South African Journal of Animal Science 2018, 48 (No. 1)

Comparison of greenhouse gas emissions from Mexican intensive dairy farms

J. A. Rendón-Huerta[1], J. M. Pinos-Rodríguez[2#], E. Kebreab[3], J. C. García-López[1] & J. G. Vicente[2]

[1] Coordinación Académica Región Altiplano Oeste e Instituto de Investigación de Zonas Desérticas Universidad Autónoma de San Luis Potosí, 78000, S.L.P. México
[2] Facultad de Medicina Veterinaria y Zootecnia
Universidad Veracruzana, 91710, Veracruz, México
[3] Department of Animal Science
University of California, Davis, 95616, California, USA

(Received 3 May 2017; Accepted 1 November 2017; First published online 8 November 2017)

Abstract

The objectives of this study were to compare estimates of greenhouse gas emissions (GHG) as CH_4 (enteric-manure), N_2O (manure), and CO_2 (fuel and energy use), the use of water and soil, the excretion of nutrients in manure, and feed efficiency from Mexican intensive dairy farms. Data from 26 dairy farms were analysed with a multivariable cluster analysis. Three grades of intensifications were identified (low, medium and high). Mathematical models were used to estimate GHG. Feed efficiency (kg milk per kg DMI) was better in high intensive production systems. Enteric methane was identified as the major source of GHG in all types of systems. High intensive dairies generated the lowest emissions of CH_4, N_2O and CO_2 equivalent by unit of product, 18.6 g, 0.12 g and 828 g, respectively. Water footprint was lower in low intensive dairies using 427 L of water/L of milk. Cropland was highest in intensive systems but milk yield per area was better (30,938 kg/ha). Excretions of N, P, and K were lower in intensive dairies per kg of milk, at 13.2, 2.4, and 6.4 g, respectively. As intensification in the dairy system increased feed efficiency (kg milk/kg DMI) was better. Per unit of product (kg of milk), dairies with the highest intensification generated the lowest GHG emissions, nutrient excretion values and land and water use as compared to dairies with medium and low intensification. Increasing intensification and therefore feed efficiency of Mexican dairy systems could help to decrease GHG emissions, natural resources use and nutrient excretion.

Keywords: Carbon footprint, environmental impact, methane, milk production
[#] Corresponding author: jpinos@uv.mx

Introduction

In México, the milk production process is developed in technological, socioeconomic, and agroecological heterogeneous conditions with four different kinds of systems: intensive, semi-intensive, rural, and dual purpose. Livestock production is recognized to contribute significantly to emission of greenhouse gases (GHG) into the agriculture sector, mainly through emission of methane (CH_4) and nitrous oxide (N_2O) (Steinfeld *et al*., 2006). The global dairy sector contributes 4.0 percent (1,969 Million tonnes CO_2-eq) to the total global anthropogenic GHG emissions (FAO, 2010). Capper *et al*. (2009) pointed out that nowadays the dairy production practices have a lower environmental impact than those of the 1940s. Efficiency of production is defined as the minimum quantity of inputs (feed, fossil fuels) and emissions of GHG and nutrients in order to produce a certain quantity of milk (Place & Mitloehner, 2010). The variety of milk production systems, but mainly intensive systems, make use of better nutritional feeds produced with inorganic and organic fertilizers (Smith, 1991; Capper *et al*., 2009), where in many scenarios losses of nutrient in manure (faeces and urine) can occur. In particular, nitrogen, phosphorus, and potassium, when they are present in excess, can have a negative impact on the environment (atmosphere, soil and water), human health and wild animals (Kojima *et al*., 2005). Milk production systems also require other kinds of inputs, such as fuels and electric energy, which contributes to CO_2 emission from combustion of fossil fuels to power machinery, or electric energy generation (Rotz *et al*., 2010). Gas measurements, such as CH_4,

URL: http://www.sasas.co.za
ISSN 0375-1589 (print), ISSN 2221-4062 (online)
Publisher: South African Society for Animal Science
http://dx.doi.org/10.4314/sajas.v48i1.6

N_2O, and CO_2, are complex and require expensive equipment; one alternative has been the development and use of mathematical models to estimate GHG emissions (Kebreab *et al*., 2008). Mathematical models allow prediction of GHG emissions from ruminants related to the intake of nutrients without performing costly experiments (Kebreab *et al*., 2006). At the same time, another concept that applies to animal production is the water footprint, which is analogous to the ecological and the carbon footprint, but indicates fresh water use instead of land or fossil energy use and GHG emissions (Hoekstra, 2003). Therefore, the objective of this study was 1) to compare estimations of CH_4 (enteric and manure), N_2O (manure), and CO_2 (fuel and energy use) emissions in different kinds of intensive dairy farms in México, and 2) to estimate the use of natural resources such as water and soil, efficiency of production and excretion of nutrients in manure such as N, P, and K in different milk production systems.

Material and methods

A face-to-face, on-farm questionnaire was conducted. The same questionnaire was used on each dairy. Data on animal performance, diet composition, manure and soil samples from lactating, dry heifers and bulls, were collected from 26 dairy farms in Central and North of México (Queretaro, Jalisco, Guanajuato and Aguascalientes). Ration and manure samples of each ranch were kept frozen at -20 °C until they were analysed. For feed and manure samples, analysis of dry matter content, crude protein, fat, ash (AOAC, 1990) NDF and ADF (Van Soest *et al*., 1991), where done in order to fit the COWPOLL model and analyse nutrient losses, respectively. In order to classify the extent of intensification among various livestock systems, a multivariable cluster analysis was made using Cluster function of R statistical software (R Development Core Team, 2012).

To estimate enteric fermentation, manure CH_4 and N_2O, a mechanistic model COWPOLL (based on Dijkstra *et al*., 1992), and two empirical models (IPCC, 2006) were selected based on input data requirement, their ease of application, and widespread use to predict CH_4 and N_2O emissions and also their potential relevance to Mexican dairy production system, due to a lack of information on environmantal impact by dairy farms in Mexico.

As described by Rendón-Huerta *et al.* (2013), enteric and manure CH_4 emissions were estimated with COWPOLL (Dijkstra *et al*.,1992) and IPCC (2006), respectively. Manure N_2O emissions were calculated as 0.001 kg of N_2O per kg of N excreted (IPCC, 2006); however, the estimations did not include N_2O emissions from inorganic fertilizers. Carbon dioxide emissions from animal respiration were not considered due to CO_2 sequestration by plants in the photosynthesis process. For carbon footprint, the global warming potential of CO_2, CH_4, and N_2O were 1, 34, and 298, respectively, on the basis of IPCC (2013) recommendations. Carbon dioxide from fuels and electric energy utilization were obtained through a questionnaire. According to the US EPA (2016), emissions from 1 kWh energy use, 1 L gasoline, and 1 L of diesel burned are equivalent to 0.73, 2.33, and 2.83 kg of CO_2 equivalents. For nutrient excretion, the efficiency of nitrogen (N), phosphorus (P), and potassium (K) utilization were analyzed. Chemical analysis of nutrients (N, P, and K) in feed and manure samples, as well as dry matter content was carried out (AOAC, 1990).

Information on land used for pens, milking facility, and cropland were collected through a questionnaire. Similarly, information on main crops grown and yields per ha were collected. Water footprint was calculated considering the green water, defined as water from rainfalls; data of precipitation was taken from climatological stations close to each dairy (Servicio Metereologico Nacional, 2017). The blue water was considered, which is defined as water consumption for irrigation crops, cleaning, and drinking water from wells. It was calculated according to volume flow rate equation based on pumping time and seasons during the year:

$$Q = Av,$$

where: Q is the water flow rate in m^3/s,
A is the pipe section area in m^2, and
v is the average flux velocity in m/s (Mott, 1996).

In order to classify the extent of intensification among various livestock systems a multivariable cluster analysis was made using Cluster function of R statistical software (R Development Core Team, 2012). The variables considered were cow population, cropland, electricity use, fossil fuels and water consumption. Comparison of GHG emissions, water footprint and nutrient excretion were analysed with a completely randomized design through an analysis of variance (ANOVA). Comparison of GHG, milk production, DMI and efficiency of production were performed through a Pearson correlation. When differences were found means were compared using the Tukey test (P <0.05).

Results and discussion

According to the Cluster analysis, three kinds of intensive systems were identified as low, medium, and high production intensity. The average total animal populations in the three categories of production were 285, 588, and 1940, respectively. Lactating cows made up 128, 281, and 786 animals in low, medium and high intensive systems, respectively (Table 1). Highest milk yield values by cow per day were obtained in high intensive dairies compared with medium and low intensive dairies (31.4, 29.6 and 25.9 kg, respectively; P <0.001). Total milk production values per year were highest in high intensive compared to low intensive systems (7.52 *vs*. 1.21 Mtonne milk, respectively; P <0.0001). Production efficiency (milk per kg of feed intake) was found to be highest in the largest dairies in contrast to small dairies (1.31 *vs*. 1.07 kg milk/kg of DMI; P<0.05). This effect was mainly due to the diet composition, where in high intensive dairies the forage: concentrate ratio (F: C) averaged 45:55 and medium and low intensive dairies F: C averaged 52:48 and 60:40, respectively. Silage corn and alfalfa were the main forage in diets, while commercial concentrate and corn (TMR) were in the concentrate proportion.

Table 1 Animal population distribution by category and milk production in three different intensive systems

	Level of intensification			SEM	***P*-value**
	Low	**Medium**	**High**		
Category					
Early lactation cows	115	237	590	29.2	***
Mid-lactation cows	15	35	154	46.7	**
Late lactation cows	4	9	42	16.5	ns
Dry cows	28	38	135	16.8	**
Heifers	88	153	400	9.17	***
Calves	43	93	589	55.8	***
Bulls	2	23	31	23.8	ns
Total	295	588	1941	67.5	***
Milk yield, kg/cow.d	25.9	29.6	31.4	1.05	**
Milk yield, kg/cow.yr × 10^3	7.89	9.02	9.57	0.31	**
Total milk production, kg/yr × 10^6	1.21	2.53	7.52	0.49	***
DMI, kg/d	24.1	23.2	23.9	0.84	ns
Efficiency, kg milk /kg DMI	1.07	1.27	1.31	0.05	*

SEM= Standard error of the mean; DMI = dry matter intake
* = P <0.05, ** = P <0.01, *** = P <0.001, ns = non-significant.

Greenhouse gases estimated in this trial were enteric CH_4, manure CH_4 and N_2O, and CO_2 from electric energy use and fuels combustion (Table 2). Estimates of total enteric methane was greater in high intensive dairies followed by medium and low intensive dairies, 379, 148 and 70.6 kg/d (P <0.0001). The differences were in function of herd size, with similar trend for total manure methane, manure nitrous oxide, carbon dioxide emissions from energy and fuel consumption, and total carbon dioxide equivalent emissions.

Estimated manure CH_4 emissions per cow were significantly different (P <0.0001) in all categories with the highest values obtained from low intensive systems compared to medium and high intensive systems (55.4, 49.4, and 41 g/d, respectively). Enteric CH_4 emissions were similar, however, enteric CH_4 was identified as the greatest source of GHG in CO_2e defined as CO_2e equivalent followed by energy and fuels consumption. Total CH_4 per cow were similar to those found by Aguerre *et al.* (2011), who point out that cows fed diets with F: C ratio of 47:53, produced 538 g CH_4/d and, as the forage proportion increased, CH_4 emissions increased as well. Although their value was greater compared to those obtained in our study, the authors admitted that their values were greater to chambers measurements.

Table 2 Greenhouse gas emissions by three different intensive systems

	Level of intensification			SEM	*P*-value
	Low	Medium	High		
Total cows	285	588	1940	136	***
Lactating cows	134	281	786	51	***
Total milk production, kg/d	3470.6	8317.6	24680	1197	***
Milk yield, kg/cow/d	25.9	29.6	31.4	1.05	**
GHG emissions from whole system, g/d					
Enteric $CH_4 \times 10^3$	70.6	147.5	379.3	20.3	***
Manure $CH_4 \times 10^3$	15.8	29	79.5	4.8	***
Total $CH_4 \times 10^3$	86.4	176.6	458.9	25	***
Manure $N_2O \times 10^3$	0.56	1.01	3.05	0.18	***
Energy & Fuel CO_2 e $\times 10^6$	1.74	2.22	8.06	0.19	***
Total CO_2 e $\times 10^6$	4.84	8.52	24.5	0.76	***
GHG emissions for lactating cow, g/d					
Enteric CH_4	469	459	456	12.3	ns
Manure CH_4	55.4	49.4	41	2.3	***
Total CH_4	524.4	507.4	497	4.3	***
Manure N_2O	4.21	5.38	3.83	0.77	ns
Energy & Fuel CO_2 e $\times 10^3$	8.29	5.70	6.13	1.38	ns
Total CO_2 e $\times 10^3$	27.4	24.5	24.2	4.4	ns
¥*GHG emissions for unit product, g/L*					
Enteric CH_4	20.4	17.7	15.4	1.35	**
Manure CH_4	4.5	3.5	3.2	0.28	***
Total CH_4	24.9	21.2	18.6	1.80	**
Manure N_2O	0.16	0.12	0.12	0.008	***
Energy & Fuel CO_2 e	501.7	267	327	55.3	ns
Total CO_2 e	1396	1023	995	77.3	**

¥Include the whole system; GHG: greenhouse gas emissions; CH_4: methane, N_2O: nitrous oxide, CO2: carbón dioxide
SEM= Standard error of the mean.
* = *P* <0.05, ** = *P* <0.01, *** = *P* <0.001, ns = non-significant.

Emissions per unit of product were different (P <0.05). For enteric CH_4, the greatest values were estimated from the low intensive dairy systems, followed by medium, and high intensive dairy systems (21.7, 18.6, and 15 g/L of milk, respectively). Emissions from intensive farms were similar with those found by Aguerre *et al.* (2011), who showed that cows fed diets with 47:53 F: C ratio and intake of 21 kg DM produced 14.0 g of CH_4/kg of milk. Although there was a difference in DMI between our study and the authors', the main differences may be attributed to type of feed ingredients in diet such as soybean extract, roasted soybeans, etc. According to Hristov *et al.* (2013), there are some practices that could increase milk production and reduce enteric methane reduction. These practices include improving forage quality, and optimizing rumen function for higher microbial protein synthesis through feeding of a balanced diet. Manure (faeces and urine) are mainly stored for about 4 to 6 months before application to crops as fertilizer. Manure CH_4, and total CH_4 were statistically significant as well. Nitrous oxide estimations were highest in low intensive dairy systems 0.16 g/L of milk (P <0.001). Even if highly intensive systems use high quantity of energy (electric and fuels) in order to produce milk, emissions of CO_2 were highest in low intensive dairies compared to medium and high intensive dairies (P <0.005). Finally total CO_2 equivalent (CO_2e) emissions per litre of milk were found significantly different (P <0.05). The highest values were obtained in low intensive dairies, followed by medium, and high intensive dairies (1.39, 1.02, and 0.99 kg CO_2e/L of milk). Methane was the highest source of GHG, followed by energy and fuel consumption. These results agree with those found by Rotz *el at.* (2010). The results were also in close agreement to those reported by Hörtenhuber *et al.* (2010) who found emissions up to the farm gate ranging from 0.90 to 1.17 kg CO_2e/kg milk. Phetteplace *et al.* (2001) found that for a cow producing 7,880 kg milk per year, the carbon footprint was 1.09 kg CO_2e/kg of milk. Capper *et al.* (2008) reported that a lactating cow producing 9,050 kg of milk generated 1.5 kg CO_2e/kg of milk, the difference between this last value and our values may be due that the farms that we visited do not produce the total feeds.

A Pearson correlation (Table 3), indicates that increasing milk production (kg milk/kg DMI), decreased (P <0.05) CH_4, N_2O and CO_2 per unit of product.

Table 3 Pearson correlation coefficients for efficiency, lactating cows, milk production and GHG

	Efficiency	Lactating cows	Milk production/d
Efficiency	1.00000	0.38284	0.47965
		0.0648	0.0177
Milk production/d	0.47965	0.95148	1.0000
	0.0177	<.0001	
CH_4 per cow	0.06270	-0.19864	-0.04914
	0.7710	0.3521	0.8196
N_2O per cow	0.18762	-0.25656	-0.06442
	0.3800	0.2262	0.7649
CO_2 per cow	0.07249	-0.35132	-0.14806
	0.7364	0.0923	0.4899
CH_4 per L of milk	-0.39429	-0.58271	-0.59812
	0.0566	0.0028	0.0020
N_2O per L of milk	-0.55534	-0.57879	-0.64581
	0.0048	0.0030	0.0007
CO_2 per L of milk	-0.56895	-0.53776	-0.55525
	0.0037	0.0067	0.0049

GHG: greenhouse gas emissions; CH_4: methane, N_2O: nitrous oxide, CO2: carbón dioxide

Results of nutrient excretion are shown in Table 4. When we look at nutrient excretion by animal, our results showed that animals with higher concentrate ratio (high intensive dairies) excreted greater quantities of N compared to low concentrate ratio (low intensive dairies) i.e., 415 and 392 g/d, respectively (P <0.005). However, when we compared N excretion per unit of product, losses were lower in high intensive systems (13.2 g N/L of milk, P <0.001). Our results were close to those found by Brito & Broderick (2006), who mentioned that diets containing 50:50 F: C ratio, 25.4 kg DMI, and 16% CP, N excretion in manure was around 431 g N/d and 10.5 g N/L of milk. On the other hand, Groff and Wu (2005) found that when lactating cows were fed diets containing 50:50 F: C ratio, 16.3% CP and 24.7 kg DMI, N excretion was 484 g/cow and 13.5 g N/L of milk. Finally Hristov *et al.* (2004) mentioned that dairy cows fed 48:52 F: C ratio, 15.8% CP and 23.5 kg DMI, shows N losses in manure of 437 g/cow/d. The greatest values per cow of P excretion were obtained in high intensive systems (74.9 g/d) compared with low and medium intensive systems (P <0.005).

However, when P excretions were compared on unit of product basis, high intensive systems showed lower losses (2.4 g/L of milk; P <0.05). Our results were higher in contrast to those made by Weiss and Wyatt (2004) where they show cows consuming 21 kg/d producing 30.4 kg milk /d and P intake of 79 g/d, excreted 47.7 g P/d. In agreement with the present study, Arriaga *et al*. (2009) reported manure P excretion of about 59.3 g/d per cow when P intake was 84.8 g/d. For K excretion in manure, the greatest values per cow were found in high intensive dairies compared with medium and low systems (200, 198 and 192 g/d, respectively). These results agree with those found by Van Horn *et al*. (1994) and Nennich *et al*. (2005), for a lactating cow producing 31.8 and 31.4 kg of milk/d (K excretion was 204 and 200 g/d, respectively). Similarly, Kojima *et al.* (2005) reported high K excretion (282 g/d) in cows producing 29.5 kg of milk/d. Differences were found in K excretion to the environment per unit of product as well (P <0.005), greatest values of excretion were from low intensive dairies, i.e., 7.5 g K/L of milk compared with high intensive dairies (6.4 g of K/L of milk). Cows in high intensive milk production systems made better use of K.

Table 5 shows the area designated to growing crops and dairy facilities, where low, medium and high

Table 4 Nutrient excretion in manure by total system population, cow and unit of product

	Level of intensification			SEM	*P*-value
	Low	Medium	High		
		Nutrient excretion by total population, g/d			
Nitrogen	52926	115155	327475	19709	***
Phosphorus	6110	14190	43151	3560	***
Potassium	25887	55732	157806	9415	***
		Nutrient excretion by cow, g/d			
Nitrogen	392	407.5	415.4	3.63	**
Phosphorus	70.6	73.5	74.9	0.68	**
Potassium	192	197.6	200.3	1.28	**
		Nutrient excretion by unit product, g/d			
Nitrogen	15.2	13.9	13.2	0.32	**
Phosphorus	2.74	2.5	2.4	0.05	**
Potassium	7.5	6.7	6.4	0.03	**

SEM= Standard error of the mean.
* = *P* <0.05, ** = *P* <0.01, *** = *P* <0.001.

Table 5 Energy, land, and water use for growing crops in three different intensive systems

	Level of intensification			SEM	*P*-value
	Low	Medium	High		
Electricity[±], kWh/mo × 10^3	64.9	81.1	288.1	13.0	***
Gasoline, L/mo × 10^3	0.413	0.712	2.029	0.18	**
Diesel, L/mo × 10^3	1.36	2.26	9.88	1.70	**
Area for growing crops, milk facility and pens					
Land, ha	52	114	246	21.2	***
Milk yield, kg/ha × 10^3	19.6	25.6	30.9	4.49	**
Main crops, yield (tons/ha)					
Corn	51	58	61	2.6	***
Alfalfa	16	16	16	-	-
Triticale	37	40	40	5	ns
Oats	10	23	15	2.1	**
Barley	-	-	8	-	-
Sorghum	6	8	-	-	-
Wheat	-	-	2	-	-
Grass	-	32	30	-	-
Water, L/yr × 10^9	0.74	2.17	6.51	0.29	***
Water, L/L of milk	611.5	857.7	865.7	51.3	**

[±]Electricity for the dairy facility and for irrigation (water pumps), - crops are not growing in these systems, SEM = Standard error of the mean. * = *P* <0.05, ** = *P* <0.01, *** = *P* <0.001, ns = non-significant.

intensive dairies used 52, 114 and 246 ha, respectively. The main crops grown in the spring-summer cycle was corn, alfalfa, sorghum, triticale and grasses. In the autumn-winter cycle oats are grown. Corn has the highest yield in tons/ha compared to other crops.

Among systems, yield values were highest in high intensive dairies followed by medium, and low intensive systems (51, 58, and 61, respectively). Second crop with high yield was triticale with 17, 40, and 40 tons/ha for low, medium, and high intensive systems, respectively. Alfalfa presented the lowest yield with 4 tons/ha, which was similar in all production systems. Highly intensive systems used the greatest amount of water followed by medium and low intensive systems. Most of the water use was for crop irrigation, then for drinking water and finally for cleaning (milk facility and pens that use flushing systems). It is important to mention that farms have permissions to extract water from subsoil at least 9 months a year or through the whole year. Water footprint did not present statistical differences per unit of product. Our results showed that in order to produce one litre of milk, 610, 846, and 870 L of water were required in low, medium, and high intensive systems, respectively. Our results show lower values compared with those found by Hoekstra and Chapagain (2007), who reported a worldwide water footprint of 990 L of water/L milk. Furthermore, the same authors mentioned that water required to produce one litre of milk in Mexico was about 2382 L; however, they did not mention if calculations came from an intensive Holstein dairy system or from a dual purpose system (meat and milk production system) or both. This is important because dual purpose systems have very low milk production per cow (4561 kg/cow per year or 15 kg/d; Espinoza-Ortega *et al*., 2005). The relatively low water footprint calculated in this study could be because farms visited produced around 40 to 50% of crops required for animal feed and the rest were purchased or imported.

Conclusions

Low GHG emissions per unit of product were estimated for highly intensive dairy farms, mainly due to diet composition and efficiency of production. Enteric methane was identified as the major source of GHG emissions, therefore, any mitigation strategy to reduce carbon footprint especially in low intensive milk production systems, should be focused in reducing enteric methane through increasing efficiency of production. Second source of GHG was energy consumption; manure management could be another practice to mitigate carbon footprint through anaerobic digesters in order to produce electric energy and low use of fertilizers on croplands. These practices could make a more sustainable production system. Emission intensity is likely to decrease in the future as cow productivity and management practices are expected to follow trends similar to those in intensive systems.

Acknowledgements

This research was funded by CONACYT through a doctor of science scholarship (208836) and by UC MEXUS-CONACYT Collaborative Grants. Authors also want to thank Tirado G., Mora J.C., Saucedo L.R. and Juárez J., for taking us to the farms and finally to dairy farm owners for allowing us to take the samples and for giving us information.

Authors' Contributions

JARH doctoral student who conducted the experiment. JMPR & EK mentors, conception and design, JCGL & JGV chemical and data analysis.

Conflict of Interest Declaration

The authors have declared that no competing interests exist.

References

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., Broderick, G.A. & Arndt, C., 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. J. Dairy Sci. 94, 3081-3093. 234

AOAC, 1990. Official methods of analysis (15th ed.). Association of Official Analytical Chemists, Inc., Arlington, Virginia, USA.

Arriaga, H., Pinto, M., Calsamiglia, S. & Merino, P., 2009. Nutritional and management strategies on nitrogen and phosphorus use efficiency of lactating dairy cattle on commercial farms: An environmental perspective. J. Dairy Sci. 92, 204-215.

Brito, A.F. & Broderick, G.A., 2006. Effect of varying dietary ratios of alfalfa silage to corn silage on production and nitrogen utilization in lactating dairy cows. J. Dairy Sci. 89, 3924-3938.

Capper, J.L., Castañeda-Gutíerrez, E., Cady, R.A. & Bauman, D.E., 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proc. Natl. Acad. Sci. USA 105, 9668-9673.

Capper, J.L., Cady, R.A. & Bauman, D.E., 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87, 2160-2167

Dijkstra, J., Neal, H.D., Beever, D.E. & France, J., 1992. Simulation of nutrient digestion, absortion and outflow in the rumen: Model description. J. Nutr. 122, 2239-2256.

Espinoza-Ortega, A., Álvarez-Macías, A., del Valle, MC. & Chauvete, M., 2005. Small-holder (campesino) milk production systems in the highlands of Mexico. Tec. Pecu. Mex. 43, 39-56.
FAO, 2010. Greenhouse Gas Emissions from the Dairy Sector A Life Cycle Assessment. Food and Agriculture Organization of the United Nations, Rome, Italy.
Groff, E.B., Wu, Z., 2005 Milk production and nitrogen excretion of dairy cows fed different amounts of protein and varying proportions of alfalfa and corn silage. J. Dairy Sci. 88, 3619-3632.
Hoekstra, A.Y., 2003. Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, UNESCO-IHE Value of water research report series, No 12, Delf, The Netherlands.
Hoekstra, A.Y. & Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a fuction of their consumption pattern. Water Resour. Manag. 21, 35-48.
Hörtenhuber, S., Lindenthal, T., Amon, B., Markut, T., Kirner, L. & Zollitsch, W., 2010. Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change. Renew. Agr. Food Syst. 25, 316-329.
Hristov, A.N., Etter, R.P., Ropp, J.K. & Grandeen, K.L., 2004. Effect of dietary crude protein level and degradability on ruminal fermentation and nitrogen utilization in lactating dairy cows. J. Anim. Sci. 82, 3219-3229.
Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B. & Tricarico, J.M., 2013. Special topics-Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91, 5045-5069.
IPCC, 2006. Emissions from livestock and manure management. Agriculture, forestry and other land use. Intergovernmental Panel on Climate Change. Geneva, Switzerland.
IPCC, 2013. Climate Change 2013: The physical basis. Contribution of working group I to the fifth assessment report. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
Kebreab, E., Clark, K., Wagner-Riddle, C. & France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci., 86, 135-158.
Kebreab, E., Johnson, K.A., Archibeque, S.L., Pape, D. & Wirth, T., 2008. Model for estimating enteric methane from United States dairy and feedlot cattle. J. Anim. Sci. 86, 2738-2748.
Kojima, H., Kume, S., Nonaka, K., Oshita, T., Kozakai, T. & Hirooka, H., 2005. Effects of feeding and animal performance on nitrogen, phosphorus and potassium excretion by Holstein cows. Anim. Sci. J. 76, 139-145.
Mott, L.R., 1996. Applied Fluid Mechanics (4th ed.). Prentice Hall Inc., New York, USA.
Nennich, T.D., Harrison, J.H., VanWieringen, L.M., Meyer, D., Heinrichs, A.J., Weiss, W.P., St-Pierre, N.R., Kincaid, R.L., Davidson, D.L. & Block, E., 2005. Prediction of manure and nutrient excretion from dairy cattle. J. Dairy Sci. 88, 3721-3733.
Phetteplace, H.W., Johnson, D.E. & Seidl, A.F., 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutr. Cycl. Agroecosyst. 60, 99-102.
Place, S.E. & Mitloehner, F.M., 2010. Contemporary environmental issues: A review of the dairy industry´s role in climate change and air quality and the potential of mitigation through improved production efficiency. J. Dairy Sci. 93, 3407-3416.
R Development Core Team, 2012. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria.
Rendón-Huerta, J.A., Pinos-Rodríguez, J.M., García-López, J.C., Yáñez-Estrada, L.G. & Kebreab, E., 2014. Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010. Anim. Prod. Sci. 54, 292-298.
Rotz, C.A., Montes, F. & Chianese, D.S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93, 1266-1282.
Servicio Metereologico Nacional. 2017. Información climatólogica. http://smn.cna.gob.mx/es/climatologia/informacion-climatologica
Smith, L.W., 1991. Production systems. In: Handbook of Animal Science. Ed: Putmnam, P.A., Academic Press, USA. pp. 279-291.
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organization, Rome, Italy.
US EPA. 2016. Greenhouse Gases Equivalencies Calculator – Calculations and References. US Environmental Protection Agency. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
Van Horn, H.H., Wilkie, A.C., Powers, W.J. & Nordstedt, R.A., 1994. Components of dairy manure management systems. J. Dairy Sci. 77, 2008-2030.
Van Soest, P.J., Robertson, J.B. & Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583-3597.
Weiss, W.P. & Wyatt, D,J., 2004. Macromineral digestion by lactating dairy cows: Estimating phosphorus excretion via manure. J. Dairy Sci. 87, 2158-2166.