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How can farming intensification affect the environmental impact of milk production?

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ABSTRACT

The intensification process of the livestock sector has been characterized in recent decades by increasing output of product per hectare, increasing stocking rate, including more concentrated feed in the diet, and improving the genetic merit of the breeds. In dairy farming, the effects of intensification on the environmental impact of milk production are not completely clarified. The aim of the current study was to assess the environmental impacts of dairy production by a life cycle approach and to identify relations between farming intensity and environmental performances expressed on milk and land units. A group of 28 dairy farms located in northern Italy was involved in the study; data collected during personal interviews of farmers were analyzed to estimate emissions (global warming potential, acidification, and eutrophication potentials) and nonrenewable source consumption (energy and land use). The environmental impacts of milk production obtained from the life cycle assessment were similar to those of other recent studies and showed high variability among the farms. From a cluster analysis, 3 groups of farms were identified, characterized by different levels of production intensity. Clusters of farms showed similar environmental performances on product basis, despite important differences in terms of intensification level, management, and structural characteristics. Our study pointed out that, from a product perspective, the most environmentally friendly way to produce milk is not clearly identifiable. However, the principal component analysis showed that some characteristics related to farming intensification, such as milk production per cow, dairy efficiency, and stocking density, were negatively related to the impacts per kilogram of product, suggesting a role of these factors in the mitigation strategy of environmental burden of milk production on a global scale. Considering the environmental burden on a local perspective, the impacts per hectare were positively associated with the intensification level.

Key words: milk production, intensive farming, environmental impact, life cycle assessment

INTRODUCTION

In recent decades, the European livestock sector has shown a general trend toward enlarging farm size and increasing intensification in terms of output per hectare. The intensification of production is generally characterized by increasing stocking rate, including more concentrated feed in the diet and improving the genetic merit of the breeds (Alvarez et al., 2008). Such evolution has also affected the Italian dairy sector, which has shown a strong decrease in the total number of dairy cows over the last 30 yr (from 2.6 million in 1980 to 1.6 million presently) and an increase in the number of cows per farm (from 7.9 to 31.8 in the same period; ISTAT, 2012). Furthermore, in northern Italy, favorable climatic and infrastructure conditions have led to a very high livestock concentration with a consequent intensive utilization of natural resources (i.e., land, air, water) and high environmental pressure. Intensification of livestock production systems is generally considered detrimental from an environmental point of view. A study from New Zealand (Basset-Mens et al., 2009) showed that increasing the number of cows per land unit (with higher N-fertilization and more land used to grow maize for silage instead of permanent grass) reduced dairy farm eco-efficiency in terms of both milk production and land use functions. Penati et al. (2011), assessing environmental sustainability of a group of alpine dairy farms, found that the best environmental performances were obtained by the farms characterized by low stocking density, low production intensity, high feed self-sufficiency, and large land availability in the valley floor. But other results from the literature showed some positive effects of the intensification of livestock production in terms of environmental impact mitigation. A review study by Crosson et al. (2011) concluded that increased output per hectare obtained through intensification can reduce emissions per kilogram of product. Kristensen et al. (2011) identified herd efficiency and farming intensity as relevant strategies for environmental impact reduction. Yan et al. (2013)

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found that, as milk production increases, a mitigation of environmental impact is observed. Casey and Holden (2005) suggested that, to improve the environmental efficiency of dairy farms, a move toward fewer cows producing more milk at lower stocking rates is required. This represents an extensification in terms of area but an intensification in terms of animal husbandry systems.

Life cycle assessment (**LCA**) is a generally accepted method for estimating the environmental impact of agricultural products on a global perspective. The main environmental effects quantified in LCA studies on dairy systems are the acidifying and eutrophic effects on watercourses, the global warming effect, and the utilization of resources such as land and nonrenewable energy during the production of milk (O'Brien et al., 2012).

Even if climate change is a global issue, for environmental aspects with a local connotation (especially acidification and eutrophication), environmental impact should be evaluated not only per unit of product but also per hectare of land. In particular, eutrophication pertains directly to the leaching and run-off of nitrate and phosphate to the ground and surface water; therefore, this parameter contains a local aspect (Oudshoorn et al., 2011). Many authors showed significantly worse environmental performances of the intensive livestock systems when the impacts were expressed in terms of land unit (Haas et al., 2001; Casey and Holden, 2005).

The first objective of the current study was to analyze the environmental performances of a sample of dairy farms, both on a global and on a local perspective, through an LCA approach. The second objective was to identify the relation between environmental impacts and main farm characteristics, focusing in particular on farming intensity.

MATERIALS AND METHODS

System Description and Data Collection

A group of 28 dairy cattle farms were involved in the current study. All the farms were located in northern Italy and were members of a cheese factory producing Grana Padano. All cows were Italian Holstein kept in permanent confinement without pasture. This rearing system is the most commonly used in the north of Italy.

Data were collected through personal interviews of farmers. Questions were addressed to obtain precise information about cropping systems and field operations, fuel consumption, number of animals and housing systems, and manure storage and animal rations. Moreover, data regarding the inputs entering the farms were acquired, including amount of purchased feeds (both

roughages and concentrates), fertilizers and pesticides, bedding materials, and number and origin of purchased replacement animals.

In each farm, forages (hays and silages) and TMR were sampled and analyzed for the content of DM ash, CP, ether extract, and crude fiber by AOAC International (1995) methods; starch by AOAC International (1998) methods; NDF analyzed following the protocol of Mertens (2002); and ADF and ADL by the method of Van Soest et al. (1991). Data obtained from the analyses were used for the estimation of digestibility of the feeding rations. The amount of milk produced by each farm was provided by the cheese factory, whereas the amount of meat (as animal liveweight) was estimated on the basis of the number of animals sold for slaughter and their liveweight declared by the farmers.

Composition of concentrated feed was estimated on the basis of the raw materials reported on the commercial labels using CPM-Dairy Ration Analyzer Beta V3 software (Cornell-Penn-Miner, 2004). Table 1 summarizes the inventory of the most important data used for impact assessment. All the data are expressed as the average value of the 28 dairy farms.

The income over feed cost (**IOFC**) was used as economic indicator of farm profitability, as proposed by Hutjens (2007), and it was calculated as the income from milk minus feeding costs (self-produced and purchased feed) per cow per day.

Emission Estimation

Greenhouse Gas Emissions On Farm. Table 2 shows the models used for on-farm greenhouse gas emission (**GHG**) estimation. Methane (CH_4) emissions from livestock enteric fermentations were estimated using an equation from Ellis et al. (2007). To convert the energy of enteric methane in kilograms of methane emitted, the factor 55.65 MJ/kg of CH_4 (IPCC, 2006a) was used. Methane emissions from manure management were estimated using the Tier 2 method suggested by the Intergovernmental Panel on Climate Change (IPCC, 2006a). Volatile solid excretion was estimated considering gross energy of the diets (kJ/kg of DM) evaluated using an equation of Ewan (1989). Digestibility of the feed was estimated using a calculation model developed for each type of forage and concentrate feed on the basis of the equation proposed by INRA (2007). Feed nutritional characteristics were obtained from the laboratory analyses.

In the current study, animal nitrogen excretion was estimated as proposed by the IPCC (2006a) Tier 2 method considering the nitrogen intake (on the basis of CP% of the diet) minus the nitrogen retained by the animals and excreted with milk. Nitrous oxide (N_2O)

Table 1. Inventory data (average of the 28 farms)

Item	Unit	Mean	SD	Minimum	Maximum
Land					
Farm land	ha	40.7	27.8	8.5	120
Permanent grassland	% land	52.1	23.8	12.9	100
Maize land for silage	% land	36.5	20.3	0.0	87.1
NE _L yield	MJ/ha	74,965	20,924	34,901	134,248
Nitrogen yield	kg/ha	180	38.2	103	238
N synthetic fertilizers	kg/ha	84.3	51.1	0.0	202
Pesticides (active substances)	g/ha	791	614	0.0	1,849
Herd					
Dairy cows	n	90.3	52.0	17.0	195
Livestock unit (LU)	n	143	86.7	25.7	308
Milk production	kg of FPCM ¹ /cow per day	27.1	4.3	18.1	35.4
Production intensity	kg of FPCM/ha	19,764	7,955	12,005	46,455
Meat production ²	kg/farm per year	130	45.6	53.1	223
Manure type					
Solid manure	%	40.3	38.0	0.0	100.0
Liquid slurry	%	59.7	38.0	0.0	100.0
Feed					
Feed produced on farm	t of DM/LU per year	3.8	1.2	1.6	6.5
Purchased forages	t of DM/LU per year	0.3	0.4	0.0	1.4
Purchased concentrates	t of DM/LU per year	1.7	0.7	0.4	3.0
Energy					
Diesel use	kg/LU per year	88.6	21.3	54.0	141
Electricity use	KWH/LU per year	211	79.9	52.3	336

¹FPCM = fat- and protein-corrected milk.

²Liveweight sold.

emissions from manure storages occurred in direct and indirect forms, and in both cases they were estimated using the Tier 2 method from IPCC (2006a). Direct and indirect N₂O losses from fertilizer application were estimated following the Tier 2 and Tier 1 methods suggested by IPCC (2006b), respectively; the amount of nitrogen applied to the soils from synthetic fertilizers and from manure (slurry and solid) plus the nitrogen from crop residues were accounted for in the estimation.

Carbon dioxide (CO₂) emissions from fuel combustion were estimated on the basis of fuel consumption of each farm. Emissions occurring during field operations (i.e., plowing, harrowing, sowing, harvesting, and so on) were estimated using the processes of the Ecoinvent (2007) database; whereas, for other fuel consumptions (i.e., use for feeding mixer), the emission factor used was 3.12 kg of CO₂/kg of diesel, as proposed by Nemecek and Kägi (2007). Emissions from livestock respiration and the variation in soil carbon stocks were not accounted for.

Other Emissions On Farm. Table 3 reports the models used for the estimation of acidifying and eutrophic substances emitted on farm. Ammonia (NH₃) and nitrogen oxide (NO_x) emissions that occur during animal housing, manure storage, and spreading were estimated following the method proposed by the European Environment Agency (EEA, 2009a,b) on the basis of the total amount of nitrogen excreted by the animals. The Tier 2 method used a mass flow approach

based on the concept of a flow of total ammonia nitrogen through the manure management systems. The NH₃-N and NO_x emission factors, as a proportion of total ammonia nitrogen, were specific for each manure type (slurry or solid) and each step in manure handling (EEA, 2009a). The NH₃ and NO_x emitted during manure spreading and application of synthetic fertilizers were estimated following EEA (2009b) guidelines. The amount of nitrogen leached was estimated following the IPCC (2006b) model (Table 2). To estimate emissions of PO₄³⁻, the amount of phosphorus lost in dissolved form to surface water (run-off) and leached was considered as proposed by Nemecek and Kägi (2007).

Off-Farm Processes. The emissions related to off-farm activities were calculated using LCA software, Simapro PhD 7.3.3 (PRé Consultants, 2012), and were modeled using the databases reported in Table 4. The processes considered included the production chain of commercial feed (from crop growing to feed factory processing), production of purchased forages and bedding material, rearing of purchased replacing heifers, production of chemical fertilizers and pesticides, and diesel and electricity used in the farms. Transportation was accounted for only in feed, bedding materials, and purchased replacement animals.

As farms bought a quota of their replacement heifers, a simplified LCA was performed to assess the impacts associated to heifer rearing, considering animals sold at 24 mo of age, average feed intake, average diet

Table 2. Models and emission factors (EF) used for the estimation of greenhouse gas emissions on farm

Pollutant	Source	Amount ¹	Reference
CH ₄	Enteric	CH ₄ (MJ) = 2.16 (±1.62) + 0.493 (±0.192) · DMI (kg) – 1.36 (±0.631) · ADF (kg) + 1.97 (±0.561) · NDF (kg)	Ellis et al. (2007)
	Manure storage	CH ₄ = VS × B ₀ · 0.67 · MCF/100 · MS VS = [GE · (1 – DE/100) + (UE · GE)] · [(1 – Ash)/18.45] GE (kJ) = 17,350 + (234.46 · EE%) + (62.8 · CP%) – (184.22 · Ash %) DE: feed digestibility MCF solid storage: 4 MCF liquid slurry: 17 MCF pit storage: 27	Equation 10.23 in IPCC (2006a) Equation 10.24 in IPCC (2006a) Ewan (1989) INRA, 2007 IPCC (2006a)
N ₂ O direct	Manure storage	N ₂ O = Nex · MS · EF · 44/28 Nex = Nintake · (1 – N retention) N intake: DMI · (CP %/100/6.25) N retention: N retained per animal with milk and weight gain EF solid storage: 0.005 (0.0027 – 0.01) EF liquid slurry: 0.005 EF pit storage: 0.002	Equation 10.25 in IPCC (2006a) Equation 10.31 in IPCC (2006a) Equation 10.33 in IPCC (2006a) Table 10.21 in IPCC (2006a)
	Field	N ₂ O = (N _{sn} + N _{on} + N _{cr}) · EF · 44/28 N _{on} : annual amount of N from managed animal manure applied to soil (Nex – Frac_loss + N bedding) Frac_loss solid storage: 40% (10 – 65) Frac_loss liquid slurry: 40% (15 – 45) Frac_loss pit storage: 28% (10 – 40) EF: 0.01 (0.003 – 0.03)	Equation 11.2 in IPCC (2006b) Equation 10.34 in IPCC (2006a) Table 10.23 in IPCC (2006a)
N ₂ O indirect	Manure storage	N ₂ O _G = N volatilization · EF · 44/28 Nvolatilization: Nex · MS · Frac_GasMS/100 Frac_GasMS solid storage: 30 (10 – 40) Frac_GasMS liquid slurry: 40 (15 – 45) Frac_GasMS pit storage: 28 (10 – 40) EF: 0.01 (0.002 – 0.05)	Table 11.1 in IPCC (2006b) Equation 10.27 in IPCC (2006a) Table 10.22 in IPCC (2006a)
	Field	N ₂ O _(ATDN) = [(N _{sn} · Frac_GasF) + (N _{on} · Frac_GasM)] · EF · 44/28 Frac_GasF: 0.1 (0.03 – 0.3) Frac_GasM: 0.2 (0.05 – 0.5) EF: 0.01 (0.002 – 0.05) N ₂ O _(L) = (N _{sn} + N _{on}) · Frac_Leach · EF · 44/28 Frac_Leach: 0.3 (0.1 – 0.8) EF: 0.0075 (0.0005 – 0.025)	Table 11.3 in IPCC (2006b) Equation 11.9 in IPCC (2006b) Table 11.3 in IPCC (2006b) Table 11.3 in IPCC (2006b) Table 11.3 in IPCC (2006b) Equation 11.10 in IPCC (2006b)
CO ₂	Field operations		Table 11.3 in IPCC (2006b)
	Diesel combustion ²	CO ₂ = kg diesel · EF EF: 3.12 kg of CO ₂ /kg of diesel	Ecoinvent (2007) Nemecek and Kägi (2007)

¹VS = daily volatile solid excreted (kg of DM /animal); B₀ = maximum methane-producing capacity for manure (m³); MCF = methane conversion factors for each given manure management system (%); MS = fraction of livestock manure handled using each given manure management system (dimensionless); GE = gross energy intake (MJ/ d); DE% = energy digestibility of feed (%); (UE · GE) = urinary energy expressed as fraction of GE (dimensionless); EE% = ether extract of feed (% DM); Nex = annual N excretion (kg of N/animal); EF = emission factor for direct N₂O emissions from a given manure management system (kg of N₂O-N/kg of N in manure management system); N_{sn} = annual amount of synthetic fertilizer N applied to soils (kg of N); N_{on} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (kg of N); N_{cr} = annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils (kg of N); Frac_loss = fraction of managed manure N that is lost in a given manure management system (%); N_bedding = annual amount of N from bedding (kg of N/animal); N volatilization = annual amount of manure N that is lost due to volatilization of NH₃ and nitric oxide compounds (NO_x; kg of N); Frac_GasMS = fraction of managed manure N that volatilizes as NH₃ and NO_x in a given manure management system (%); Frac_GasF = fraction of synthetic fertilizer N that volatilizes as NH₃ and NO_x (%); Frac_GasM = fraction of applied organic N fertilizer materials and of urine and dung N deposited by grazing animals that volatilizes as NH₃ and NO_x (%); Frac_Leach = N fraction lost through leaching and runoff (%).

²Excluding the quota used during field operations.

Table 3. Models and emission factors (EF) for the estimation of ammonia, nitric oxide, and phosphate emissions on farm

Pollutant	Source	Amount ¹	Reference
NH ₃	Housing	TAN = Nex · EF_TAN	Equation 10 in EEA (2009a)
		EF_TAN: 0.6	Table 3–8 in EEA (2009a)
		NH ₃ build_slurry = TANbuild_slurry · EFbuild_slurry · 17/14	Equation 15 in EEA (2009a)
		EFbuild_slurry: 0.2	Table 3–8 in EEA (2009a)
	Manure storage	NH ₃ build_solid = TANbuild_solid · EFbuild_solid · 17/14	Equation 16 in EEA (2009a)
		EFbuild_solid: 0.19	Table 3–8 in EEA (2009a)
		NH ₃ storage_solid = TANstorage_slurry · EFstorage_slurry · 17/14	Equation 29 in EEA (2009a)
	Field	EFstorage_slurry: 0.20	Table 3–8 in EEA (2009a)
		NH ₃ storage_solid = TANstorage_solid · EFstorage_solid · 17/14	Equation 30 in EEA (2009a)
		EFstorage_solid: 0.27	Table 3–8 in EEA (2009a)
NH ₃ applic_slurry = TANslurry_applic · EFapplic_slurry · 17/14		Equation 35 in EEA (2009a)	
EFapplic_slurry: 0.55		Table 3–8 in EEA (2009a)	
NH ₃ applic_solid = TANsolid_applic · EFapplic_solid · 17/14		Equation 36 in EEA (2009a)	
NOx	Manure storage	EFapplic_solid: 0.79	Table 3–8 in EEA (2009a)
		NH ₃ applic_fert = Nfert_applic · EFfert_type	Equation 3 in EEA (2009b)
		EF urea: 0.1067 + 0.0035 · Ts	Table 3–2 in EEA (2009b)
		EFamm.nitr. and NPK: 0.0080 + 0.0001 · Ts	
		NOxstorage_solid = TANstorage_slurry · EFstorage_slurry · 17/14	Equation 29 in EEA (2009a)
	Field	EFstorage_slurry: 0.0001	Table 3–9 in EEA (2009a)
		NOxstorage_solid = TANstorage_solid · EFstorage_solid · 17/14	Equation 30 in EEA (2009a)
		EFstorage_solid: 0.01	Table 3–9 in EEA (2009a)
		NOxapplic_tot = (Nslurry_applic + Nsolid_applic + Nfert_applic) · EFapplic	
		EFapplic: 0.026	Table 3–1 in EEA (2009b)
PO ₄ ³⁻	Field	P _{gw} (leached to ground water) = P _{gw1} · F _{gw}	Paragraph 4.4.3 in Nemecek and Kägi (2007)
		P _{gw1} arable land: 0.07	
		P _{gw1} permanent pasture and meadow: 0.06	
		F _{gw} : 1 + 0.2/80 · P ₂ O ₅ slurry	
		P _{ro} (P lost through run-off to rivers) = P _{rol} · F _{ro}	
		P _{rol} open arable land: 0.175	
		P _{rol} extensive meadow: 0.25	
		F _{ro} fert: 0.2/80 · P ₂ O ₅ fert	
		F _{ro} slurry: 0.7/80 · P ₂ O ₅ slurry	
		F _{ro} manure: 0.4/80 · P ₂ O ₅ manure	

¹TAN = total ammoniacal-N; Nex = annual average N excretion per head (kg of N/animal); EF_TAN = emission factor of TAN; build_slurry = liquid slurry in the livestock buildings; build_solid = solid manure in the livestock buildings; storage_solid = solid manure in storages; storage_slurry = liquid slurry in storages; applic_slurry = application of liquid slurry to the field; applic_solid = application of solid manure to the field; NH₃ applic_fert = emission from fertilizer application to the field; N fert_applic = total N from fertilizer application; EF fert_type = emission factor for fertilizer type; Amm nitr = ammonium nitrate; NPK = nitrogen-phosphorus-potassium fertilizer; Ts = mean spring temperature (°C); NOx = nitric oxide compounds (NO + NO₂); P_{gw} = quantity of phosphorus leached to ground water (kg/ha); P_{gw1} = average quantity of phosphorus leached to ground water for each land use category (kg/ha); F_{gw} = correction factor for fertilization by slurry; P_{ro} = quantity of phosphorus lost through runoff to rivers (kg/ha); P_{rol} = average quantity of phosphorus lost through runoff to rivers for each land use category (kg/ha); F_{ro} = correction factor for fertilization with each source of phosphorus.

Table 4. Inventory of off-farm processes

Process	Reference
Feed production	
Crop	Ecoinvent, 2007; Baldoni and Giardini, 2002; Ribaudo, 2002; data from the current study
Milk powder	Nielsen et al., 2007
Feed processing	Nielsen et al., 2007
Forage production	Ecoinvent, 2007; Baldoni and Giardini, 2002; Ribaudo, 2002; data from the current study
Bedding material production	Ecoinvent, 2007
Rearing animals	Data from the current study
Fertilizer production	Patyk and Reinhardt, 1997; Ecoinvent, 2007
Pesticide production	Ecoinvent, 2007
Energy production	Ecoinvent, 2007
Transportation	Ecoinvent, 2007

composition, standard housing conditions, and manure management.

Impact Assessment

The environmental impact of milk production in each dairy farm was evaluated through a detailed cradle-to-farm-gate LCA (Belflower et al., 2012). The system boundaries included all the on-farm processes plus the off-farm activities linked to the production of external inputs (Figure 1).

The selected environmental impact categories were global warming, acidification, eutrophication, nonrenewable energy use, and land use (O'Brien et al., 2012). The impact assessment was performed with the EPD (2008) 1.03 method, updated with IPCC (2007) global-warming potential (**GWP**) conversion factors (100-yr time horizon). Land use was estimated on the basis of total area (on- and off-farm land).

On a global perspective the functional unit (**FU**) was established as 1 kg of fat- and protein-corrected milk (**FPCM**) leaving the farm gate (Thomassen et

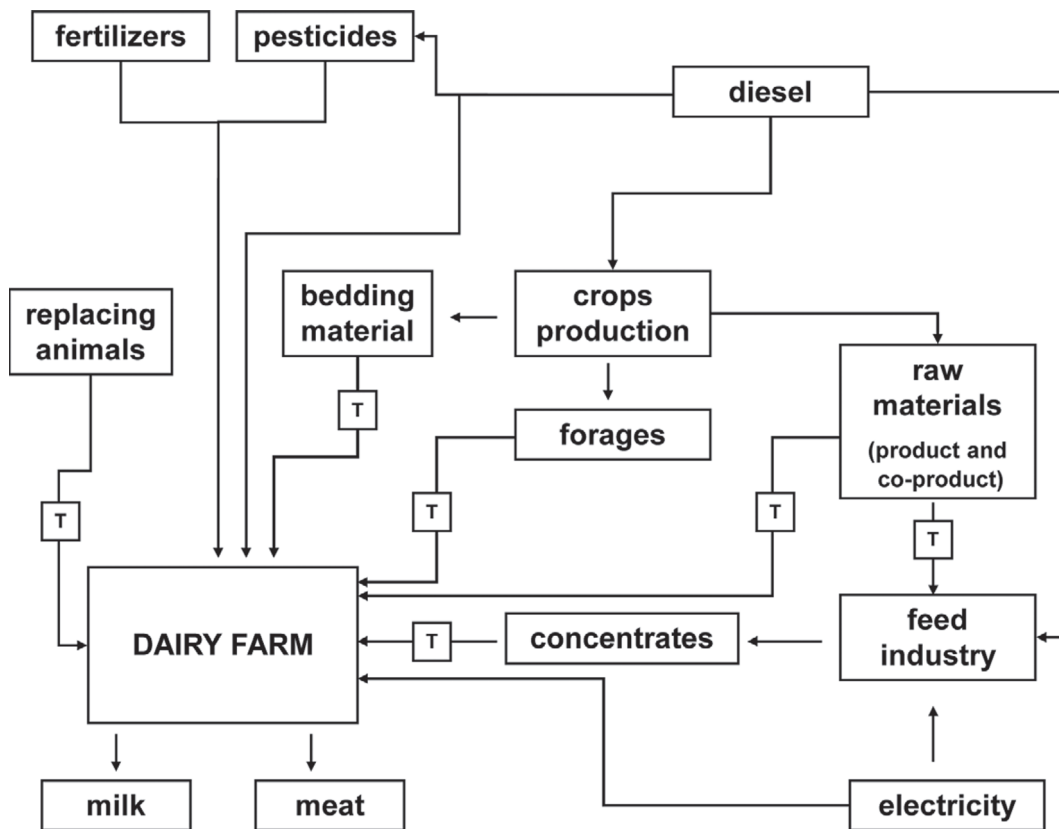


Figure 1. System boundaries. T = transportation.

al., 2008) estimated using the formula $FPCM \text{ (kg)} = \text{raw milk (kg)} \times (0.337 + 0.116 \times \% \text{ fat} + 0.060 \times \% \text{ protein})$ from Gerber et al. (2010). The biological allocation method developed by IDF (2010) for the dairy farming system was calculated using the formula $AF = 1 - 5.7717 \times R$, where AF = allocation factor for milk; $R = M \text{ meat}/M \text{ milk}$; $M \text{ meat}$ = sum of liveweight of all animals sold, including bull calves and culled mature animals; and $M \text{ milk}$ = sum of sold FPCM. The environmental impacts were also estimated from a local point of view, assuming 1 ha of farm land as FU.

Statistical Analysis

Statistical analysis was performed using SAS 9.2 software (SAS Institute, 2001) and was carried out in 3 steps. The first step was performed through a principal component analysis (**PCA**; PROC PRINCOMP) to study the relationships among total environmental impacts per kilogram of milk and per hectare, their on-farm contributions, and several quantitative variables related to farming intensity, including production level (kg of FPCM/cow per day), dairy efficiency (kg of FPCM/kg of DMI), number of dairy cows, stocking rate as livestock units (**LU**; LU/ha), total farm land (ha), shares of maize land for silage and grassland on total farm land, and IOFC (€/cow per day). In the second step, farms were grouped through a CLUSTER procedure (using average linkage method) considering as variables total farm land (ha), number of dairy cows, stocking rate (LU/ha), production level (kg of FPCM/cow per day), percentage of grass hay and maize silage on DMI, percentage of maize land for silage on farm land, dairy efficiency (kg of FPCM/kg of DMI), and feed self-sufficiency (expressed as the ratio between the DM produced on farm and the total DM used for animal feeding). For each cluster, average farm characteristics and environmental impacts on a global (FU = 1 kg of FPCM) and local (FU = 1 ha of farm land) scale were computed. Moreover a Pearson correlation

analysis was used to identify the relationship between farm characteristics and each environmental impact expressed per hectare of farm land.

RESULTS

Environmental Impacts of Milk Unit

Table 5 reports the average results of the environmental impact assessment of milk production in the farms under consideration expressed per milk unit. The on-farm percentage of GHG emissions was much higher compared with the off-farm one. The most important contributor to global warming was enteric and manure storage emission ($52.9 \pm 4.40\%$), followed by emissions related to the production of concentrated feed ($19.9 \pm 6.78\%$). Almost all the acidification was due to on-farm activity and the main role was played by farm crop production ($39.1 \pm 8.54\%$), animal housing ($22.7 \pm 2.63\%$), and manure storage ($22.5 \pm 5.25\%$). Also, for eutrophication, on-farm contribution was the most important factor; in particular, farm crop production was the major driver ($51.6 \pm 7.89\%$), whereas, in off-farm processes, the production of concentrate feed accounted for $21.2 \pm 7.66\%$ of total eutrophication potential. In nonrenewable energy use, the on- and off-farm contributions were similar; the production of concentrated feed covered $46.6 \pm 13.9\%$ of the total energy consumption alone. Similar to energy consumption, land use did not show any important difference between on- and off-farm shares; crop production for purchased concentrated feed contributed $33.0 \pm 10.8\%$ of total impact alone, followed by growing of purchased forages ($5.82 \pm 7.58\%$).

Figure 2 shows the average contributions of different substances to GWP, acidification, and eutrophication. Overall, methane was responsible for $49.9 \pm 3.64\%$ of total GHG emission, followed by carbon dioxide and nitrous oxide, which had similar weights (25.4 ± 2.59 and $24.5 \pm 3.25\%$, respectively). Enteric fermentation

Table 5. Total environmental impacts expressed per kilogram of fat- and protein-corrected milk (FPCM) for the 28 dairy farms and on-farm contributions

Environmental impact	Location	Mean	SD	Minimum	Maximum
Global warming (kg of CO ₂ -equivalent)	Total	1.26	0.17	0.90	1.56
	On-farm %	74.3	7.05	61.1	87.8
Acidification (g of SO ₂ -equivalent)	Total	15.2	3.34	8.63	21.7
	On-farm %	86.6	5.60	70.1	94.9
Eutrophication (g of PO ₄ -equivalent)	Total	7.33	1.39	5.00	9.69
	On-farm %	74.6	8.10	59.5	90.3
Energy use (MJ)	Total	5.47	0.89	2.85	7.33
	On-farm %	43.3	12.5	22.9	72.1
Land use (m ²)	Total	0.95	0.16	0.59	1.24
	On-farm %	58.1	12.4	40.1	83.1

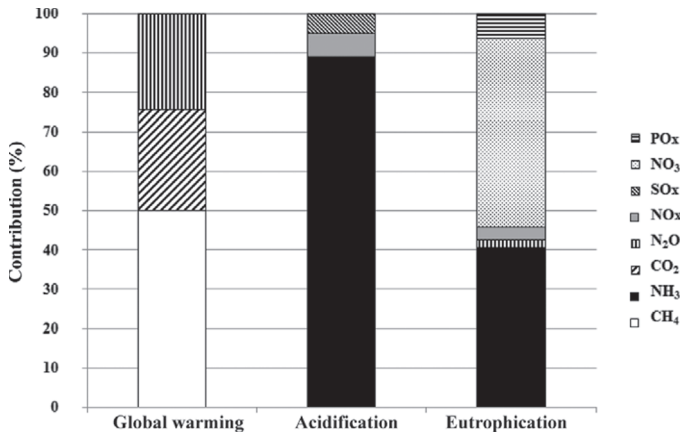


Figure 2. Contribution of different substances to the impact categories.

was the most important source of CH₄, as $74.3 \pm 8.87\%$ of total methane was produced in the gastrointestinal tract of the animals.

Ammonia emission accounted for $88.8 \pm 2.34\%$ of acidification potential. Ammonia volatilized mainly during application of manure on farm soils ($41.4 \pm 9.36\%$ of total ammonia emission) and during animal housing and manure storage (25.6 ± 2.87 and $25.1 \pm 5.66\%$ of total ammonia emission, respectively). Nitrate leaching was the main contributor to eutrophication potential ($47.8 \pm 4.01\%$), followed by volatilized NH₃ ($40.3 \pm 4.61\%$), whereas the role of phosphate losses was less important (only $6.13 \pm 1.43\%$). The percentage of nitrate leached during on-farm crop production was higher than the fraction related to purchased feed (concentrates and forages), at 67.1 ± 10.4 and $29.6 \pm 10.9\%$ of total nitrogen leached, respectively.

Interaction Between Farm Characteristics and Environmental Impact

The results obtained from the PCA are plotted in Figures 3 and 4 and the eigenvectors are reported in Tables 6 and 7. Figure 3 shows the multivariate correlation between farm characteristics and environmental impacts per kilogram of FPCM. The first dimension explains 38.7% of the total variance, whereas the second dimension explains 20.1%. Total impacts [total global warming (GW_{tot}), total land use (LAND_{tot}), and total energy use (ENERGY_{tot})] and their on-farm quotas, expressed in terms of kilograms of milk produced, are in the same area and highly correlated with each other and with feed self-sufficiency. On-farm land use and on-farm energy use are strongly related to feed self-sufficiency because the higher the quota of feed produced on farm, the higher their impact. Total and on-farm

acidification and eutrophication are very close to the percentage of land used for maize silage production, which needs high N fertilization.

The farm characteristics enclosed in the upper-left area of Figure 3 are inversely related to the total impact per kilogram of milk. The distance between the variables on the first dimension of the graph means that improving milk production and dairy efficiency, on one hand, and increasing stocking density and the share of grassland on farm land, on the other hand, may result in a reduction of all the impacts per kilogram of product. Dairy efficiency is one of the parameters that mainly influences profitability, expressed as IOFC, of a dairy farm; in fact, they are in the same area of Figure 3. Stocking density and feed self-sufficiency are on the opposite sides of the graph in Figure 3 and inversely related as a consequence of the higher amount of feeds generally bought from the market in the high-stocking density farms. Figure 4 shows the multivariate correlation between farm characteristics and environmental impacts per hectare of land. All environmental impact categories are close to each other, to the percentage of land for maize silage, and to the stocking density. On the first dimension (principal component 1), which explains 50.8% of the variance, all impact categories, expressed on unit of land, are inversely related to feed self-sufficiency.

The Pearson correlation analysis identified stocking density and feed self-sufficiency as the major drivers of environmental burden per hectare of farm land for all the impact categories. In particular, global warming (kg of CO₂-equivalent/ha of farm land) showed a strong positive correlation with stocking density ($r = 0.91$; $P < 0.001$) and a negative correlation with feed self-sufficiency ($r = -0.71$; $P < 0.001$). Significant positive correlations were shown between the percentage of land used to grow maize for silage and all on-farm impact categories, especially acidification and eutrophication (0.55 ; $P < 0.01$ and 0.58 ; $P < 0.01$, respectively).

Figure 5 shows the relationship between stocking density and eutrophication, expressed both per kilogram of FPCM and per hectare of farm land. The number of LU per hectare did not affect the emission per kilogram of milk, whereas it is a key point when the impact is expressed in land units.

Farming Intensity and Environmental Performances

The cluster analysis clearly identified 3 groups of farms differing in terms of intensity level (Table 8). The first one (high) included 10 farms characterized by a high level of intensification: high milk production per hectare, high percentage of arable land on total land, large land area sowed with maize for silage, high

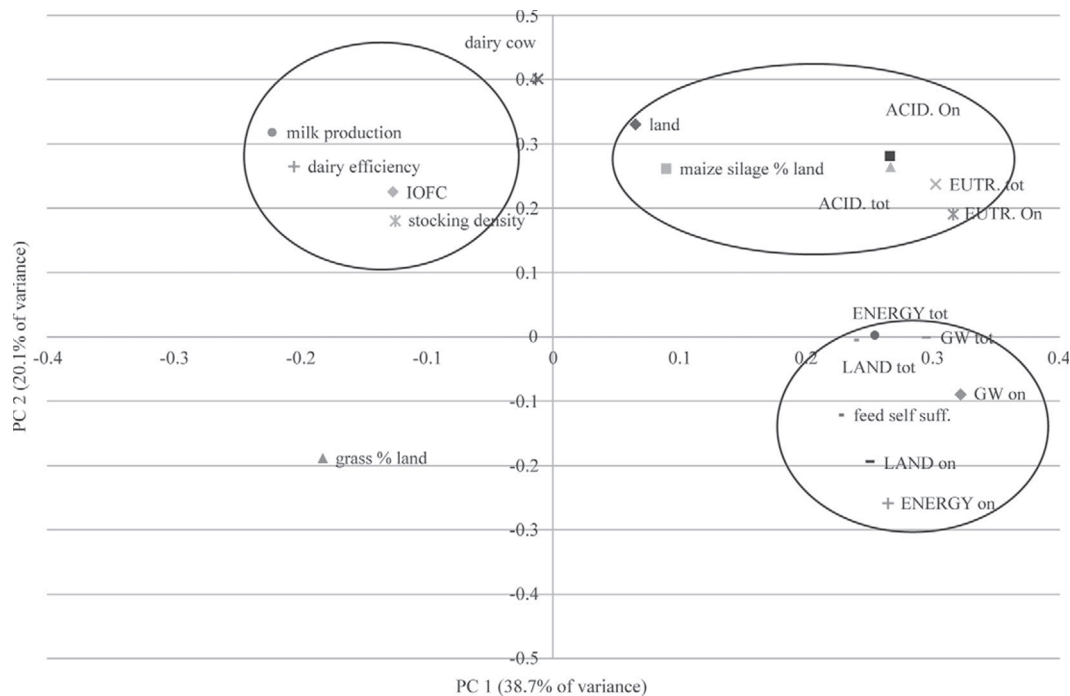


Figure 3. Principal component analysis (environmental impact expressed per kilogram of fat- and protein-corrected milk). PC = principal component; GW = global warming (kg of CO₂ equivalents); EUTR = eutrophication (g of PO₄ equivalents); ACID = acidification (g of SO₂ equivalents); LAND = land use (m²); ENERGY = energy use (MJ); tot = total impact; on = on-farm fraction of impact; IOFC = income over feed cost (€/cow per day);

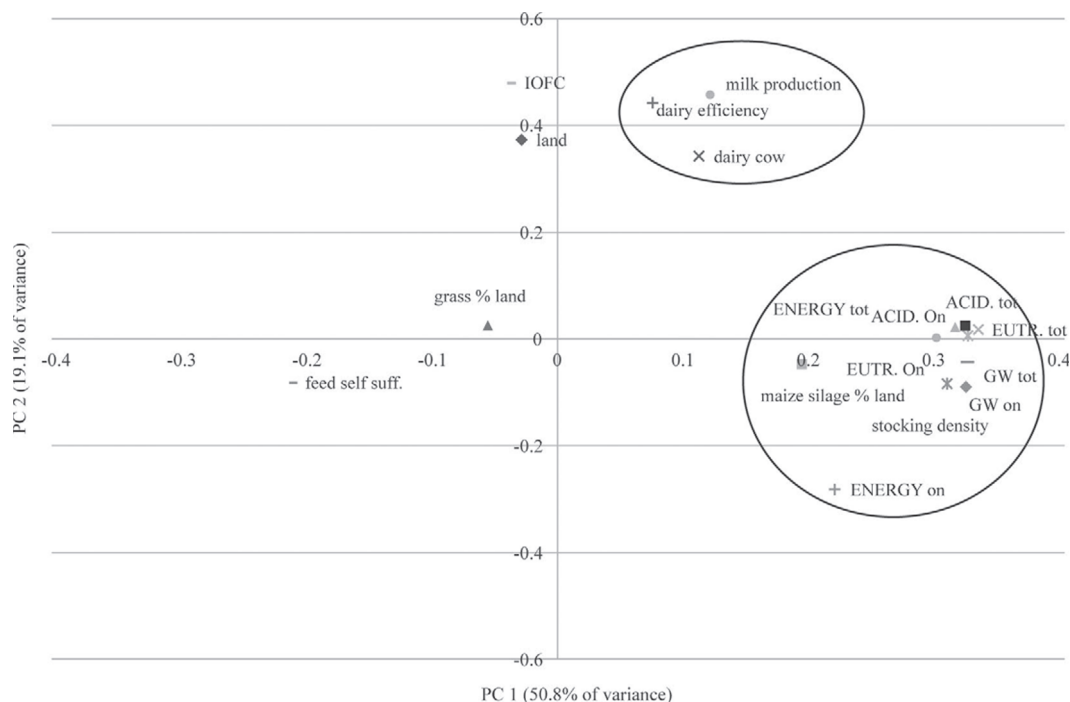


Figure 4. Principal component analysis (environmental impact expressed per hectare of farm land). PC = principal component; GW = global warming (kg of CO₂ equivalents); eutrophication (g of PO₄ equivalents); ACID = acidification (g of SO₂ equivalents); ENERGY = energy use (MJ); tot = total impact; on = on-farm fraction of impact.

Table 6. Eigenvectors corresponding to the principal components (PC) retained for the 28 dairy farms (impacts expressed per kilogram of fat- and protein-corrected milk; FPCM); the first 5 PC had eigenvalues greater than 1

Item	Unit	PC 1	PC 2	PC 3	PC 4	PC 5
Farm land	ha	0.07	0.33	0.29	0.00	-0.52
Maize land for silage	% land	0.09	0.26	-0.29	-0.25	0.07
Permanent grassland	% land	-0.18	-0.19	0.05	0.44	-0.07
Dairy cows	no.	-0.01	0.40	0.08	-0.02	-0.55
Stocking density	LU ¹ /ha	-0.13	0.18	-0.48	-0.03	-0.06
Milk production	kg of FPCM/cow per day	-0.22	0.32	0.17	0.12	0.27
Dairy efficiency	kg of milk/kg of DMI	-0.20	0.27	0.23	-0.01	0.33
Feed self-sufficiency	% of total feed DM	0.23	-0.12	0.26	-0.42	0.00
Global warming total	kg of CO ₂ -equivalent	0.30	0.00	-0.14	0.35	-0.06
Global warming on farm	kg of CO ₂ -equivalent	0.32	-0.09	-0.14	-0.03	-0.10
Acidification total	g of SO ₂ -equivalent	0.27	0.28	-0.08	0.07	0.17
Acidification on farm	g of SO ₂ -equivalent	0.27	0.27	-0.08	-0.04	0.15
Eutrophication total	g of PO ₄ -equivalent	0.30	0.24	-0.06	0.16	0.15
Eutrophication on farm	g of PO ₄ -equivalent	0.32	0.19	-0.04	-0.13	0.10
Energy use total	MJ	0.25	0.00	0.09	0.38	0.24
Energy use on farm	MJ	0.26	-0.26	0.05	-0.28	0.04
Land use total	m ²	0.24	-0.01	0.30	0.35	-0.09
Land use on farm	m ²	0.25	-0.20	0.34	-0.06	-0.03
IOFC ²	€/cow per day	-0.13	0.23	0.42	-0.16	0.23

¹LU = livestock units.²IOFC = income over feed cost.

stocking density, high milk yield per cow, high dairy efficiency, high use of concentrate and maize silage in the cow rations instead of grass hay. The second cluster (medium) consisted of 7 farms less intensive in comparison with the farms of first cluster. The third group (low) included 11 farms identified as the least intensive on the basis of their characteristics.

Total farm land was different among the 3 groups, with the highest value in the medium cluster and lower values in the others. The percentage of arable land of the low group was lower compared with the other 2

groups; high had the higher quota of land used to grow maize for silage in comparison with the low group. The number of livestock units showed the same trend among the groups observed for the farm land. Stocking rate was generally high; in the high group it was particularly elevated compared with the other groups. The milk production levels of high and medium were higher compared with low; similarly, the dairy efficiency, which is strongly related to the level of productivity, showed better results in high and medium farms. High farms had lower feed self-sufficiency compared with the

Table 7. Eigenvectors corresponding to the principal components (PC) retained for the 28 dairy farms (impacts expressed per hectare); the first 4 PC had eigenvalues greater than 1

Item	Unit	PC 1	PC 2	PC 3	PC 4
Farm land	ha	-0.03	0.37	0.35	-0.47
Maize land for silage	% land	0.20	-0.05	0.40	0.15
Permanent grassland	% land	-0.06	0.03	-0.58	-0.32
Dairy cows	LU ¹ /ha	0.11	0.34	0.30	-0.49
Stocking density	no.	0.31	-0.08	-0.08	-0.10
Milk production	kg of FPCM ² /cow per day	0.12	0.46	-0.20	0.17
Dairy efficiency	kg of milk/kg of DMI	0.08	0.44	-0.16	0.35
Feed self-sufficiency	% of total feed DM	-0.21	-0.08	0.41	0.25
Global warming total	kg of CO ₂ -equivalent	0.33	-0.04	-0.10	-0.09
Global warming on farm	kg of CO ₂ -equivalent	0.33	-0.09	-0.04	-0.08
Acidification total	g of SO ₂ -equivalent	0.33	0.03	0.03	0.05
Acidification on farm	g of SO ₂ -equivalent	0.32	0.02	0.06	0.06
Eutrophication total	g of PO ₄ -equivalent	0.34	0.02	0.02	0.01
Eutrophication on farm	g of PO ₄ -equivalent	0.33	0.01	0.11	0.05
Energy use total	MJ	0.30	0.00	-0.11	0.03
Energy use on farm	MJ	0.22	-0.28	0.10	0.18
IOFC ³	€/cow per day	-0.04	0.48	0.02	0.37

¹LU = livestock units.²FPCM = fat- and protein-corrected milk.³IOFC = income over feed cost

Table 8. Characteristics of the clusters

Item	Unit	Intensity level					
		High		Medium		Low	
		Mean	SD	Mean	SD	Mean	SD
Farm		10		7		11	
Farm land	ha	34.9	8.17	81.4	21	20	9.84
Arable crops	% of total land	54.1	17.4	61.7	20.2	34.5	25.6
Maize for silage	% of total land	45.7	18.6	38.5	13.3	26.9	22.5
Livestock unit (LU)	n	157	37.1	258	36.1	55	21.5
Stocking density	LU ¹ /ha	4.71	1.44	3.31	0.8	2.97	0.67
Daily milk production	kg of FPCM ² /cow	28.9	2.03	28.1	2.29	24.7	5.66
Production intensity	kg of FPCM/ha per year	25,917	9,043	17,771	4,875	15,439	4,668
Dry matter intake	kg/cow per day	21.22	1.3	21.2	1.92	12.0	2.12
Dairy efficiency	kg of milk/kg of DMI	1.36	0.16	1.33	0.07	1.22	0.18
Forage concentrate ratio		1.33	0.33	1.37	0.58	2.21	1.56
Maize silage intake	% DMI	30.41	6.84	34.7	3.04	22.75	17.3
Grass hay intake	% DMI	15.64	11.5	17.9	9.23	27.47	14.4
Feed self-sufficiency	% of total feed DM	54.63	10.4	69.2	12.5	71.72	14.4
IOFC ³	€/cow per day	5.96	1.23	6.76	0.82	5.78	1.27

¹LU = livestock units.

²FPCM = fat- and protein-corrected milk.

³IOFC = income over feed cost.

other groups which had similar values. Considering the economic performances, no differences were observed between the average IOFC of the 3 clusters.

Analyzing the environmental impact on the product basis, only few differences were observed among the groups, and overall they should be considered similar (Table 9). Low farms showed higher on-farm energy use compared with the high ones. High farms had lower on-farm land use impact compared with the other 2

groups, whereas low had lower off-farm land use than high and medium.

The results change widely if the environmental impacts are evaluated on land unit, as shown in Table 10. High had higher total environmental impact per hectare of farm land for all the categories in comparison to the other 2 groups, which were similar to each other. A similar trend was observed for on-farm GWP, acidification, and eutrophication, which were higher in high than in medium and low. No differences were found regarding on-farm energy use.

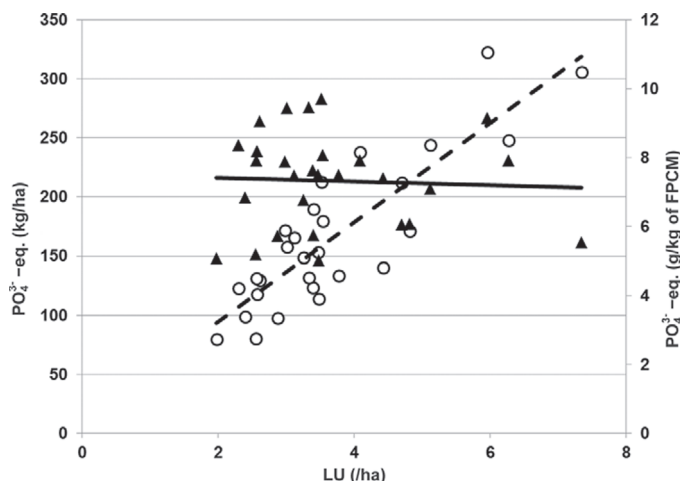


Figure 5. Relation between stocking density and eutrophication expressed per kilogram of fat- and protein-corrected milk (FPCM) and per hectare of farm land. Open circles (○) represent eutrophication per hectare and stocking density: $y = 42.025x + 10.561$; $R^2 = 0.74$. Triangles (▲) represent eutrophication per kilogram of FPCM and stocking density: $y = -0.0543x + 7.5317$; $R^2 = 0.0025$. LU = livestock unit.

DISCUSSION

Environmental Impacts of Milk Unit

The estimated GWP for the production of 1 kg of FPCM was comparable to the value found by Guerci et al. (2013) and in agreement with Castanheira et al. (2010), who similarly obtained a higher contribution of on-farm activities to GHG emission compared with off-farm activities. The acidification and the eutrophication potentials were similar to Castanheira et al. (2010), but higher compared with findings reported by O'Brien et al. (2012) and Basset-Mens et al. (2009). Total nonrenewable energy use was consistent with the results reported by Thomassen et al. (2008) for conventional Dutch dairy farms. Considering land use, the total impact and on-farm contribution were similar to O'Brien et al. (2012) and Basset-Mens et al. (2009). The contributions of the different substances to GWP were comparable with Castanheira et al. (2010).

Table 9. Environmental impacts expressed per kilogram of fat- and protein-corrected milk corresponding to each cluster of farms

Item	Location	Intensity level					
		High		Medium		Low	
		Mean	SD	Mean	SD	Mean	SD
Global warming (kg of CO ₂ -equivalent)	Total	1.26	0.17	1.27	0.13	1.25	0.21
	On farm	0.90	0.13	0.95	0.09	0.96	0.21
	Off farm	0.36	0.09	0.32	0.08	0.29	0.13
Acidification (g of SO ₂ -equivalent)	Total	16.0	3.07	16.2	4.05	13.9	2.91
	On farm	13.9	2.79	14.3	4.24	12.0	2.89
	Off farm	2.13	0.51	1.94	0.48	1.86	1.09
Eutrophication (g of PO ₄ -equivalent)	Total	7.59	1.24	7.71	1.10	6.86	1.63
	On farm	5.45	0.82	5.96	1.38	5.23	1.65
	Off farm	2.14	0.56	1.75	0.51	1.63	0.74
Energy use (MJ)	Total	5.44	1.17	5.44	0.66	5.51	0.80
	On farm	2.00	0.42	2.19	0.38	2.77	0.91
	Off farm	3.44	0.98	3.25	0.54	2.74	1.01
Land use (m ²)	Total	0.89	0.16	1.02	0.18	0.97	0.14
	On farm	0.44	0.13	0.59	0.14	0.64	0.14
	Off farm	0.45	0.09	0.43	0.11	0.32	0.13

Similarly, several other studies reported CH₄ to be the predominant contributor to the total climate change emissions (Flysjö et al., 2011; Kristensen et al., 2011; O'Brien et al., 2012), whereas Thomassen et al. (2008) found a methane contribution to total climate change of only 34% in the conventional system and of 43% in the organic system. Enteric methane is generally recognized as the major driver of GHG emissions in milk production, and the abatement of enterically derived CH₄ is considered one of the most promising strategies for the reduction of GHG emissions from the dairy sector (Mc Geough et al., 2012).

The main contribution of ammonia to total acidification potential was found also by Thomassen et al. (2008) and Castanheira et al. (2010), who observed that NH₃ emissions have a strong impact on the total acidification potential, whereas SO₂ and NO_x play a

minor role. Castanheira et al. (2010) reported NH₃ and NO₃ as the major contributors to total eutrophication potential, whereas Thomassen et al. (2008) found phosphate to be more important in terms of impact on eutrophication. In the study of O'Brien et al. (2012), nitrate losses occurring on-farm were around 90% for the seasonal grass-based dairy system, but only about 30% for the confinement dairy system.

Interaction Between Farm Characteristics and Environmental Impact

The negative relationships shown by the PCA between total environmental impact per milk unit, on one side, and dairy efficiency and milk production level, on the other, are in agreement with numerous results from the literature. In fact, feed conversion efficiency of the

Table 10. Environmental impacts expressed per hectare corresponding to each cluster of farms

Item	Location	Intensity level					
		High		Medium		Low	
		Mean	SD	Mean	SD	Mean	SD
Global warming (kg of CO ₂ -equivalent)	Total	36,269	10,026	26,094	8,130	22,475	5,907
	On farm	25,992	7,500	19,384	5,542	16,935	3,618
	Off farm	10,277	3,088	6,711	2,845	5,540	3,442
Acidification (g of SO ₂ -equivalent)	Total	464	154	316	56	252	85.5
	On farm	404	141	276	63.5	216	66.6
	Off farm	60.0	17.8	40.2	18.2	36.2	28.6
Eutrophication (g of PO ₄ -equivalent)	Total	218	65.6	155	31.6	123	35.0
	On farm	158	51.7	118	22.6	92.0	24.5
	Off farm	60.3	18.2	37.1	19.8	30.7	18.3
Energy use (MJ)	Total	152,327	36,184	111,278	32,997	99,317	26,930
	On farm	56,063	12,714	43,844	8,653	47,436	10,663
	Off farm	96,264	28,116	67,434	26,867	51,881	30,655

animals is known to be an effective strategy in mitigating the environmental impact per unit of product (Hermansen and Kristensen, 2011; Yan et al., 2013); according to Capper et al. (2008), a general increase in productivity might positively affect the environmental sustainability of milk. Guerci et al. (2013) showed that farming strategies based on high production intensity and high dairy efficiency could mitigate environmental impact per kilogram of milk. The mitigation effect of enhancing dairy efficiency is based on the dilution of environmental costs associated with maintenance. Moreover high-producing cows usually receive low-fiber rations, reducing their methane emission per kilogram of milk.

The negative correlation between stocking density and total impact (per kilogram of FPCM) is a little surprising, especially when eutrophication and acidification potentials are considered. But farms with high stocking density were also characterized by high production levels and high dairy efficiency.

Grassland, instead of arable land, seemed to have a positive effect on the environmental impact, but its role was not clear due to the opposite effects of many factors. Generally grassland needs less fertilization than arable land and this has positive effects on GWP, eutrophication, and acidification, but arable crops (e.g., maize silage) have higher yield per hectare and require less field operations and less energy compared with grass hay production (Rotz et al., 2010).

Profitability, expressed as IOFC, shows a negative relationship with total environmental impact per kilogram of FPCM. Farms with cows more efficient in converting feed to milk have higher income per cow and lower impacts per milk unit.

Regarding environmental impact per hectare of land, PCA showed that the farm management characteristics mostly related to the different impact categories were stocking density and percentage of land for maize silage production. High LU per hectare means a high quantity of organic nitrogen on soil and low feed self-sufficiency. With respect to percentage of land for maize silage production, its positive relationship with environmental impact per hectare depends mainly on the high demand of maize in terms of nitrogen application (organic and chemical), which is positively related to environmental impact per unit of land, as found by Casey and Holden (2005).

Farming Intensity and Environmental Performances

The current study did not show any difference between the environmental impact per milk unit of the 3 clusters of farms, despite important differences among the groups in terms of farm characteristics and farming

intensity. On the contrary, when the functional unit was the hectare of farm land, most of the impacts were much higher in the group of farms with high intensity levels. In general, intensification, defined as increased output per hectare, invariably led to increased emissions when expressed on an area basis; however, the result was less obvious when expressed on a product basis (Crosson et al., 2011). Basset-Mens et al. (2009) highlighted better environmental performances for the low-input dairy systems compared with more intensive systems from both a product and local perspective; similar results were obtained by O'Brien et al. (2012) for a grass-based farm versus a confinement system. van der Werf et al. (2009) observed no difference in terms of environmental impact between conventional and organic dairy systems when milk sold was considered as functional unit; however, on a land basis, the conventional systems showed a significantly higher environmental burden compared with the organic systems. Similar results were found by Haas et al. (2001), who reported significantly worse environmental performances in the intensive system than in the extensive system when the impact was expressed on land unit. Casey and Holden (2005) found a significant positive linear correlation between stocking rate and the amount of CO₂-equivalent per hectare, but no relationship between stocking rate and GHG emissions per kilogram of milk. Similarly, Oudshoorn et al. (2011) found that no correlation between surplus N per hectare and emission of GHG per kilogram of ECM existed.

As a consequence, when the environmental impacts related to the product unit are considered, the identification of the more sustainable production strategy seems to be difficult. Several studies compared organic versus conventional farms or grass-based versus confined farms; some authors attributed better environmental performances to the low-input systems (Belflower et al., 2012; O'Brien et al., 2012), others associated the more intensive systems with a potential reduction of the environmental pressure (Thomassen et al., 2008; Kristensen et al., 2011), still other researchers reported different results depending on the impact category considered (Cederberg and Mattsson, 2000).

CONCLUSIONS

When assessing the environmental impact per milk unit, it is difficult to clearly identify the relationship between farming intensity and environmental performances, despite important differences in terms of farm intensification level, management, and structural characteristics. However, the PCA showed that some characteristics related to farming intensification, particularly milk production per cow, dairy efficiency, and

stocking density, were negatively related to the impact per kilogram of product; this suggests a role of these factors in the mitigation strategy of the environmental impact of milk production on a global scale. Besides an important role in global environmental impact (i.e., climate change), livestock systems are often responsible for local and not less important impacts (i.e., eutrophication of soils and water). Considering the environmental burden on a local perspective, the impacts were positively associated with the intensification level.

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