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Journal
Animal Production Science, 54(3)

ISSN
1836-0939

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Publication Date
2014

DOI
10.1071/an12327

Peer reviewed

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Animal Production Science
http://dx.doi.org/10.1071/AN12327

Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010

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Abstract. The objective of the present work was to estimate and assess trends in greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O), from dairy cows in Mexico from the base year of 1970 to 2010. Empirical and mechanistic models were used to estimate enteric methane emissions based on chemical composition of diets. Methane from manure was calculated using Intergovernmental Panel for Climate Change (IPCC) and US Environmental Protection Agency recommended equations. N_2O emission was calculated according to IPCC recommendations. Compared with the 1970s, current management practices using modern dairy cows increased feed conversion efficiency 32% and milk yield 62%. GHG emission intensity (i.e. emissions per unit of product) was reduced 30%, 25% and 30% for CH_4, N_2O and total emissions, respectively. The study showed that although GHG emissions in absolute terms increased in the past 40 years, emission intensity decreased due to higher level of production. This trend is likely to continue in the future, assuming milk production follows the same increasing trend as in other countries in North America.

Additional keywords: environmental impact, methane, milk production, nitrous oxide.

Received 19 September 2012, accepted 4 April 2013, published online 21 May 2013

Introduction

In Mexico, livestock activities use 110 million hectares, 28% of which are located in hot and humid areas, 23% in central part of the country and 49% in desert and semi-desert areas that are mainly devoted to poultry farming, swine breeding and production of bovine milk and meat (SEMARNAT–INE 2002). Bovine milk is one of the most in demand products in Mexico because it is considered to be a good source of energy and protein (Espinoza *et al.* 2005). The majority of milk is produced in the states of Coahuila, Durango, Jalisco, Estado de Mexico, Veracruz, Chihuahua, Querétaro, Guanajuato, Hidalgo and Aguascalientes (SIAP–SAGARPA 2008). Dairy production systems in the 1970s were based on grazed pasture and were characterised by low levels of low milk production (9.2 kg/day) (FAO 2012); in contrast, current intensive systems make better use of natural resources and minimise the intensity of greenhouse gas (GHG) emissions (i.e. emission per product) (Capper *et al.* 2008). Capper *et al.* (2009) reported that intensive systems are more efficient in utilising energy, which reduces environmental impact of dairy farming. Thus, recent research in animal science has been focussed on improving feed efficiency and other mitigation strategies to reduce emission intensity.

Direct measurement of GHGs such as methane (CH_4) and nitrous oxide (N_2O) is complex and requires expensive equipment. However, several simple empirical and more complex mechanistic models have been developed to estimate GHG emissions by dairy cattle. Mechanistic models allow prediction of CH_4 and N_2O emissions on the basis of type and amount of nutrient intake (Kebreab *et al.* 2006). In Mexico, there is a lack of studies in this field and the most recent GHG census was made using data from 1990–2002 (SEMARNAT–INE 2002). In the census, IPCC Tier I guidelines were used to calculate enteric CH_4 emissions. A fixed emission factor of 72 kg CH_4/year (applicable to all Latin American countries) was used, assuming annual milk production of 800 kg. The objective of the present work was to estimate and assess trends in CH_4 and N_2O emissions from the dairy cow population in Mexico from the base year of 1970 to 2010, by using mathematical models.

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Materials and methods

Data sources

Analysis of the environmental impact of dairy systems in Mexico was conducted on the basis of the methodology described by Capper *et al*. (2008, 2009) (Table 1), which requires estimates of herd size, milk production and milk yield (Fig. 1; FAO 2012). For this study, experiments that report dietary characteristics (Table 2) needed to run the models described below were chosen. Therefore, data from Cabello *et al*. (1971), Mendoza-Martínez *et al*. (1986), Plascencia-Jorquera *et al*. (1999), Ayala *et al*. (2001) and Weiss and Pinos-Rodríguez (2009) were obtained. Cow's nutritional requirements were calculated using the National Research Council recommendations (NRC 2001). Dairy cows were assumed to be managed under a confinement system. In the study, human population in Mexico and *per capita* consumption were also considered as variables affecting milk production and, consequentially, GHG emissions (CONAPO 2005; INEGI 2011).

Table 1. Characteristics of the dairy production systems in Mexico

Variable	1970	2010
Breed	90% Holstein^{A}	95% Holstein^{E}
Milk yield per cow (kg/year)	2800^{B}	4541^{B}
Lactation period (days)	305^{A}	305^{D}
Milk fat content (%)	3.50^{A}	3.31^{D}
Milk protein content (%)	4.00^{A}	3.04^{D}
Main forage source	Corn silage	Corn silage and alfalfa silage^{D}
Type of diet	Forage + concentrate^{C}	Total mixed rations^{D}

^{A}Saucedo (1984).
^{B}FAO (2012).
^{C}Cabello *et al*. (1971).
^{D}Pinos-Rodríguez *et al*. (2010).
^{E}SAGARPA (2010).

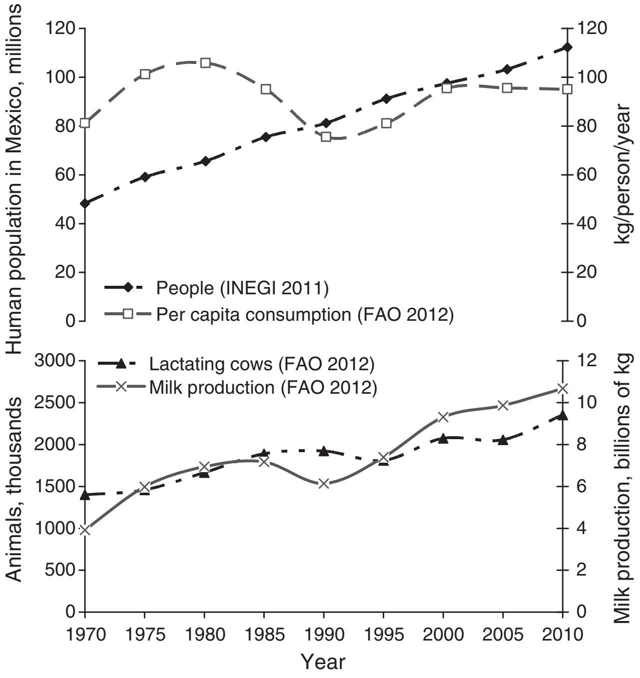

Fig. 1. Changes in the human population, *per capita* consumption, lactating cows and milk production in Mexico.

Mathematical models

To estimate enteric fermentation, three models were selected on the basis of input data requirement, their ease of application and widespread use to predict CH_4 emissions and also their potential relevance to Mexican dairy production system. Daily enteric CH_4 production was calculated using two empirical models (Moe and Tyrrell 1979; IPCC 2006) and a mechanistic model COWPOLL (based on Dijkstra *et al*. 1992).

Moe and Tyrrell equation

An empirical model of Moe and Tyrrell (1979) that takes into consideration the relationship between intake and diet composition was used to estimate CH_4 emissions. The model is described as follows:

$$\begin{aligned}\text{Methane (MJ/day)} &= 3.38 + 0.51\ \text{NFC (kg/day)}\\ &\quad + 2.14\ \text{HC (kg/day)} + 2.65\ \text{C (kg/day)},\end{aligned} \tag{1}$$

where NFC is non-fibre carbohydrate, HC is hemicellulose and C is cellulose.

Intergovernmental Panel for Climate Change (IPCC) Tier II

The IPCC, in its revised reference manual (IPCC 2006), outlined two methodologies to estimate CH_4 emissions from livestock enteric fermentation, namely Tier I and Tier II. A third methodology, Tier III, is also recommended for countries with detailed information on animal and diet characteristics using mechanistic models. Tier I is a simplified approach that assigns default CH_4 emissions for distinct animal categories. Therefore, only readily available animal population data are needed to estimate emissions. When more detailed livestock data are available, Tier II method estimates enteric CH_4 emissions from ruminants on the basis of their gross energy intake (GEI, MJ/day) and the default CH_4 conversion rate (*Ym*, %GEI). Feed intake is estimated from bodyweight, average daily gain, milk production per day, average amount of work performed per day, percentage of cows that give birth in a year, and feed digestibility. Methane conversion rate is the extent to which feed energy is converted to CH_4. The default *Ym* value proposed by IPCC (2006) is 6.5% ± 1% for dairy cows.

$$EG = \frac{GE \cdot \left(\frac{ym}{100}\right) \cdot 365}{55.65}, \tag{2}$$

where EF is an emission factor (kg CH_4/animal.year), GE is the gross energy intake (MJ/day), *Ym* is the CH_4 conversion factor (%) and the factor 55.65 is the energy content of CH_4 (MJ/kg).

COWPOLL

The original rumen model developed by Dijkstra *et al*. (1992) was used as the base model. The model contains a series of dynamic, deterministic and non-linear differential equations. Designed to simulate the digestion, absorption and outflow of nutrients in the rumen, the model contains 17 state variables that

Table 2. Diet composition for mature cows

Energy content of methane calculated with the models (MJ/day) was divided between the factor 55.65 (MJ/kg CH_4)

Item	Cabello *et al.* (1971)	Mendoza-Martínez *et al.* (1986)	Plascencia-Jorquera *et al.* (1999)	Ayala *et al.* (2001)	Weiss and Pinos-Rodríguez (2009)
			Ingredient (% of DM)		
Corn silage	74.0	–	–	–	26.8
Alfalfa silage	–	58.3	45.0	15.0	13.2
Alfalfa hay	–	–	–	26.0	–
Concentrate 16% crude protein	–	–	–	25.0	–
Corn	4.8	–	44.6	–	–
Sesame paste	1.8	–	–	–	–
Wheat bran	6.5	–	–	–	–
Brewers grains dried	6.5	–	–	–	–
Rice bran	5.5	–	–	–	–
Sorghum grains	–	25.0	–	20.0	–
Safflower	–	8.4	–	–	–
Ground corn	–	–	–	–	20.8
Hominy	–	–	–	–	4.0
Soybean hulls	–	–	–	–	8.9
wheat middings	–	–	–	–	7.0
Soybean meal 44% crude protein	–	–	–	–	8.7
Treated soybean meal	–	–	–	–	3.4
Distillers grains	–	–	–	–	5
Meat meal	–	–	1.0	10.25	–
Blood meal	–	–	1.0	–	–
Feather meal	–	–	1.0	–	–
Molasses	–	4.2	5.75	–	–
Limestone	–	–	–	–	1.08
Magnesium oxide	–	–	–	–	0.03
Poultry litter	–	2.1	–	–	–
Urea	–	0.6	0.43	–	–
Phosphate rock	0.52	0.9	0.32	0.5	–
Salt	0.26	0.5	0.5	1.0	–
Mineral mix	0.1	–	–	1.5	0.49
Vitamin A	0.08	–	–	–	–
			Model predictions (MJ/day)		
Moe and Tyrrell (1979)	16.1	16.1	16.4	16.7	15.9
COWPOLL (based on Dijkstra *et al.* 1992)	13.8	12.5	15.5	15.3	15.8
IPCC (2006)	17.9	17.7	17.2	17.6	18.6

represent N, carbohydrate (NDF, starch, and sugar), lipid and volatile fatty acid pools. Three microbial groups, namely amylolytic and celluloytic bacteria, and protozoa, are represented in the model. Using the principle of Baldwin (1995), CH_4 production in the rumen and hindgut was added to the rumen model by Mills *et al.* (2001). The principle was based on excess hydrogen produced during fermentation being partitioned between its use for microbial growth, biohydrogenation of unsaturated fatty acids and the production of glucogenic volatile fatty acids (Mills *et al.* 2001). The model was run for several days with a time-step of 1 h, until a steady-state was achieved.

The total amount of enteric methane (ECH_{4j}, kg/year) produced by the Mexican dairy cattle herd in Year *j* can be calculated as follows:

$$ECH_{4j} = C_j \times EEF_j, \tag{3}$$

where C_j is the total number of dairy cows in Year *j*, and EEF_j is the corresponding annual CH_4 enteric emission factor for Year *j*.

Enteric CH_4 emissions were considered to be zero for calves (birth to pasture), as described by Le Du *et al.* (1976) who observed that at 90 days of age, calves on milk consumed less than 1 kg/day of herbage.

Manure CH_4 emissions were estimated using the IPCC Tier II methodology (IPCC 2006; US EPA 2007), which is a function of the quantity of volatile solids excreted, CH_4 maximum potential production (0.24 m^3 per kg volatile solids) and a CH_4 conversion factor (21.7) for liquid systems.

$$MEF_j = (VS_j \times 365) \cdot (B_{0(j)} \times 0.67 \times \Sigma(MCF_{S,j} \times MS_{S,j})), \tag{4}$$

where MEF_j = manure management CH_4 emission factor (kg CH_4/animal.year), VS_j = daily excreted volatile solid (kg DM/animal.day) in Year *j*, 365 is the basis for calculating annual VS production (days/year), $B_{0(j)}$ is the maximum CH_4 producing capacity from manure produced (m^3 CH_4/kg DM of VS excreted) in Year *j*, $MCF_{S,j}$ = CH_4 conversion factors that reflect the proportion of VS actually converted to CH_4 compared with $B_{0(j)}$ (dimensionless) in manure-management System S and Year *j*, the factor 0.67 kg/m^3 is a conversion factor of m^3 CH_4 to kg CH_4, $MS_{S,j}$ is the fraction of manure handled using manure-management System S in Year *j* (dimensionless). The default values of VS, B_0 and MCF. for dairy cattle are provided in IPCC (2006). Due to lack of information, all manure was assumed to have been managed in the same way.

The total amount of CH_4 from manure MCH_4j (kg/year) produced by the Mexican dairy cattle herd in Year j can be calculated as

$$MCH_{4j} = C_j \times MEF_j, \tag{5}$$

where C_j is the total number of dairy cows in Year j, and MEF_j is the corresponding annual CH_4 manure emission factor for Year j.

The prediction of the total amount of CH_4 produced by the Mexican dairy herd in Year j (TCH_{4j}, kg/year) is calculated as

$$TCH_{4j} = ECH_{4j} + MCH_{4j}. \tag{6}$$

Manure N_2O emissions were calculated as 0.001 kg of N_2O per kg of N excreted (IPCC 2006); however, the model did not include N_2O emissions from inorganic fertilisers. Carbon dioxide emissions from animal respiration were not considered due to CO_2 sequestration by plants in the photosynthesis process. Fuel CO_2 emissions from combustion were not included in the present study due to lack of data. The global warming potentials of CH_4 and N_2O were 25 and 298, respectively, on the basis of IPCC (2007) recommendations. Emissions from manure were then added to eneteric CH_4 emissions predicted by each model to obtain the total amount of GHG emitted per cow.

Results

In the past 40 years, the human population in Mexico has grown 133% and demand for milk 172%. Dairy production systems in the 1970s were pasture based, with forage to concentrate ratio (F : C) of 65 : 35. In contrast, in 2010 most dairy production systems use total mixed rations formulated to meet the cow's nutrient requirements (F : C ratio 40 : 60). Average milk yield has increased from 9.2 kg/day in 1970 to 14.9 kg/day in 2010. Feed conversion efficiency increased 32% (from 0.8 to 1.06 kg of milk/kg of DM intake) (Table 3).

Trends in enteric and manure CH_4 emissions in the years 1970 and 2010 are provided in Table 3, and Fig. 2 shows a comparison of ECH_4 with results obtained from COWPOLL model and IPCC-derived manure CH_4 estimates for the period1970–2010. Methane emissions estimated by the Moe and Tyrrell equation were 165 and 274 Gg per year for years 1970 and 2010, respectively. COWPOLL estimated 144 and 272 Gg of CH_4/year and the IPCC equation predicted 181 and 309 Gg of CH_4/year. All three models agreed that the highest emission estimates were in 2010. Regardless of the annual variation among models in absolute ECH_4 production, the

Table 3. Comparison of resource inputs, management and environmental impact of dairy production systems

DMI, DM intake; IPCC, Intergovernmental Panel on Climate Change

Variable	1970	2010	Difference (%)
Human population^A (millions)	48	112	133
Per capita consumption^B (mL/day)	222	260	17
Milk annual production^B (Mt)	3.91	10.6	172
Lactating cows^B (thousands)	1400	2351	68
Annual milk production^B (kg/cow)	2800	4541	62
Feed consumption^C (kg DMI/cow.day)	11.5	15.5	35
Total feed required (million t/year)	5.87	13.3	126
Efficiency (kg milk/kg DMI)	0.8	1.06	32
Total annual greenhouse gas emission (Mt/year)			
Methane^D	144	270	88
Nitrous oxide^E	0.349	0.713	104
Carbon dioxide equivalent^F	3704	6962	88
Emission by cow (kg/year)			
Methane^D	103	115	11
Nitrous oxide^E	0.249	0.303	22
Carbon dioxide equivalent^F	2649	2965	12
Emissions by litre of milk (g/L)			
Methane^D	36	25	–30
Nitrous oxide^E	0.089	0.067	–25
Carbon dioxide equivalent^F	926	645	–30

[A] INEGI (2011).

[B] FAO (2012).

[C] Calculated with NRC (2001).

[D] Methane emissions from enteric fermentation (COWPOLL) + manure (IPCC).

[E] Nitrous oxide estimated with IPCC model.

[F] Global warming potential, CH_4 = 25 (enteric CH_4 from COWPOLL model, and manure CH_4 from IPCC) and N_2O = 298 (from IPCC methodology).

overall trend was similar for all three models. Methane emissions increased particularly between 1996 and 2004 but decreased between 2005 and 2008. An interesting point was that although CH_4 emissions per cow increased 11%, CH_4 emissions per unit of milk decreased 30% (Table 3). Methane from manure fermentation ranged between 17.08 in 1970 and 28.6 Gg in 2010.

Trends in annual N_2O production are provided in Table 3 and Fig. 3. In the past 40 years, total N_2O emission increased 104%. Although N_2O emissions per cow increased (22%) in the same period, N_2O emissions per unit product decreased 25%. Nitrous oxide emissions showed a tendency to increase between 1970 and 1986, remained relatively constant from 1987 to 2008, and started to increase again between 2009 and 2010 (Fig. 3.).

Estimations of total GHGs are shown in Table 3 and Fig. 4. Trends of carbon footprint of Mexican dairy system (total GHG emissions in CO_2 equivalents) were similar to those of CH_4 emissions. All models showed that the highest emission estimates were in 2010. Carbon footprint per herd and per cow increased 88% and 12%, respectively, in the past 40 years; during the same time, emissions per unit product declined 30%. Using the Moe and Tyrrell equation, we estimated that total emissions from dairy population in Mexico increased from 1972 to 1990; decreased between 1991 and 1997 and then increased between 1998 and 2004. The COWPOLL model estimated total GHG emissions to increase from 1972 to 1984, decrease between 1985 and 1998, and then increase between 1999 and 2010. The IPCC model showed an increase from 1970 to 1984, a decrease between 1986 and 1996, followed by an increase between 1998 and 2004, a decrease between 2004 and 2006, and finally an increase between 2008 to 2010 (Fig. 4). In general, ECH_4 production was the highest source of emissions (85.3%), followed by CH_4 and N_2O from manure (11.5% and 3.2%, respectively).

Regardless of the models considered, the trend of carbon footprint was similar to that of CH_4 emissions because the majority of emissions came from ECH_4 (Fig. 5). A comparison of emissions (CO_2 equivalents) between models for the Year 2010 indicated 1.13% difference between Moe and Tyrrell and COWPOLL, 10% between Moe and Tyrrell and IPCC, and 11.1% between COWPOLL and IPCC.

Finally, a comparison between forecasted dairy production systems in Mexico and the US for the year 2020 is shown in Table 4. Data of the US system were based on Kebreab *et al.* (2008). If the efficiency of dairy production in Mexico increased at the same level as the US, fewer lactating cows would be required, and CH_4, N_2O and the carbon footprint would be reduced 38.8%, 75.6% and 39.4%, respectively, assuming constant demand for milk.

Discussion

In the past four decades, livestock production in Mexico has been growing; however, there is paucity of information regarding GHG emissions from cattle. On average, our estimates of ECH_4 emissions were 2.3%, 18.5% and 32.7% higher with COWPOLL, Moe and Tyrrell (Eqn 1) and IPCC Tier II (Eqn 2) models, respectively, than the latest available inventory for

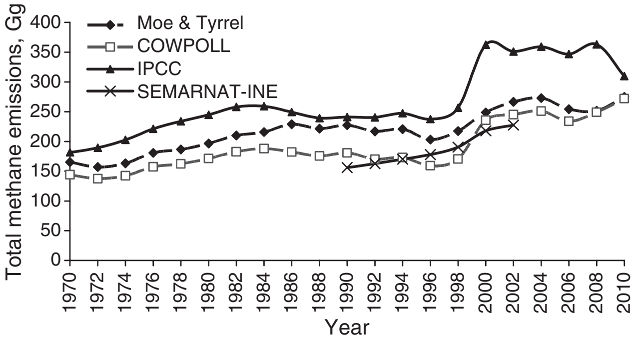

Fig. 2. Pattern of total methane (CH_4) emissions (enteric and manure CH_4). For the enteric CH_4 production for dairy cows, values are calculated using the equation of Moe and Tyrrell (1979), IPCC Tier II (IPCC 2006), and COWPOLL (Dijkstra *et al.* 1992) and five diets described in Table 2.

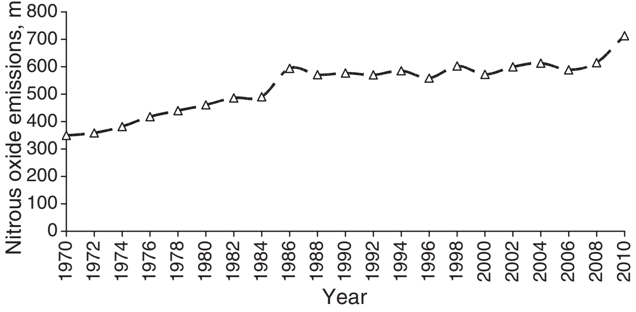

Fig. 3. Trends of nitrous oxide emissions from manure.

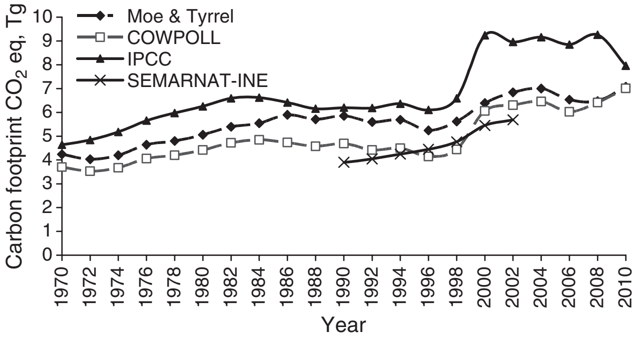

Fig. 4. Pattern of greenhouse gas emissions from enteric and manure fermentation (methane (CH_4) and nitrous oxide (N_2O)).

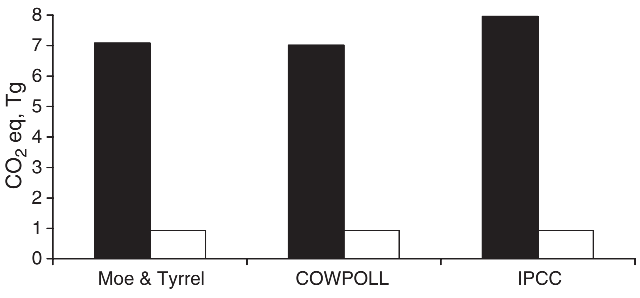

Fig. 5. Model comparison in estimates of enteric methane (black bars) and manure methane + nitrous oxide (white bars) emissions in 2010 in CO_2 equivalents.

Table 4. Comparison of the predicted environmental impact trend by dairy cattle to the year 2020, using current production systems from Mexico and USA

Trend of environmental impact according to the population size (115 762 289; CONAPO (2005) *per capita* consumption (260 mL/day = 11 billion kg of milk/year) and the current milk production system. USA data were calculated with dairy cattle characteristics from Kebreab *et al.* (2008)

Variable	Mexico	USA	Difference (%)
Milk production (kg/cow.day)	14.9^A	33.1	122
Milk yield (kg/cow.year)	4541^A	10095	122
Lactating cows (thousands)	2422	1089	–55.0
Feed (Mt)	37.4	26.7	–28.6
GHG emission			
Methane (Mt)	278^B	170	–38.8
Nitrous oxide (t)	734^B	179^C	–75.6
Carbon dioxide equivalent (Gt)	7.1^B	4.3	–39.4

[A] FAO (2012).

[B] Values are taken from Table 3, using estimated data from 2010, where total CH_4 = 115 kg/animal.year, N_2O = 0.303 kg/animal.year, and CO_2 equivalent = 2790 kg/animal.year, and multiplied by animal population.

[C] Estimations were not realised in Kebreab *et al.* (2008). Manure N_2O emissions were estimated as 0.001 kg of N_2O per kg of N excreted (US EPA 2007). Nitrogen excretion by animal = 0.45 kg/day (ASABE 2005).

2002. Kebreab *et al.* (2008) compared mechanistic models such as COWPOLL and empirical models including IPCC and reported that mechanistic models were superior in their ability to predict CH_4 emissions. The authors reported that statistical models such as Tier II from IPCC tend to overestimate CH_4 emissions because CH_4 predictions depend on the amount of DM intake and do not respond to the types of nutrients supplied to the animals.

Other models for calculating GHG inventories have been developed by Ruiz-Suárez and González-Avalos (1997), but these authors included only enteric and manure CH_4 emissions from dairy and beef cattle. The authors modified IPCC Tier I model (EEF given for Mexican region) by calculating energy intake on the basis of bodyweight. Their estimates were not in agreement with our results; for example, in the year 1995, they estimated a CH_4 emission of 288 Gg for dairy cattle, which was 17.5%, 32.7%, and 69.4% more than the values we obtained in our study (with IPCC Tier II, Moe and Tyrrell and COWPOLL, respectively). These differences are likely due to models used (IPCC Tier I uses a fixed value) and also differences in the type of production system considered. Farming systems based on high-forage diets produce higher enteric emissions and lower milk yield per cow than do modern intensive systems (Haas *et al.* 2001; Hagemann *et al.* 2011).

The general trend observed in the present study was similar to that found for western Canada, which was heavily affected by cow numbers and improvement in milk production (Alemu *et al.* 2011). There was a downward trend in CH_4 emissions and carbon footprint during 1990–1998, most probably due to a decrease in cow numbers. Losada *et al.* (2000) reported such reduction to be due to national economic crisis and the high cost of production in the 1990s. For example, in the town of Tizayuca, Estado de Mexico, producers were forced to sell their herds or at least reduce the number of animals; however, after 1998, a tendency to increase the number of animal was ~15–20% per year, in the same area of Tizayuca.

In the current study, the higher CH_4 emissions and low milk yield per cow in the 1970s are attributed to more extensive systems with higher F : C ratio in the diet than in modern production systems, where intensification has been going on for at least two decades. Similar results have been described by Capper *et al.* (2009), who reported that an improvement in the management practices in intensive dairy production systems is an important way to reduce the environmental impact. This could be achieved through better crop yields, higher-quality feedstuffs, improvements in genetic and diet composition and greater milk yields (Boadi *et al.* 2004). This would then reduce GHG emissions and the number of cows required to produce a comparable amount of milk. Eastridge (2006) and LeBlanc *et al.* (2006) also pointed out that advances in dairy production in the past six decades have resulted in remarkable increases in production efficiency granted by genetic selection, ration formulation, preventative health programs, improved cows' performance and better management practices.

For a complete life-cycle analysis, data on, for example, fuel and electricity use, water consumption, crop and feedstuff production, land required, ration formulation, herd distribution and manure management will be required. Such a system-wide analysis will be able to assess GHG mitigation options to improve environmental sustainability of the Mexican livestock production system.

Conclusions

All three models used in the study were in agreement with the trend of emissions, which were generally rising as the years progressed but were heavily influenced when cow numbers changed during the study period. Enteric CH_4 emissions have been identified to be the major source of GHG emissions in Mexican livestock production systems; therefore, any mitigation strategy to reduce carbon footprint should include strategies to reduce enteric fermentation. Emission intensity is likely to decrease in the future as cow productivity and management practices are expected to follow trends similar to those in other North American countries. Any policy change to reduce emissions should use quantification methods that take into account diet composition and intake rather than fixed emission factors such those currently used in the Mexican national inventory.

Acknowledgements

This research was funded by CONACyT through a doctor of science scholarship (208836), UCMEXUS–CONACYT Collaborative Grants and Sesnon Endowed Chair fund (UC Davis).

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