)
	Field	N_2O = (Nsn + Non + Ncr + Nsom) * EF * 44/28	EF: 0.01 (0.003–0.03)	IPCC (2006b)
	Pasture	N_2O = Nex (pasture) * MS * EF * 44/28	EF pasture: 0.02 (0.007–0.06)	
kg N_2O indirect	Storage	$N_2O_{(G)}$ = Nvolatilization * EF * 44/28	EF: 0.01 (0.002–0.05)	IPCC (2006a)
	Field/pasture	$N_2O_{(ATDN)}$ = [(Nsn * Frac_GasF) + ((Non + Nprp) * Frac_GasM)]*EF * 44/28	EF: 0.01 (0.002–0.05)	IPCC (2006b)
		$N_2O_{(L)}$ = (Nsn + Non + Ncr + Nsom + Nprp) * Frac_Leach * EF * 44/28	EF: 0.0075 (0.0005–0.025)	
kg NH_3	Storage	Nvolatilization: Nex (conf. syst.) * MS * Frac_GasMS/100 *17/14	Frac_GasMS solid storage: 40 (10–40) Frac_GasMS liquid slurry: 40 (15–45) Frac_GasMS pit storage: 28 (10–40)	IPCC (2006a)
	Field/pasture	NH_3 = (Nsn + Non + Nprp) * EF	EF: 0.084 (0.06–0.1)	EEA (2009)
kg NO_x	Field/pasture	NO_x = (Nsn + Non + Nprp) * EF	EF: 0.026 (0.005–0.104)	EEA (2009)
kg NO_3	Field/pasture	NO_3 = (Nsn + Non + Ncr + Nsom + Nprp) * Frac_Leach * 62/14	Frac_Leach: 0.3 (0.1–0.8)	IPCC (2006b)
kg $PO_4{}^{3-}$	Field/pasture	$P_{gw} = P_{gwl} * F_{gw}$	P_{gwl} arable land: 0.07 P_{gwl} permanent pasture and meadow: 0.06	Nemecek et al. (2007)
		$P_{ro} = P_{rol} * F_{ro}$	P_{rol} arable land: 0.175 P_{rol} intensive permanent pasture and meadow: 0.25 P_{rol} extensive permanent pasture and meadow: 0.15	
kg CO_2	Soil change	CO_2 = ha * kg $CO_{2\ soilchange}$ ha^{-1}	kg $CO_{2solichange}$ ha^{-1} grassland rotation: +1900 kg $CO_{2\ soilchange}$ ha^{-1} grassland permanent: 0 kg $CO_{2solichange}$ ha^{-1} maize and other arable crops: −3000	Kristensen et al. (2011)
kg CO_2-eq.	Diesel use	CO_2-eq. = l diesel * EF	EF: 3.31	Nielsen et al. (2003)
	Electricity use	CO_2-eq. = kWh * EF	EF: 0.654	

are mineral fertilizers and manure (EEA, 2000). It was assumed that 30% of the N from fertilizer and manure ex storage is lost through leaching in the form of nitrate (NO_3) as proposed by IPCC (2006b).

Phosphorus loss was in the form of phosphate (PO_4^{3-}) and was estimated by the methodology proposed by Nemecek and Kägi (2007) for run-off and leaching. This method calculates the amount of phosphorus excreted by the animals and applied to the field and also the input from chemical fertilizers.

The variation in annual soil carbon stock of farmland was estimated from the annual net soil change for different crop types, as illustrated by Kristensen et al. (2011).

The off-farm emissions are mainly those deriving from the production of feed concentrate – from the cultivation of crops to the arrival of the final commercial product to the farm – including processing of raw materials and transport. The estimation of off-farm emissions also included the production of roughages and bedding material purchased including transportation, the production of chemical fertilizers and pesticides (herbicides and insecticides) but not the related transportation, and the production of diesel and electricity. Only soymeal (conventional and organic) and barley grain (conventional and organic) were included as feed concentrates due to the lack of data on commercial feed composition. Data on crop production were taken from Jungbluth et al. (2007) and Nemecek and Kägi (2007). The amounts of soymeal and barley grain purchased were estimated on the basis of the total N and total DM imported to the farm in commercial feed (excluding roughages). Emissions related to fertilizer production were estimated using values proposed by Williams et al. (2006). Data for pesticide production were taken from Nemecek and Kägi (2007).

Estimation of biodiversity loss was carried out using the method proposed by De Schryver et al. (2010) and also used by Tuomisto et al. (2012). This method uses characterisation factors (CF), the ecosystem damage for different land uses and agricultural practices. The impact on biodiversity is expressed as Damage Score (DS), which describes the relative change in species richness within the occupied area compared with the baseline. The CF and other data used to assess the biodiversity in this work are shown in Table 2.

As proposed by Tuomisto et al. (2012), first the local Damage Score was estimated for 1 m^2 of the farm's land and in order to relate this to 1 kg of ECM the DS was multiplied by the value of on-farmland use (m^2 kg^{-1} ECM) carried out in the LCA analysis. The DS linked to the cultivation of off-farm crops was estimated for 1 m^2, differentiating between conventional or organic arable land (soybean and barley) used for concentrate production, or grassland used for roughage production and then related to 1 kg of ECM on the basis of off-farmland use (m^2 kg^{-1} ECM). The global value of DS kg^{-1} ECM is the sum of on- and off-farm DS values: DS kg^{-1} ECM = (DS m^{-2} on-farm) * (m^2 land use on-farm kg^{-1} ECM)+(DS m^{-2} off-farm)*(m^2 land use off-farm kg^{-1} ECM).

2.1.3. Live cycle impact assessment

For this study the selected impact categories and the related units were:

- Global Warming Potential (GWP) for a time horizon of 100 years: kg CO_2-eq.
- Eutrophication: g $PO_4{}^{3-}$-eq.
- Acidification: g SO_3-eq.
- Non-renewable energy use: MJ-eq.
- Land occupation: m^2
- Biodiversity: Damage Score (DS)

Table 2
Characterization factors (CF) related to type of crop and country of production used for the estimation of biodiversity damage score (DS) for the dairy farming systems.

CROP[c]	Denmark			Germany			Italy	
	CF-conv.	CF-org.	mo.	CF-conv.	CF-less.int.	mo.	CF-conv.	mo.
Maize silage I[a]	0.79	0.36	12	0.79	0.44	12	0.79	12
Maize silage II[b]							0.79	5
Whole-crop silage	0.79	0.36	5					
Cereal grains-other grains	0.79	0.36	5				0.79	12
Ryegrass/green crops	0.79	0.36	7				0.79	7
Lucerne							0.65	12
Meadow (permanent grassland)	0.65	−0.01	12	0.65	0.36	12	0.65	12
Grassland in rotation	0.65	−0.01	15	0.65	0.36	12		
Beans	0.79	0.36	12					
Sugar beet	0.79	0.36	12					

CF: Characterization factor individualistic perspective for each land use.
Intensive arable land: 0.79.
Intensive fertile grassland: 0.65.
Less intensive arable land: 0.44.
Less intensive fertile grassland: 0.36.
Organic arable land: 0.36.
Organic fertile grassland: −0.01.
mo: time of occupation by land use type.
[a] sown in spring (April) and harvested in summer (August).
[b] sown in late spring (May) and harvested in late summer (September). This crop follows the harvest of ryegrass that occupies the land during the winter season.
[c] for off-farm crops are considered intensive arable land and organic arable land (barley and soy) and intensive grassland (grass and lucerne hey).

The life cycle assessment was carried out with the assistance of a commercial LCA software package, SimaPro 7.3.3 PhD (Pré Consultants, 2012). The EPD 1.03 (2008) module of this package was used particularly in the evaluation of GWP, eutrophication, acidification and non-renewable energy use, updated with IPCC (2007) GWP conversion factors (100 yr time horizon), and the value of CO_2 emission from land transformation was set to 0. Although emissions due to land use change can be substantial, their quantification and allocation is conceptually and methodologically difficult (Lesschen et al., 2011) and for that reason they were not taken into account in the assessment of the environmental impact of the different farming systems. However, it is well recognized that accounting for direct land use change in soybean production can strongly affect the final result of an LCA study, and for that reason a very simplified sensitivity analysis was performed incorporating the values of direct land use change for soybean production as proposed by Flysjö et al. (2012). Land occupation was evaluated, differentiating into on- and off-farm area used in crop production for animal feeding.

In order to quantify the environmental impact as a single value, an analysis with the Stepwise2006 1.03 method was performed (Weidema et al., 2008). This method combines the values of all the different impact categories into a single score expressed in monetary units (EUR2003) (Weidema, 2009). A correlation analysis (Pearson correlation, SAS, 2009) was performed, taking all the impact categories into account and some farms characteristics considered relevant for the environmental performances of the dairy systems.

3. Results and discussion

3.1. Farm descriptions

The main characteristics of the studied farms are listed in Table 3, divided into herd, land and farm-related results.

3.1.1. Herd

The size of the herd in number of cows varied considerably, from 35 to 36 (IT-2 and GER-1 respectively) to 350 (IT-4). The production levels in kg ECM per year as an average of all cows in the herd varied from around 6300 kg ECM cow^{-1} at farms DK-1, GER-2 and IT-2 to more than 10,200 kg ECM cow^{-1} at farms DK-4, GER-1, IT-1 and IT-4, compared to the 6300 kg average of EU 15, and an average production in IT, GER and DK of, respectively, 5800, 7000 and 8300 kg milk cow^{-1} in 2011 (Eurostat, 2012). Feed intake as an average of all livestock units (cows, heifers and calves) at the farm also varied widely in their respective contents of concentrates and use of pasture. The efficiency of converting dry matter intake (DMI) to milk, which traditionally is both economically and environmentally important, ranged from 0.82 (IT-2) to more than 1.3 kg ECM kg^{-1} DMI at DK-4, GER-1, GER-2 and IT-4. For ruminants the N efficiency was typically low and in the range 18.2–25.6%.

3.1.2. Land

The Danish farms had more land compared to the German and the Italian farms, especially the organic farms DK-1 and DK-2. Land use differed both between countries and between farms within a country. At the two organic DK farms, as little as, 2.3% and 0% of the land was used to produce maize silage. Neither did GER-2 grow maize for silage, but the three farms instead had the largest share of grassland (in rotation and permanent). Of the Italian farms, IT-1 had most grassland (all permanent). The Danish conventional farms and GER-1 had more land growing maize for silage, and the Italian farms had the most, ranging from 36.2% (IT-1) to 100% (IT-4) when also the maize of the second harvest (sown in May following ryegrass) was included. The local climate and crop choice partly explains the variation in production, from a low of around 5200 kg DM ha^{-1} to more than three times this figure at some of the Italian farms.

3.1.3. Farm

The stocking rate ranged from 1.1 for the Danish organic farms (DK-1 and DK-2) and the German pasture-based farm (GER-2) to 9.8 and 11.0 LU ha^{-1} for the very intensive Italian farms (IT-4 and IT-5). The milk production intensity, expressed as kg ECM ha^{-1}, was highly variable with a figure of less than 5000 kg milk (DK-1) to more than 10 times this for the two farms with the highest stocking rate (IT-4 and IT-5). The total amount of nitrogen applied to the soil (organic + chemical) was lowest in DK-1 and GER-2. For GER-1 the amount was much higher than for DK-5, despite these farms having the same number of LU ha^{-1}, due to a larger application of fertilizer at GER-1 and an export of manure from DK-5. For the Italian farms

Table 3
Characteristics of the studied dairy farms in Denmark (DK), Germany (GER) and Italy (IT).

		DK-1[c]	DK-2[c]	DK-3	DK-4	DK-5	GER-1	GER-2[d]	IT-1	IT-2	IT-3	IT-4	IT-5
Herd													
Cows	No.	168	122	116	127	123	92	36	77	35	98	350	170
Production level	kg ECM cow^{-1}	6275	7718	8527	10,427	7976	10,964	6277	10,222	6330	9391	10,481	7891
Feed concentrate	% of DMI herd	27	27	45	40	62	37	3	44	13	45	42	25
Pasture	% of DMI herd	22	25	6	7	0	0	71	0	0	0	0	0
Feed efficiency	kg ECM kg^{-1} DMI cow	0.91	1.18	1.22	1.34	1.19	1.40	1.34	1.31	0.82	1.16	1.40	1.19
N efficiency ex animal	%	18.2	19.7	20.3	22.6	21.9	23.7	18.7	23.3	16.3	21.7	25.6	23.7
Land													
Area	ha	225.5	162.5	135.7	142.5	74.4	64.0	43.0	58.0	21.4	30.0	60.0	23.0
Maize	% area	2	0	16	32	33	51	0	36	38	53	25	26
Ryegrass + Maize II[a]	% area	0	0	0	0	0	0	0	0	0	23	75	26
Total grassland[b]	% area	58	62	26	50	1	49	100	64	42	24	0	48
Land productivity	kg DM ha^{-1}	6374	5178	6065	7169	6831	8563	5261	8847	13,286	19,478	29,071	16,387
Farm													
Stocking rate	LU ha^{-1}	1.1	1.1	1.2	1.2	2.1	2.1	1.1	2.2	2.5	5.6	9.8	11.0
Milk production intensity	kg ECM ha^{-1}	4661	5523	6722	8695	11,863	15,692	5255	12,690	10,343	30,686	61,141	58,325
N fertilizer (organic + chemical)	kg N ha^{-1}	134	141	264	274	290	435	134	340	501	798	1291	1138
N surplus	kg N ha^{-1}	86	89	194	217	224	324	125	177	197	792	1001	498
Feed self-sufficiency (based on DM)	%	92.9	82.9	84.6	85.3	50.5	63.1	96.7	65.1	76.0	54.3	47.5	27.7

[a] sown in late spring (May) and harvested in late summer (September). This crop follows the harvest of ryegrass that occupies the land during the winter season.
[b] sum of grassland in rotation, permanent grassland and lucerne.
[c] organic.
[d] low input.

the values ranged from 340 kg N ha^{-1} (IT-1) to 1237 and 1123 kg N ha^{-1} (IT-4 and IT-5). The feed self-sufficiency (expressed as herd DMI) is related to the number of LU ha^{-1}. Generally, farms with a low value for LU ha^{-1} are more self-sufficient in feed because they do not need to buy in large amounts of concentrate or forage, and in our study farms DK-1, DK-2, DK-3, DK-4 and GER-2 had the highest self-sufficiency values and IT-4 and IT-5 the lowest.

3.2. *Environmental impact*

Table 4 presents the results of the life cycle assessment for the 12 farms. The data show the total environmental impact per kg milk for each category and the contribution from on-farm activities, while Fig. 1 gives an overall picture of the variability of the results obtained from the environmental assessment of each farm based on a scale from 0 to1 for each impact category where 0 is the lowest impact.

The allocation on milk ranged from 76.2% for DK-2—90.2% for IT-5 and 91.6% for GER-1, showing that the latter two farms had the more specialized milk production.

The GWP related to the production of 1 kg of ECM varied from 0.55 (GER-2) to 1.91 kg CO_2-eq. (IT-2). This agrees with the findings of O'Brien et al. (2012) of a lower environmental impact for a seasonal pastured-based dairy farm than for confinement dairy farms. The lowest-impact Danish farm was the organic DK-2, while in the Italian group the very intensive IT-5 had the lowest greenhouse gas emission per kg ECM.

Fig. 2 shows the contribution (absolute values) of the different parts of the production chain to the GWP.

Enteric emission of methane was the largest contributor to GWP, followed by emissions from manure storage. The combined contribution of enteric and storage contribution to GWP (mainly in the form of CH_4) ranged from 44.1% (DK-3) to 65.9% (IT-5). For GER-2 the contribution of storage emission was lower than at the other farms because the cows here spend around 260 days on pasture. However, the contribution from enteric emissions alone was very high (83.5%). On-farm crop production had a strong impact on GWP, and values ranged from 10.5% (IT-5) to 28.0% (DK-3) and 21.9% (IT-2). These values are strongly related to the emissions from fertilizer use (especially N_2O) and also to variations in soil carbon stocks. The negative value for GER-2 (−12.4%) is due to CO_2 storage in soil exceeding the emissions from crop production, due to the high proportion of grassland on this farm.

The other main contributor to greenhouse gas emissions is the production of commercial feed, with contributions for DK-5, IT-1,

Table 4
Environmental impact of 12 dairy farms expressed per kg of energy corrected milk (ECM) with the on-farm contributions (%).

Impact categories		DK-1	DK-2	DK-3	DK-4	DK-5	GER-1	GER-2	IT-1	IT-2	IT-3	IT-4	IT-5
Global Warming kg CO_2-eq. kg^{-1} ECM	**Total**	1.43	1.10	1.57	1.27	1.66	1.32	0.55	1.36	1.91	1.47	1.18	1.11
	On-farm %	95.2	87.5	83.0	85.3	74.7	74.2	93.4	75.2	85.8	73.5	75.1	82.6
Acidification g SO_2-eq. kg^{-1} ECM	Total	16.75	14.65	18.73	16.07	19.22	18.06	7.44	17.28	25.64	18.57	15.58	15.22
	On-farm %	94.3	89.9	92.4	93.8	83.2	87.2	95.9	85.0	93.6	85.2	85.7	90.4
Eutrophication g PO_4^{3-}-eq. kg^{-1} ECM	Total	7.56	6.37	9.17	7.50	7.78	7.69	4.61	7.06	11.12	7.70	6.22	5.85
	On-farm %	91.4	91.6	94.9	94.6	86.1	89.6	95.1	87.4	95.0	83.2	82.2	84.9
Non-renewable energy MJ-eq. kg^{-1} ECM	Total	2.87	2.55	3.08	2.96	5.29	3.71	0.92	4.09	3.73	4.12	3.37	2.40
	On-farm %	77.1	40.7	50.4	62.5	26.6	26.8	57.4	28.9	49.8	17.7	23.9	29.9
Land occupation m^2 kg^{-1} ECM	Total	1.87	1.62	1.30	1.07	1.43	1.07	1.63	1.34	1.05	1.09	0.90	0.68
	On-farm %	90.5	81.4	84.9	83.5	43.4	54.2	95.3	48.5	72.7	26.6	15.1	22.8
Biodiversity DS kg^{-1} ECM	Total	0.27	0.25	1.11	0.92	1.25	0.81	0.56	1.00	0.79	0.85	0.69	0.51
	On-farm %	98.5	97.1	86.2	84.9	48.9	52.0	99.7	45.5	71.1	25.7	15.6	21.9

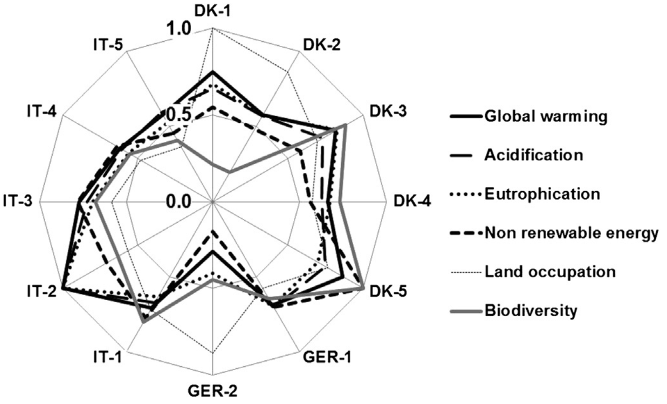

Fig. 1. Environmental impact from 12 dairy farms expressed in values (0–1) within six impact categories.

IT-3 and IT-4 accounting for, respectively, 21.2%, 19.6%, 22.0% and 20.5% where for DK-1, DK-3, DK-4 and GER-2 the contribution from commercial purchased feed was at most 6%.

In addition to the previous results (GWP estimated without land use change emissions) the simplified sensitive analysis showed that, accounting the emissions from direct land use change proposed by Flysjö et al. (2012) in the "worst scenario", the impact changed considerably for the conventional farms, that bought conventional soymeal, whereas the impact remained the same for the organic farms, that bought organic soymeal. Especially DK-5, IT-1, IT-3, and IT-4 showed a new impact of 5.38, 4.60, 4.27 and 4.03 kg CO_2-eq. kg^{-1} ECM, respectively. In this new scenario the commercial feed production contributes, respectively, 75.7%, 76.3%, 73.0% and 76.7% and the on-farm crop production 6.06%, 4.44%, 4.74% and 3.53% for DK-5, IT-1, IT-3, and IT-4.

The acidification values (g SO_2-eq. kg^{-1} ECM) varied from 7.44 at GER-2–25.64 at IT-2. The best Danish farm in terms of acidification potential was DK-2 at 14.65 and the best Italian IT-5 at 15.22 g SO_2-eq. kg^{-1} ECM. Acidification is strongly influenced by on-farm activities, with emissions from storages (especially ammonia) being particularly important (from 55.2% for GER-2–77.9% for IT-5) followed by emissions from crop production (from 11.0% for DK-5–40.1% for GER-2). The contribution of these two areas to total acidification ranged from 82.3% (DK-5)–95.3% (GER-2). For GER-2, emissions from the dung and urine deposition of grazing animals are included as part of crop production emissions.

The lowest and the highest values for eutrophication belong, respectively, to GER-2 and IT-2 at 4.61 and 11.12 g PO_4^{3-}-eq. kg^{-1} ECM. For the Danish and the Italian groups the lowest-impact farms were DK-2 and IT-5 at 6.37 and 5.85 g PO_4^{3-}-eq. kg^{-1} ECM, respectively. As shown in Fig. 3, by far the largest contribution to eutrophication comes from on-farm activities. Emissions from manure storage (mainly ammonia) and from crop production (especially nitrogen losses due to leaching) contributed from 81.8% (IT-4) to 94.5% (IT-2) to total eutrophication.

GER-2 had the lowest and DK-5 the largest consumption of non-renewable energy at, respectively, 0.92 and 5.29 MJ-eq. kg^{-1} ECM (Table 4). The lowest impact Danish and Italian farms were DK-2 and IT-5 at, respectively, 2.55 and 2.40 MJ-eq. kg^{-1} ECM. On-farm activities contributed from 17.7% (IT-3) to 77.1% (DK-1) to non-renewable energy consumption. Of the off-farm activities, commercial feed production had the highest energy use – its contribution ranging from 19% (DK-4) to 72.3% (IT-3). Fertilizer production can also have a high energy consumption; on the farms that used fertilizers this activity swallowed from 1.4% (IT-5) to 29.2% (DK-3) of the energy used.

The most extensive use of land was for the organic farms DK-1 and DK-2 with, respectively, 1.87 and 1.62 m^2 kg^{-1} ECM and the low-input GER-2 with 1.63 m^2 kg^{-1} ECM. This supports the theory that these types of farm generally need more land to produce feed due to their lower relative crop yields (de Boer, 2003). However, the more intensive farms such as DK-5, GER-1 and all five Italian farms (especially IT-4 and IT-5) had a higher off-farmland use due to a larger import of feed.

The last impact category provides an estimation of biodiversity losses caused by the different land uses with values expressed in Damage Score (DS) kg^{-1} ECM, which explains how the production of 1 kg ECM affects the relative change in species richness.

The farms that had the lowest impact on biodiversity losses were the organic DK-2 and DK-1 at 0.25 and 0.27 DS kg^{-1} ECM, respectively, followed by conventional farm IT-5 at 0.51 DS kg^{-1} ECM. For this category the share of the on- and off-farm impacts was related to the share of on- and off-farmland use.

The correlation analysis showed that there were strong and positive relations ($P < 0.01$) between GWP, acidification,

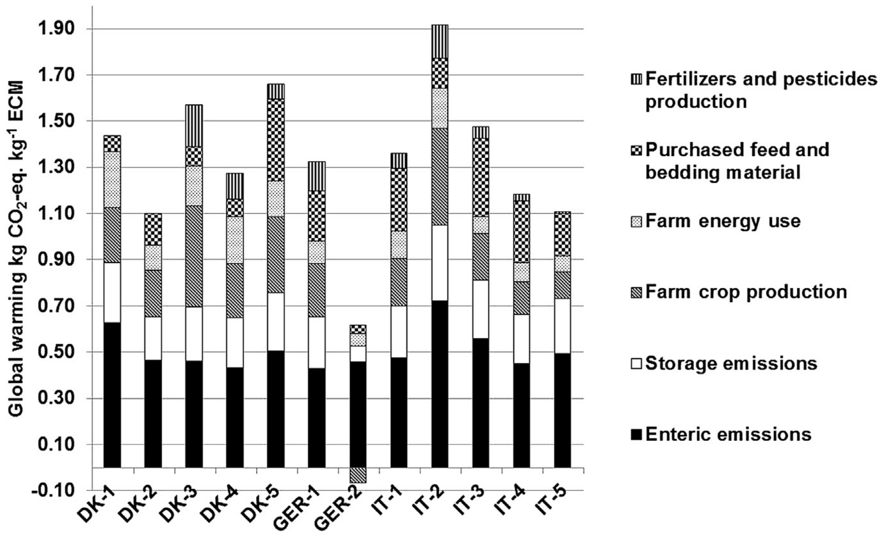

Fig. 2. Global warming potential at 12 dairy farms (reported in absolute values: kg CO_2-eq. kg^{-1} ECM) and the contribution from different parts of the production chain.

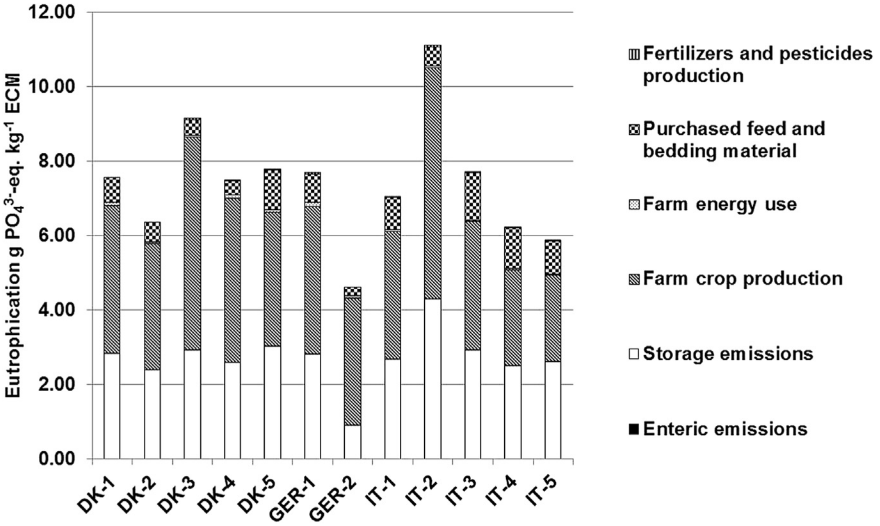

Fig. 3. Eutrophication at 12 dairy farms (reported in absolute values: g PO_4^{3-}-eq. kg^{-1} ECM) and the contribution from different parts of the production chain.

eutrophication and energy use, while land use was negatively, albeit non-significantly, related to the four categories. Biodiversity DS had a significant, positive relation ($P < 0.05$) to energy use and a non-significant relation to GWP, acidification and eutrophication. The negative, but not significant, correlation between biodiversity losses and land use was probably influenced by the organic farms (DK-1 and DK-2) and the low-input farm (GER-2) which had a high land occupation but adopted a crop management that limited the biodiversity losses. Overall, the results indicate that improving greenhouse gas emissions would improve the general environmental sustainability of the dairy farm.

The results obtained from the Stepwise analysis show that the EUR2003 single score is strongly correlated to GWP, acidification, eutrophication and non-renewable energy use (0.80, 0.68, 0.74, 0.60, respectively), confirming the conclusion of the correlation analysis.

3.3. Parameters affecting the environmental impact

This paper deals with only 12 farms, each of them based on different production strategies and management efforts. A more general analysis of the relation between the production and the environmental impact therefore has to be handled with care, also due to the geographical bias for some of the expected important farm characteristics like stocking rate, use of fertilizer and crop productivity. Due to the limited number of observations, we only performed one-way correlation analyses between selected farm parameters and the six impact categories.

A parameter that affected several impact categories was feed efficiency and it is important to remember that this feature had a significant ($P < 0.05$) negative correlation with global warming, acidification and eutrophication. This supports the theory that a better animal efficiency (in term of feed conversion rate) is one of the ways of reducing the environmental impact in milk production (Hermansen and Kristensen, 2011). A positive relation was observed between GWP, acidification, energy use, biodiversity DS and the share of grassland of the farmed area, where the farms with the largest share of grassland (DK-1, DK-2 and GER-3) had cows on grass during the summer season. Fig. 4 gives a graphic representation of the observed significant effect between grassland and GWP.

The role of grassland in GWP mitigation is probably due to its greater capacity for carbon sequestration. Rotz et al. (2010) found a

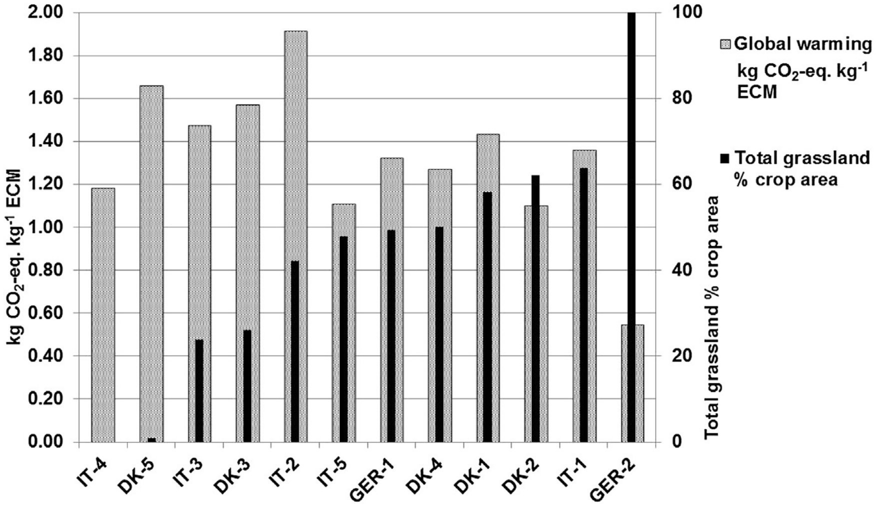

Fig. 4. Global warming potential at 12 dairy farms (kg CO_2-eq. kg^{-1} ECM) in ascending order of percentage of grassland of farmed area.

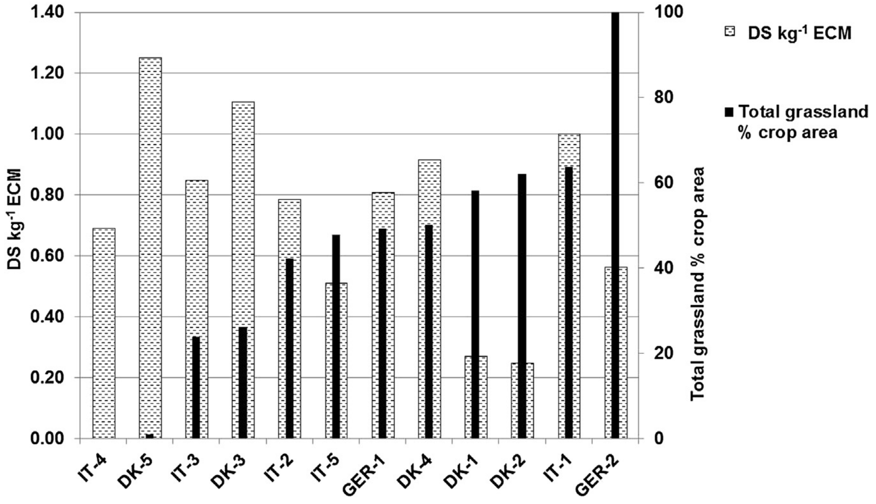

Fig. 5. Biodiversity damage score at 12 dairy farms (DS kg^{-1} ECM) ranked by proportion of grassland on farm cropland (%).

strong decrease in the carbon footprint per kg milk when carbon sequestration in grassland was included. Belflower et al. (2012) found a reduction in CO_2 emissions for pasture-based dairy farms compared to confinement farms because fewer field operations are required for tillage, planting, harvesting and feeding of these crops. This is consistent with a higher proportion of grassland in the rotation having a positive effect on energy consumption in our study, plus that farms with more grassland are more self-sufficient in feed so they avoid the heavy impact from commercial feed production and transport on total energy consumption. The influence of grassland of lowering acidification could be because of the lower fertilizer input for this type of crop. Finally, grassland plays an important role in reducing biodiversity losses, especially on organic and pasture-based farms. The positive effect of grassland on biodiversity (as seen in Fig. 5) was influenced by the organic farms (DK-1 and DK-2) having the lowest DS and a high proportion of grassland, while the effect within the conventional farms was less clear.

The correlation analysis showed that land occupation (on- and off-farm) was on the whole significantly ($P < 0.05$) reduced when the farming intensity increased (stocking rate, N surplus and use of fertilizer) and – not surprisingly – when crop production on the farmland increased. The first effect was an indirect effect as the farms with the highest intensity were also the farms with the highest import of feed, and the area of land used per DM of imported feed was less than the average area of land used by the farms to produce one kg DM.

A higher production level (kg ECM cow^{-1}) could be expected to reduce GWP per kg of product, as the relative amount of feed for maintenance is reduced, but as shown by Gerber et al. (2011), there is only a minor effect at yield levels below 5000 kg milk cow^{-1}.

We expected to find higher values of acidification and eutrophication for the farms with higher stocking rates (Thomassen et al., 2008; O'Brian et al., 2012), but we found none of these relations to be significant. This result is influenced by the trend of farms IT-4 and IT-5 which, despite a high stocking rate and a consequently high nitrogen surplus per hectare, had a low impact on acidification and eutrophication.

There was no significant contribution of stocking rate to the off-farm impact on GWP, acidification and energy use, while for eutrophication, land occupation and biodiversity the off-farm impact increased with stocking rate.

The animal nitrogen use efficiency was only weak ($P = 0.18$) and negatively correlated with eutrophication, despite several studies indicating that animal nitrogen efficiency is a key parameter to improving nitrogen emissions to the environment (Arriaga et al., 2009). Farm GER-2 had a low nitrogen use efficiency, but also the lowest impact on eutrophication, which could explain why in this work there was only a slight correlation between this impact category and animal nitrogen use efficiency.

4. Conclusions

The environmental impact of milk production is dependent upon many factors, which is why this analysis did not set out to find the farming system with the lowest impact, but to identify the factors that contribute to environmental pressure in different farming systems in different countries. The study shows huge variability in environmental impact within the group of farms analysed, and this was expected because of the differences in both structural characteristics and management strategies. It should be kept in mind that the final environmental results are restricted to a sample of 12 farms and for that reason they cannot be upscaled to either a regional or national level. We found the parameters to most strongly influence environmental impact to be the proportion of grassland in the farming system and the feed efficiency in the herd. We found no relation between environmental impact and the milk production per cow or the farm's stocking rate. In this work we have merely shown the result of a first attempt to quantify the biodiversity losses of producing 1 kg of milk, and this was mainly affected by the proportion of grassland in the system.

Most of the impact categories were strongly, positively intercorrelated, meaning that improvements to one of them would help improve the general sustainability of the milk chain. There was large variation in the relationship between on-farm and off-farm contributions, both between impact categories and between farms, showing the importance of a holistic approach and the difficulties in evaluating a farming system both in a product and area-based perspective. Moreover, the simplified sensitive analysis carried out in this study confirms previous findings that including land use change for the imported soybeans can increase the GWP considerably for the conventional farms.

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