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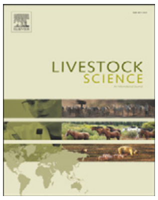

Productivity gains and greenhouse gas emissions intensity in dairy systems[☆]

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ABSTRACT

This paper explores the relationship between productivity of dairy production and greenhouse gas (GHG) emissions on a global scale. A Life Cycle Assessment (LCA) methodology was used to assess GHG emissions from dairy production and processing chains. Milk yield expressed as kg fat and protein corrected milk (FPCM) per animal was chosen as a proxy for system productivity. On a per cow basis, GHG emissions increase with higher yields. However, GHG emissions per kg FPCM decline substantially as animal productivity increases. The contribution of different gases to total GHG emissions of dairy production systems vary; methane and nitrous oxide emissions decrease with increasing productivity, while carbon dioxide emissions increase, but on a lower scale. Productivity increase therefore offers not only a pathway to satisfying increasing demand for milk but also a viable mitigation approach, especially in areas where milk yields are currently below 2000 kg/cow and year.

1. Introduction

Global production of meat, milk and eggs has expanded rapidly during the last decades, in particular in developing countries (FAO, 2009). Economic growth, rising incomes, urbanization and population growth have been major drivers of sector growth. Livestock will continue to be the most dynamic agricultural sub-sector: global production of milk is projected to increase from 580 to 1043 million tonnes in 2050 (FAO, 2006a).

Animal production systems are important and complex sources of greenhouse gas (GHG) emissions, notably methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Concerns over the contribution of the livestock sector to climate change have led to a plethora of scientific studies aimed at improving the scientific knowledge regarding the sector's emissions, at global (FAO, 2006b, 2010) and national (Dalgaard et al., 2007; Garnett, 2007; Kool et al., 2009) levels as well as locally (de Vries and de Boer, 2009; Mills et al., 2003).

Following a comprehensive food chain approach by including emissions occurring at the input level (feed production and processing, land use change) and those related to processing and transportation, the global livestock sector is estimated to contribute approximately 18% (7.1 billion tonnes of CO_2 equivalent) of total greenhouse gas emissions (FAO, 2006b). GHG emissions from livestock systems are expected to rise over the coming decades due to the projected increase in demand for livestock products (FAO, 2009).

Dairy is an important part of the livestock sector, producing globally about 553 million tonnes of milk in 2007 (FAOSTAT, 2010) and 34 million tonnes of meat from the dairy related herd (FAO, 2010). It is also rapidly developing: raw milk production increased by 44% between 1980 and 2007, with most of the growth taking place in South Asia (FAO, 2009); in volume terms, the production of dairy commodities (e.g. butter, cheese and milk powder) is expected to grow by 20 to 30% between 2008 and 2019 (OECD-FAO, 2010).

A global Life Cycle Assessment (LCA) of the cattle dairy sector revealed that in 2007 the sector emitted 1 969 million tonnes CO_2-eq of which 1328 million tonnes were attributed to milk, 151 million tonnes to meat from culled animals and 490 million -tonnes to meat from surplus calves. Thus, the overall contribution of milk production, including processing and transportation of

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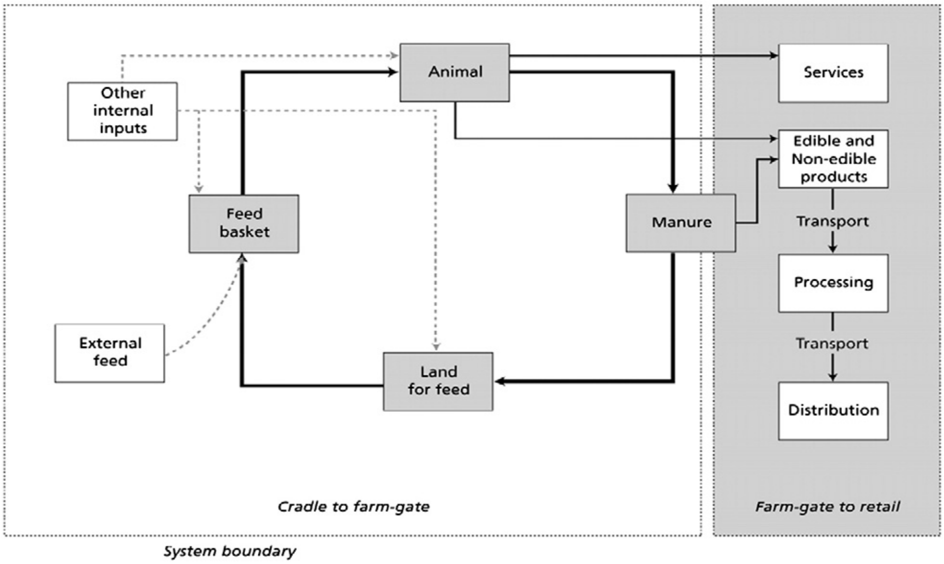

Fig. 1. System boundary as defined for this assessment.

milk and milk products and meat from the dairy herd to total anthropogenic GHG emissions is estimated at 4.0% (±26%). The contribution of the global milk production, processing and transportation to total anthropogenic emissions is therefore given at 2.7% (FAO, 2010) of the total anthropogenic GHG emissions reported by IPCC (2007). Dairy chains also contribute to other environmental issues, notably water resource management, through withdrawals, modification of runoff and release of pollutants.

Emissions per unit of milk product vary greatly among different regions; with emissions from Europe and North America ranging between 1 and 2 kg CO_2-eq per kg FPCM at the farm gate. The highest emissions are estimated for sub-Saharan Africa with an average of 7.5 CO_2-eq per kg FPCM at the farm gate. GHG emissions for South Asian, West Asian and North African and Central and South American countries ranged between 3 and 5 kg CO_2-eq per kg FPCM at the farm gate. The global average is estimated at 2.4 kg CO_2-eq (FAO, 2010).

Methane emissions are by far the largest contributor to the GHG profile of the cattle dairy sector; accounting for about 52% of the total CO_2-eq. from the sector. Nitrous oxide emissions account for 27 and 38% of the GHG emissions in developing and developed countries, respectively, while CO_2 emissions account for a higher share of emissions in developed countries (21%), compared to developing countries (10%).

Improvements in livestock productivity have been locally shown to have resulted into reduced (direct) emission intensity (described as CO_2 eq per physical unit of output) while allowing to meet increasing demand, with large absolute reduction in ruminant production (Capper et al., 2009; European Comission, 2005). Such productivity gains were achieved through the introduction of a combination of production and management practices that increase yields; notably through increased and improved use of inputs such as feed and related fertilizer use, genetic material, animal health inputs and energy.

This paper examines the relationship between productivity of dairy production and emission intensity on a global scale, and whether productivity growth could be a viable climate change mitigation strategy. Results are discussed in a broader development context with a view to identify concrete mitigation options.

2. Materials and methods

2.1. Methodology

The concerns about global climate change have given rise to a large research effort into assessing different emission sources and processes, and identifying mitigation options. This includes the analysis of emissions associated with the production and use of different products or commodities. For livestock commodities, the Life Cycle Assessment (LCA) approach has been frequently used to determine emission intensity and to identify suitable mitigation. (Casey and Holden, 2005; Cederberg and Mattsson, 2000; Dalgaard et al., 2007; de Boer, 2003; de Vries and de Boer, 2009; FAO, 2006b, 2010; Garnett, 2007; Kool et al., 2009; Thomassen et al., 2008a). The main strengths of LCA lie in its ability to provide a comprehensive assessment of production processes. The approach also provides a framework to identify effective strategies to reduce environmental burdens, avoiding those that simply shift environmental problems from one phase of the life cycle to another (ISO, 2006).

Although the principles of LCA are well defined (ISO, 2006), previous studies vary considerably in their level of detail, their definition of system boundaries, the emission factors applied, and other technical aspects such as the allocation techniques and functional units they employ. The analysis presented here uses the attributional LCA method[1] and database developed by FAO (2010).

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[1] The attributional LCA method is a static approach that estimates the environmental burden of a production chain under constant production and market conditions, and allocates impacts to the various co-products of the production system using “attribution techniques”. This is in contrast to the consequential LCA approach, which considers potential consequences of changes in production technologies, and relies on a system expansion analysis to allocate impacts of co-products (Thomassen et al., 2008b).

The system boundary is defined by GHG emissions associated with milk production from 'cradle to retail'. Fig. 1 illustrates the limits of the system studied and includes: (i) emissions associated with the production, transportation and processing of feed; (ii) emissions associated with fertilizer production, transport and application; (iii) emissions associated with livestock production and manure management; (iv) emissions associated with energy use for operations in feed and livestock production; (v) emissions related to land use change ; and (vi) emissions related to processing and transport of product from farm to processing point and to retailer.

In coherence with IPCC guidelines (2006), emissions related to land use under constant management practices are excluded from the analysis. Also omitted are emissions from production of capital goods (buildings and equipment, roads, etc.), and the production of cleaning agents, antibiotics, and pharmaceuticals which can be considered to be minor.

In this assessment, the functional unit used to report GHG emissions is defined as 1 kg of CO_2 equivalents per kg of fat and protein corrected milk (FPCM), at farm gate. FPCM was determined as introduced in Eq. (1).

$$\mathrm{FPCM(kg)} = M(\mathrm{kg})^{*}\{0.337 + 0.116 * FC(\%) + 0.06 * PC(\%)\} \tag{1}$$

where *M* is the mass of raw milk (kg), *FC* is the fat content (%) and PC is the protein content. All milk was converted to FPCM with 4.0% fat and 3.3% protein.

Post-farm gate emissions are related to a kg of FPCM equivalent at farm-gate and not estimated for each processed dairy product. Emissions related to the processing, the production of packaging material and transport for the various dairy products are presented on the basis of an average kilogram of FPCM at the farm gate, i.e. emissions taking place after farm gate are attributed back to the milk leaving the farm.

Milk production generates more than one functional output; in addition to milk there is meat (from culled cows and surplus calves). Consequently, a part of the total emissions from dairy production needs to be allocated not to milk but to meat. A number of options exist to apportion that part (ISO, 2006); for the present analysis, the allocation is based on the proportion of overall protein mass found in each product, rather than on economic criteria, such as value of output. (Casey and Holden, 2005; Cederberg and Stadig, 2003; Thomassen et al., 2008a). The choice of protein mass as the allocation criterion reflects the primary function of the dairy sector, which is to provide humans with edible high-value protein. The approach also facilitates the comparison with other food products and can also be applied in situations where markets are absent. FAO (2010) in an evaluation of the effect of different allocation approaches on the partitioning of emissions between milk and meat found that the choice of different criteria did not result into much different outcomes.

The global warming potential (GWP) index was used to determine the contribution to the GHG effect. Based on the IPCC 4th Assessment Report (IPCC, 2007), the characterization factors of GWP_{100}, which correspond to the CO_2 equivalent emission for a period of 100 years, were 1, 25 and 298 for CO_2, CH_4 and N_2O, respectively.

Emissions were estimated using Tier 2 level values with all calculations based on the IPCC guidelines (IPCC, 2006). We only display here the equation used for enteric methane (Eq. (2)).

$$\mathrm{EF} = \mathrm{GE} * (\mathrm{Y_m} / 100) * 365 / 55.65 \tag{2}$$

where *EF* is the methane emission factor (kg CH_4 per head per year), *GE* is the gross energy intake (MJ per head per day), Y_m is the methane conversion factor, percent of gross energy in feed converted to methane and the factor 55.65 (MJ per kg CH_4) is the energy content of methane.

The IPCC (2006) defines the methane conversion factor (Y_m) as $6.5 \pm 1\%$, indicating that Y_m is at the high end of the range when digestibility of feed is low and at vice versa. Considering the wide range in feed digestibility all over the world we developed Eq. (3):

$$\mathrm{Y_m} = 9.75 - 0.05 * \text{Digestibility rate of feed} \tag{3}$$

2.2. Model description

Based on previous models developed (Del Prado and Scholefield, 2008; Oenema et al., 2005; Schils et al., 2007), a specific dairy chain model was developed, integrating cradle to farm gate and farm gate to retail activities. The model consists of 4 sub-modules: a herd demography module, feed basket module, emissions module and allocation module. Compared to previous studies, two methodological innovations have been introduced to deal with the shortage of global datasets. First, a herd module computes the "dairy related stock" consisting of the animals required to maintain a population of milking cows and surplus calves that will be fattened for meat production. Second, a feed basket module links feed resources available in the vicinity of the production unit with animal numbers and productivity, establishing consistency of feed supply and requirement data. These components model the biological process of livestock production and allow one to compute productivity and input use, as well as providing the basis for the estimation of emissions at various steps. In addition, module links support the mutual consistency among production parameters such as reproduction and herd size, feed intake and milk yields. The conceptual framework of the model is shown in Fig. 1.

The description of the model provided herein is restricted to the salient features of the model; a detailed description of the model can be found in FAO (2010).

2.3. Database and data sources

The input data were obtained from different sources: from statistical databases (FAOSTAT, IFPRI), gray literature (from CGIAR research institutes, national inventory reports submitted to UNFCCC, etc.), peer-reviewed journals, as well as personal communications from experts in relevant fields. Running of the LCA model required the development of a global database on: herd dynamics (fertility, death rate, growth, etc.), feed (composition, utilization, quality), manure management systems, crop yield and land use, etc. To include spatial heterogeneity in the analysis, both at the level of data management and at the level of calculation, GIS was used in the assessment to create the

Table 1
Animal parameters used in the assessment for dairy cows.
Sources: FAO, 2010.

Parameters	North America	Central and South America	Western Europe	Eastern Europe	Russian Federation	Near East and North America	Sub-saharan Africa	South and Southeast Asia[a]	South and Southeast Asia[b]	Oceania
Weights (kg)										
Adult cow	700	565	570	538	500	259	231	296	613	467
Adult bull	863	735	741	699	650	343	301	398	776	607
Calve at birth	41	38	38	36	33	20	20	20	39	31
Slaughter female	583	550	535	532	530	259	231	296	540	403
Slaughter male	607	550	535	532	530	309	301	296	552	403
Other parameters										
Replacement rate for adult cow (%)	34	24	30	29	31	13	10	21	31	22
Fertility rate (%)	77	79	83	83	83	64	57	75	82	80
Death rate calves (%)	8	9	8	8	8	20	20	20	8	8
Death rate other animals (%)	3	2	4	4	4	7	7	8	4	4
Age at first calving (year)	2.1	2.6	2.2	2.2	2.3	3.8	4.1	3.4	2.2	2.1
Production (kg/cow/year)										
Milk yield	8903	1665	6148	3805	3000	1142	363	967	2796	4246

[a] Unspecialized dairy systems.
[b] Specialized dairy systems.

database and develop the calculation model. Detailed data sources and main features of data are described by FAO (2010).

Main animal production parameters, including animal characteristics, herd dynamics, milk yield, manure management, feed composition and feed digestibility are reported in Tables 1 to 5.

Productivity in milk production is highly variable among production systems and world regions as reflected in the huge disparity in milk yields per animal (Fig. 2). The highest average milk yields per animal can be found in industrialized countries in North America, Europe and Oceania where production is highly specialized and dependant on inputs mostly sourced outside the production unit. On the other hand developing regions such as sub-Saharan Africa, South Asia, Central and South America and the Near East and North Africa are typified by very low to intermediate yield levels per animal.

Differences in milk yield are largely explained by variations in feed supply and quality, genetic material and management practices. Herd parameters (fertility, replacement rates, death rates and age at first calving) and feed characteristics (nutrient content, and digestibility) have a strong impact on productivity.

3. Results

Results were calculated for the 155 countries in the database.

3.1. GHG emissions per cow

An improvement in animal productivity was found to positively correlate with GHG emissions per animal ($r^2 = 0.79$; Fig. 3). This is because higher productivity is usually associated with larger animals and higher feed intake. However, percentage increases in emissions per animal are much lower than percentage increases in productivity.

Looking at single gases (Fig. 4), methane and carbon dioxide emissions are significantly and positively correlated with output per cow ($r^2 = 0.72$ and $r^2 = 0.84$, respectively), while nitrous oxide emissions increased with yield, but not significantly ($r^2 = 0.11$). Methane emissions (Fig. 4a) grow at diminishing pace, although countries with highest yields are above the emission intensities curve. A possible explanation may be that the effect of feed quality improvements on digestibility and thus emission intensity is less pronounced at the high end of the productivity scale. Carbon dioxide emission intensity (Fig. 4c) grows linearly with yields, as production systems increasingly depend on external inputs and fossil energy.

3.2. GHG emissions per kg of milk

A significant relationship was found between milk production per cow and total greenhouse gas emissions per kilogram

Table 2
Average manure storage systems.
Sources: FAO, 2010.

	N. America	CSA	W. Europe	E. Europe	Russian Federation	NENA	SSA	South Asia	East Asia	Oceania
Lagoon	12	0	0	0	0	0	0	0	0	4
Liquid/slurry	32	0	38	22	0	2	0	4	4	0
Solid storage	31	29	36	61	78	29	32	26	26	0
Drylot	0	19	0	0	0	20	21	18	18	0
Pasture/range	16	52	22	14	22	48	47	48	48	94
Daily spread	9	0	4	3	0	0	0	0	0	2

Table 3
Regional variations in average digestibility of fresh and conserved grass and grass legume mixtures.
Sources: FAO, 2010.

Feed quality	Average digestibility of fresh grass and grass legume mixtures (%)	Average digestibility of conserved grass and grass legume mixtures (%)
North America	68	58
Central and South America	64	54
Western Europe	75	71
Eastern Europe	70	65
Russian Federation	70	65
West Asia and North Africa	64	54
Sub-Saharan Africa	64	54
South Asia	64	54
East Asia	64	54
Oceania	70	65

of milk (Fig. 5). Emissions steeply decrease as productivity increases till 2000 kg FPCM per cow per year; from 12 kg CO_2-eq/kg FPCM to about 3 kg CO_2-eq/kg FPCM. We then observe a slower reduction of emission as productivity increases to about 6000 kg FPCM per cow per year. At this value, emissions stabilize between 1.6 and 1.8 kg CO_2-eq/kg FPCM. The asymptotic relation between emissions and yield is given by Eq. (4). The model explains 89.3% of the variance and gives an asymptotic value of emissions of 1.37 kg CO_2-eq/kg FPCM.

$$\ln(\mathrm{GHG}) = 0.3174 + 2.3837 * \left(0.9993320^{\mathrm{YIELD}}\right) \tag{4}$$

Table 4
Estimated average digestibility of feed ingredients.
Sources: FAO, 2010.

Feed component	Digestibility (%)
Whole plant silage grains	59
Whole plant silage maize	75
Rice straw	43
Wheat straw	45
Barley straw	46
Maize stover	55
Millet stover	40
Sorghum stover	49
Sugarcane tops	61
Leaves from trees	68
Fodder beet	80
Grains (wheat, barley)	86
Corn (maize)	92
Soy meal	93
Rapeseed meal	75
Cottonseed meal	78
Palm kernel expeller	67
Maize gluten meal	92
Maize gluten feed	82
Beet pulp	81
Molasses (beet and cane)	80
Grain by-products dry (brans)	73
Grain by-products wet (brewers grains)	78

where:GHG expresses the total CO_2, N_2O and CH_4 emissions, in CO_2-eq and YIELD is the output per cow, in kg FPCM yr^{-1}.

An analysis of the individual GHG emissions revealed a statistically significant relationship between CH_4 and N_2O emissions per kg FPCM and milk production per animal, with r^2 values of 0.97 and of 0.82, respectively (Fig. 6). Trends are similar to the ones described above for total GHG emissions. Carbon dioxide emissions are relatively constant, with more variation in carbon dioxide emission intensity in production systems of low productivity than in systems of high productivity. No significant correlation was however established between carbon dioxide emissions and yields.

We also analyzed the relative share of the three gases to total GHG emissions, in relation to milk productivity (Table 6). The share of CO_2 in total emissions increases with productivity gains. This trend reflects the increased use of inputs whose production requires fossil fuel, notably high value feed. Symmetrically, the share of methane and nitrous oxide emission tend to reduce as productivity increases — as previously described (Fig. 4a), we observe a methane emission rise at the highest end of the productivity scale.

4. Discussion

The LCA approach was used to gain insights into the relationship between dairy productivity and GHG emission intensity on a global scale. While improving animal productivity results in increased GHG emissions per animal, the high milk response rate results in a trend of decreasing net emissions per kilogram of milk. There are four main reasons for the reduction in emissions per unit of milk produced (Capper et al., 2009; FAO, 2010).

First, the higher quality of animal diets in intensive systems: the diets of higher yielding animals usually contain more concentrates and less roughage and hence have a higher digestibility. This contributes to reducing enteric methane production.

Second, as production intensifies, an increasing proportion of feed energy and proteins is being used for productive purposes, thereby spreading the emissions associated with herd replacement and animal maintenance over a larger amount of production.

Third, nitrogen use efficiency generally improves with intensification. The protein and amino acid content of diets is optimized, resulting in relatively lower amounts of nitrogen excreted in feces and urines and thereby reducing N_2O emission per kg of milk.

Fourth, emissions taking place on the production site, and in particular methane emissions from enteric fermentation generally account for most of emissions along the chains.

These results are in line with previous case studies. Capper et al. (2009), in a study comparing the environmental impacts of dairy production in 1944 and 2007 in USA found that modern dairy practices require considerably fewer resources than dairying in 1944 with 21% of animals, 23% of feedstuffs, 35% of the water and only 10% of the land required to produce the same one billion kg of milk. These trends result in lower GHG emission intensity in 2007, compared to 1944; the carbon footprint per billion kg of milk produced in 2007 was 37% of equivalent milk production in 1944 (3.66 kg CO_2 eq/kg milk versus 1.35 kg CO_2 eq/kg milk). This result is also similar to our

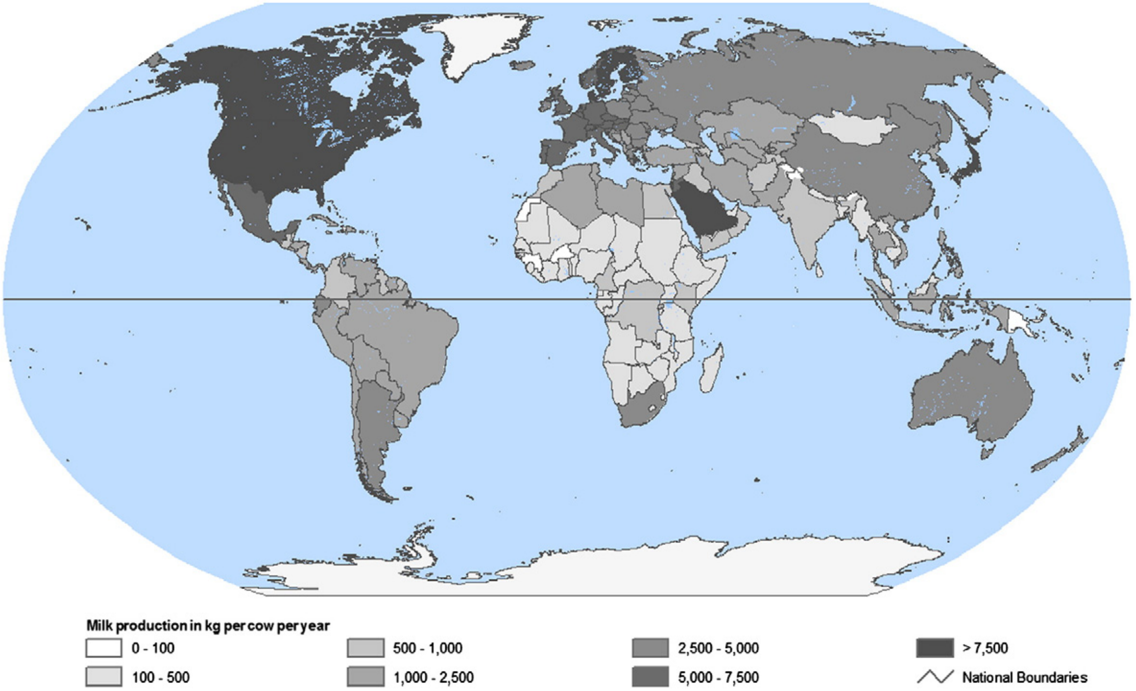

Fig. 2. Average annual milk production per cow and country (source: ?).

computation of GHG emission intensity, which averages at ca. 1.2 kg CO_2 eq/kg FPCM for North America. Other studies have also observed that more intensive dairy production generally decreases the methane production per unit of milk produced (Casey and Holden, 2005; Dragosits et al., 2008; Martin and Seeland, 1999). Rotz et al. (1999) showed that on a simulated dairy farm, a 20% increase in milk yield decreased volatile N loss per unit of milk produced by 12%. Although increased production often requires increased feed intake, the net result is less N intake and excretion per unit of milk produced.

Underlying hypotheses and methodological choices undoubtedly introduced a degree of uncertainty in the results. A sensitivity analysis conducted to test the effect of these approximations allowed the computation of a margin of error of ±26% at the 95% level of confidence within which the results are reported (FAO, 2010). Data quality is a further source of error that calls for a continuous effort to consolidate reliable databases.

While global milk production continuously increases, there still exist huge variations across countries and production systems. Across the world, but particularly in developing countries there is substantial scope for increasing milk productivity. These yield gaps are important when evaluating management strategies that can help reduce GHG emissions while at the same time meeting growing demand for dairy products. The results presented here suggest that, across all systems and regions, technical improvements targeting animal productivity simultaneously reduce GHG emissions intensity. Furthermore, they indicate that increasing yield is most effective in reducing emissions reduction at yields lower than ca. 2000 kg FPCM/cow and year. At a global level, this would suggest that emission reduction strategies targeting low productivity areas are

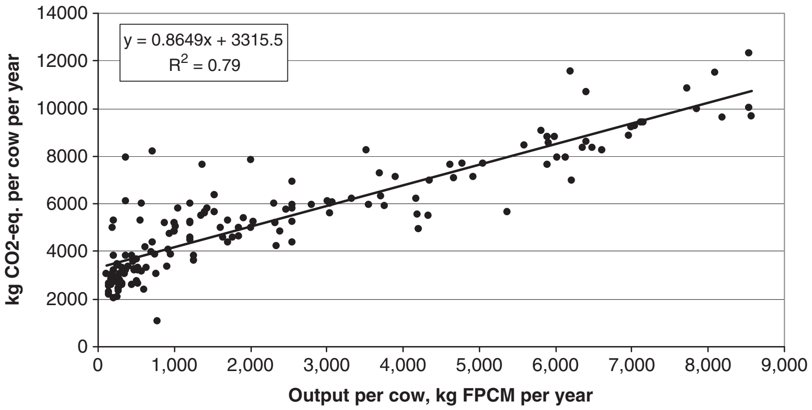

Fig. 3. Relationship between aggregated carbon dioxide, methane and nitrous oxide emissions and output per cow. Each dot represents a country in the database.

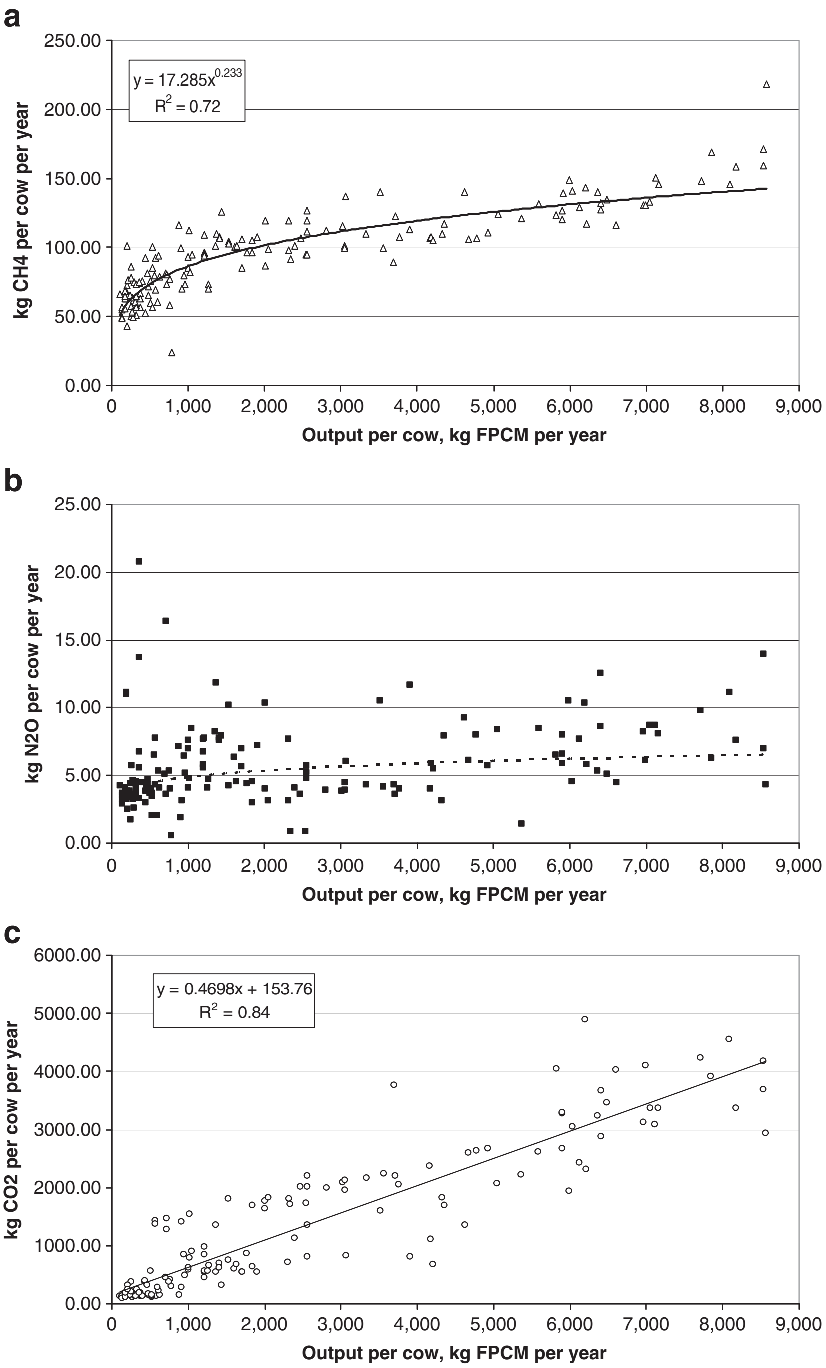

Fig. 4. Relationship between: a) methane emissions and output per cow; b) nitrous oxide emissions and output per cow; and c) carbon dioxide emissions and output per cow. Each dot represents a country in the database.

potentially the most cost-efficient in terms of mitigation. Costs and risks associated with upgrading productivity, including technology transfer, capital investment, access to markets and institution building would however need to be factored in for a complete analysis. They would probably exclude the less productive systems, facing major ecological and market access constraints.

The analysis also points to the most effective mitigation strategies subject to productivity level: methane and nitrous oxide emission reduction (feed quality, genetics, animal health) in low productivity systems and carbon dioxide emission reduction (energy efficiency) in highly productive systems — anaerobic digestion of wastes, not specifically included in this analysis was also reported as effective mitigation practice in Europe and North America. (Vellinga et al., 2011).

Our analysis focuses on GHG emissions, notably carbon dioxide, methane and nitrous oxide. It does not present a model

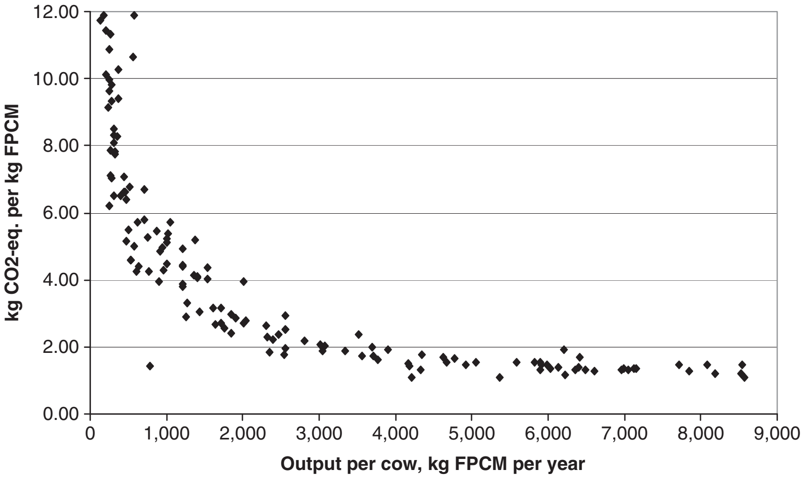

Fig. 5. Relationship between total greenhouse gas emissions and output per cow. Each dot represents a country in the database.

for estimating the full environmental impact from the dairy sector and the results regarding the relationship between productivity gains and GHG emission intensities should be evaluated in the framework of other environmental and societal issues. For example, while Capper et al. (2009) have shown the positive effects of intensification on GHG emissions in the US, other studies have shown negative effects of such trends on soil and water pollution as well as on social and health parameters. (Powell et al., 2010).

5. Conclusion

This paper aims to contribute to the debate on the impacts of livestock intensification on GHG emissions on a global scale. GHG emission intensity is found to be inversely related to productivity, reflecting the strong effect of increased efficiency and dilution of emissions across a larger volume of milk. The results point to considerable mitigation potential, especially for production systems characterized by low productivity (i.e., lower than 2000 kgFPCM/cow and year). There are important added benefits in terms of increased supply of high-value protein and enhanced rural income, of particular concern in developing countries with large smallholder populations. The possible combination of economic and environmental benefits stemming from productivity gains in dairy production suggests the presence of low cost mitigation options which warrant further analysis. However, care needs to be taken so that productivity gains occur within a context of greater overall environmental and social sustainability. They may carry unintended environmental consequences and increased risks that require to be addressed by specific policy frameworks.

Conflict of interest

The author(s) certify that they have no affiliation with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the manuscript (e.g., employment, consultancies, stock ownership, honoraria). The author's institutions have no financial or other relationship with other people or

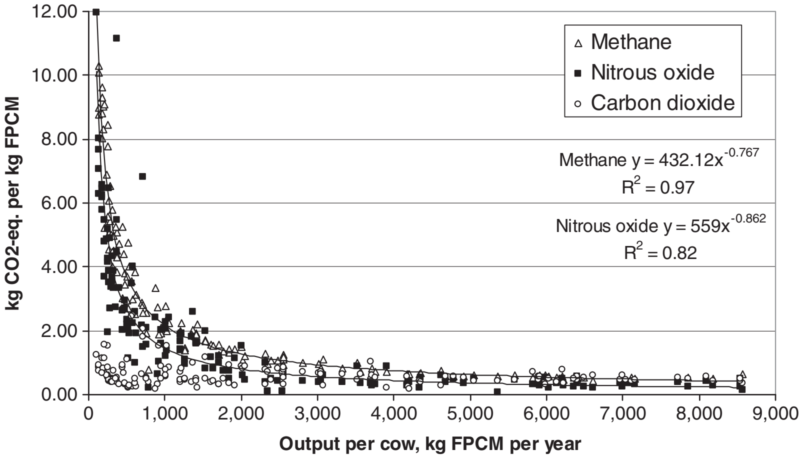

Fig. 6. Relationship between methane, nitrous oxide and carbon dioxide emissions and output per cow. Each dot represents a country in the database.

Table 5
Estimated concentrate feed composition, by FAO region.
Sources: FAO, 2010.

Component	North America	Central and South America	Europe	Africa	Asia	Oceania
Grains	30	50	40	50	50	90
Maize	20	20	20	20	20	0
Grain by products	15	5	2	5	5	0
Soy meal	5	10	13	10	10	5
Rape meal	15	0	13	0	0	0
Cottonseed meal	10	10	0	10	10	5
Maize gluten meal	5	5	12	5	5	0

Table 6
Fraction of methane, nitrous oxide and carbon dioxide in total GHG emissions, in relation to output per cow.

Output per cow per year (kg FPCM)	105 to 1000	1001 to 3000	3001 to 5000	5001 to 7000	7001 to 8570
Methane	0.52	0.50	0.47	0.38	0.47
Nitrous oxide	0.42	0.32	0.26	0.28	0.20
Carbon dioxide	0.06	0.18	0.27	0.35	0.33

organizations that may inappropriately influence the author's work. Any research or project support is identified in the 'Acknowledgments' section of the manuscript.

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