Carbon Management

ISSN: 1758-3004 (Print) 1758-3012 (Online) Journal homepage: http://www.tandfonline.com/loi/tcmt20

Assessment of the carbon footprint of four commercial dairy production systems in Australia using an integrated farm system model

Veerasamy Sejian, R. Shyaam Prasadh, Angela M. Lees, Jarrod C. Lees, Yaqoub A.S. Al-Hosni, Megan L. Sullivan & John B. Gaughan

CARBON MANAGEMENT, 2018
https://doi.org/10.1080/17583004.2017.1418595

Taylor & Francis
Taylor & Francis Group

Check for updates

Assessment of the carbon footprint of four commercial dairy production systems in Australia using an integrated farm system model

Veerasamy Sejian[a,b], R. Shyaam Prasadh[c], Angela M. Lees[a], Jarrod C. Lees[a], Yaqoub A.S. Al-Hosni[a], Megan L. Sullivan[a] and John B. Gaughan[a]

[a]School of Agriculture and Food Sciences, The University of Queensland, Gatton 4343 QLD, Australia; [b]ICAR-National Institute of Animal Nutrition and Physiology, Adugodi, Bangalore, India; [c]Indian Institute of Technology Madras, Tamilnadu, 600036, India

ABSTRACT
Integrated farm system model (IFSM) is a cost effective and efficient method of estimating greenhouse gas (GHG) emissions from dairy farms and analyzing how management strategies affect these emissions. An IFSM (DairyGHG model) was employed in this study to predict the GHG emission and assess the carbon footprints of four dairy farms in Southeast Queensland, Australia. Four representative commercial farms were selected: Farm 1 (220 cows; Jersey), Farm 2 (460 cows; Holstein Friesian), Farm 3 (850 cows; Holstein Friesian) and Farm 4 (434 cows; Holstein Friesian). The animal emission contribution to carbon footprints for Farm 1, 2, 3 and 4 were 54.2, 60.0, 59.6 and 38.6 % respectively for total output. Likewise the manure emission contribution to carbon footprints for Farm 1, 2, 3 and 4 were 30.6, 29.0, 29.0 and 58.3 % respectively. On the basis of per kg of energy corrected milk the amount of GHG produced for Farm 1, 2, 3 and 4 are 0.39 kg CO2Eq, 0.64 kg CO2Eq, 0.54 kg CO2Eq and 1.35 kg CO2Eq respectively. The method and database developed for these dairy farm GHG assessments may be considered an important step towards a harmonized methodology for the quantification of emissions in dairy farms.

KEYWORDS
Carbon footprint; dairy farm; DairyGHG model; GHGs; methane; nitrous oxide

Introduction

Agricultural production and livestock in particular is recognized as a major contributor to greenhouse gas (GHG) production [1,2]. The global livestock population contributes about 18% of global GHG emissions [3]. As per a life-cycle analysis, Gerber *et al*. [2] projected the percentile contribution of livestock-related methane, nitrous oxide and carbon dioxide to be 44, 29 and 27%, respectively. Over the past decade, research has focused on addressing the sources of GHG emissions within the dairy production system [4,101]. However, many studies have focused on the GHG emissions from a singular area of the production system (e.g. enteric fermentation, manure management, etc.). It is important to consider the complexity of the dairy production system, involving feed growth and inputs, crop and pasture systems, fertilizer application, manure production and management as well as milk transport [3,5].

Considerable research has been undertaken in the US, Canada and Europe in an attempt to quantify GHG for an individual animal [6–8]. However, sufficient research efforts are not in place to provide estimates of whole-farm-level emissions. There are other farm components that contribute immensely to the GHG pool in the livestock farms. Hence, quantifying GHG emission including all sources and sinks from the whole livestock farm is the need of the hour for the scientific community seeking a solution to livestock-related climate change [9–11]. This research gap needs to be addressed considering that, as a sector, agriculture is reported to be the greatest contributor of N_2O and the second greatest contributor of CH_4 emissions [102].

The use of predictive models provides an attractive alternative to expensive and time-consuming research trials to ascertain the effect of one or multiple changes on production, economics and GHG emissions from dairy production systems [12,13]. Simulating the whole-farm production process, an integrated farm system model (IFSM) provides the scope for a comprehensive evaluation and comparison of alternative agronomic, feeding, manure storage and disposal strategies in terms of production, profitability and nutrient cycling [14]. This model also accounts for fossil fuels used in the production process. Although the IFSM does not predict the production of GHG, it does provide the basic information required to predict GHG (CH_4 and N_2O) emissions based on factors published in the scientific literature. The IFSM also predicts the effects of climate and management scenarios on farm performance, profitability and environmental pollution [103]. Although IFSMs have been successfully used to simulate emissions from whole livestock farms in a few

CONTACT Veerasamy Sejian drsejian@gmail.com

nations, such attempts have been negligible in Australia. Therefore, it is essential to study the suitability of the developed model in several agro-ecological regions to establish its wider applicability, which might help policymakers to assess its reliability to develop appropriate universal mitigation strategies.

Australia's dairy industry is diverse and complex, specifically in terms of location, climate variability and management systems [15]. Australia expressed its commitment to addressing its contribution to the global issue of climate change by ratifying the Kyoto Protocol in late 2007. The Kyoto Protocol identified a commitment to limiting the growth of GHG emissions to 108% of its 1990 baseline by 2012. While the major focus on reducing GHG emissions has been placed on the stationary energy, industrial and transport sectors, the agricultural sector will also be required to implement its own series of measures to mitigate GHG emissions and climate change.

Agriculture is considered the dominant source of CH_4 and N_2O emissions, accounting for 59% and 84% of Australia's total CH_4 and N_2O gas emissions, respectively [11]. Within the agricultural sector, livestock are the largest contributor of emissions, at 62.8 Mt, which accounts for 69.7% of agricultural emissions, approximately 11% of Australia's total emissions. Methane production from livestock enteric fermentation was the biggest source of GHG emissions from Australian agriculture [104]. Given the significance of livestock production systems in Australia, sufficient research efforts are needed to provide clear estimations of GHG emission per kg of energy-corrected meat or milk production. Therefore, the objective of the current study was to predict GHG emission and assess the carbon footprints from four commercial dairy farms in Southeast Queensland, Australia, using an IFSM (DairyGHG model).

Materials and methods

Location and climate

The study was conducted in Southeast Queensland, Australia. The farms evaluated were all within a 50-km radius of the University of Queensland, Gatton campus. The 10-year (2006 to 2015) average ambient temperature (°C), average precipitation (mm), average solar radiation (W/m^2) and average wind speed (m/s) for Gatton were 19.48 ± 1.81, 3.12 ± 0.10, 18.45 ± 1.14 and 3.01 ± 0.06, respectively. The seasonal 10-year average weather parameters are described in Table 1.

Description of the integrated farm system model

The IFSM (DairyGHG model) used in the present study was developed and evaluated by Chianese *et al.* [1]. The DairyGHG model, originally developed for the American system, was modified by altering the input parameters pertaining to herd details, feed composition, targeted milk production and differences in manure handling. Further, the model was modified based on 10 years of local weather parameters to make the model suitable for the production environment in Australia. The model was developed to calculate CH_4, N_2O and total GHG emissions from the livestock production system as a whole. The model includes input data (see below for details) in regards to foodstuffs, herd structure, farm management and manure management. In addition, the model takes into account the prevailing local weather conditions. The input information is used in the model to determine the GHG emissions. The dairy GHG model predicts carbon (C) and nitrogen (N) flows on dairy farms. The model is designed to measure direct and indirect CH_4 and N_2O emissions from dairy farms and to assess mitigation strategies. The pre-chain emissions included in the model comprise the use of energy, fertilizers, pesticides and foodstuffs. However, energy costs associated with farm buildings and machinery are not included. The imports, exports and flows of all products through the internal chains on the farm are modeled. The model thus allows assessments of emissions from the production unit and all pre-chains.

Model structure

The DairyGHG model was developed to provide a simple tool for predicting the integrated net global warming potential (GWP) of all GHG emissions from dairy production systems. Secondary emissions from the production of farm inputs such as machinery, fertilizer, fuel, electricity and chemicals are also included to determine an overall carbon footprint for the production system. DairyGHG is designed to estimate emissions of dairy production systems. This production system generally represents a farm, but the system boundaries may be different than that of the physical

Table 1. Annual and seasonal 10-year average weather data of the study location.

Weather parameters	Winter (June, July and August)	Spring (September, October and November)	Summer (December, January and February)	Autumn (March, April and May)	Annual verage
Average ambient temperature (°C)	13.94 ± 1.31	20.37 ± 1.85	24.10 ± 2.11	19.50 ± 1.96	19.48 ± 1.81
Average precipitation (mm)	1.49 ± 0.03	2.99 ± 0.11	5.35 ± 0.10	2.66 ± 0.16	3.12 ± 0.10
Average solar radiation (MJ/m^2)	13.68 ± 0.96	20.96 ± 0.88	22.67 ± 1.15	16.49 ± 1.55	18.45 ± 1.14
Average wind velocity (m/s)	3.01 ± 0.07	3.01 ± 0.04	3.01 ± 0.7	3.01 ± 0.06	3.01 ± 0.06

farm. The boundaries of the production system include the production of all feeds used to maintain the herd. All manure nutrients are assumed to be returned and used in crop production unless a portion or all of the manure is designated as exported from the production system. Likewise, emissions during the production of all feed crops are included whether those feeds are produced on the same farm with the animals or they are purchased from another farm. This approach provides a comprehensive evaluation of the full milk production system that looks beyond the specific boundaries of the farm.

DairyGHG includes a process-based simulation of gaseous emissions from dairy barns and manure storage, following field application of manure and during grazing. These major processes that permit gaseous emissions are simulated through time over many years of weather to obtain long-term estimates of maximum and average emissions. The major components of the model include available feeds, animal intake and manure production, and manure handling. The feeds available and their nutrient contents are provided through user input. Balanced rations are prepared for each animal group on the farm and their feed intake is determined to meet their energy and protein requirements. Based upon feed intake, growth and milk production, the nutrient output in manure is predicted. From this nutrient excretion, emissions are predicted as a function of weather conditions and management practices.

Model inputs

Input information is supplied to the program through two data files: farm and weather parameter files. The farm parameter file contains data that describe the farm facilities. This includes feeds and pasture available, number of animals at various ages, housing facilities, and manure handling strategies. The feed information comprises of the type of roughage (silage and hay) and energy supplements provided to the farm animals. The grazing information, comprising types of animals sent for grazing, type of soil, annual pasture availability and grazing time, is also covered under feed information. The herd information comprises information pertaining to breed of dairy cattle, different age groups of animals, number of first-lactating animals and target milk production on the farm. In addition, the herd information also covers the management strategies such as calving strategy, level of use of forage and use of growth promoters. The manure information comprises the method of manure collection, field application method, type of manure, manure incorporation by tillage, storage period, type of storage pit with dimensions and storage capacity, type and amount of bedding materials used, manure import/export information and composition. These parameters are quickly and conveniently modified through the menus or dialog screens in the user interface.

The weather data file contains daily weather for many years at a particular location. Weather files for each state are provided with the model. All files are in a text format so they can be easily created or edited with a spreadsheet program or text editor. When creating a new weather file, the exact format for the weather data file must be followed. The first line contains a site code, the latitude and longitude for the location, the atmospheric carbon dioxide level, and a parameter set to 0 for the northern hemisphere and 1 for the southern. The remainder of the file contains one line of data for each day. The daily data include the year and day of that year, solar radiation (MJ/m^2), average temperature (°C), maximum temperature (°C), minimum temperature (°C), total precipitation (mm), and wind velocity (m/s). Only 365 days are allowed each year, so one day of data must be removed from leap years.

GHG sinks and sources included in the model

Multiple processes emit CO_2 from dairy farms. The major source is animal respiration followed by less significant emissions from manure storages and barn floors. Cropland assimilates CO_2 from the atmosphere through fixation during crop growth and emits CO_2 through plant and soil respiration. Major sources of methane include enteric fermentation and long-term storage of manure, with minor sources being the barn floor, field-applied manure and feces deposited by grazing animals. Nitrous oxide is a product of nitrification and denitrification processes in the soil, and these processes can also occur in the crust on slurry manure storage or during the storage of solid manure in a bedded pack or stack. A comprehensive evaluation of production systems is obtained by considering the integrated effect of all sources and sinks of the three gases. Figure 1 describes the various sinks and sources of all three major GHGs on the livestock farm.

Model assumptions

The model is a structured program that uses various objects or subroutines to represent processes on the farm. There are four major sub-models that represent the major component processes. These major components are: feed availability, the herd, manure handling, and gas emissions. The model begins by gathering input information. All parameters stored in the requested farm parameter file are read. The model user can modify most of these parameters by editing the displayed values in the input menus and dialog boxes. If the file is saved, the modified values become permanently stored in the file, or a new file can be created using a different name. After the input parameters are properly set, a simulation can be performed. The first step in any simulation is to initialize various arrays of information in the model. This initialization sets all simulation variables to

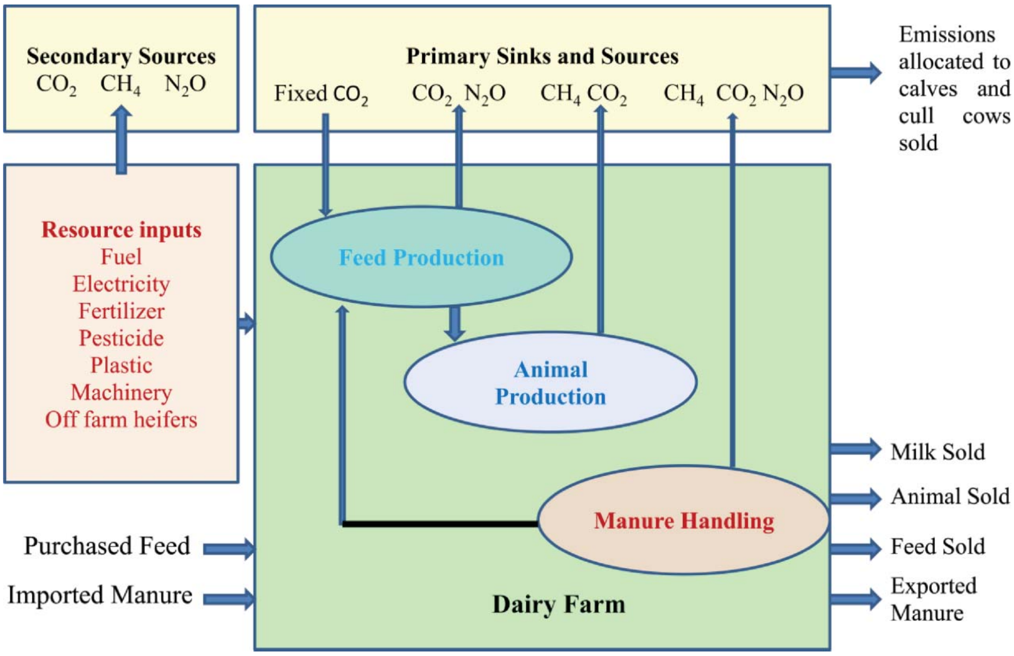

Figure 1. Carbon footprint boundaries and components (adopted from Rotz *et al*. [33]).
Different sinks and sources of all three major GHGs on the livestock farms.

their starting condition. The simulation is performed on a daily time step over each weather year. Weather data is read for the 365 days of the first year from the weather file. Each of the major farm processes is simulated through those weather conditions, and then the next year of weather data is read. This continues until 15 years are simulated. In a given year, the simulation begins with feed utilization and herd production. Feed allocation, feed intake, milk production and manure production are predicted for each animal group making up the herd. Most often these processes are simulated on an annual time step, where feed rations for all animals are formulated for the year based upon the feeds available. If pasture or a seasonal calving herd is used, feeding and herd production processes are simulated on a monthly time step. The pasture available in a given month and the stored feeds available that year are used to feed the animal groups each month. Supplemental feeds are purchased to meet protein and energy requirements of the herd. Following the herd simulation, the manure produced is tracked through the scraping, storage and application processes to predict gas emissions and the balance of nutrients around the maintenance of the herd. Manure production is predicted from the feed dry matter (DM) consumed and the digestibility of those feeds. Emissions during manure handling processes are then simulated on a daily time step as influenced by manure characteristics, temperature, rainfall and solar radiation. Following the simulation of manure handling processes, the simulation proceeds to the next weather year and the process is repeated. This annual loop continues until 10 years, or a smaller number of years in the weather file, are completed. After the simulation is complete, all performance and emission information is organized and written to output files. Table 2 describes the different emission factors for various gases for different types of animals, manure and other production input variables in the model.

Table 2. Different emission factors for various gases for different types of animals, manure and other production input variables.

Process on livestock farm	Emission factor			Ref.
	CO_2	CH_4	N_2O	
Lactating cows	3120 kg LU^{-1}	106 kg LU^{-1}	0.3 kg LU^{-1}	[1]
Dry cows	2020 kg LU^{-1}	58 kg LU^{-1}	0.3 kg LU^{-1}	[1]
Replacement heifers	2800 kg LU^{-1}	77 kg LU^{-1}	0.3 kg LU^{-1}	[1]
Manure storage	17 kg LU^{-1}	5.6 kg m^{-3}	0.13 kg LU^{-1}	[1]
Grazing land	–	–	2% of applied N × 1.57	[33]
Animal facilities	–	–	0.02 (kg N excreted) – 1	[33]
Fuel	0.374 kgCO_2 eq	–	–	[1]
Electricity	0.73 kgCO_2 eq/kWh	–	–	[1]
Machinery	3.54 kgCO_2 eq kg^{-1}	–	–	[1]
Nitrogen fertilizer	3.307 CO_2 eq kg^{-1}	–	–	[1]
Phosphate fertilizer	1.026 CO_2 eq kg^{-1}	–	–	[1]
Potash	0.867 CO_2 eq kg^{-1}	–	–	[1]
Pesticide	22.0 CO_2 eq kg^{-1}	–	–	[1]

Model outputs

The output data includes emission rates of CH_4, N_2O, CO_2 and total GHG in CO_2 equivalents from different farm sources such as housed animals, manure storage, net feed production, fuel combustion and secondary sources. The model also has the provision to calculate the carbon footprint based on CO_2 eq per kg of energy-corrected milk. In addition the model can give details of daily CH_4 emission from barn and manure storage, daily CH_4 emission from the farm as a whole, daily CO_2 emission from barn and manure storage, daily net CO_2 emission from the farm, daily GHG emission from barn and storage, and daily net GHG emission (CO_2 eq) from the farm.

Dairy farm and feeding details

Four representative commercial dairy farms were selected for the study, from Gatton and adjacent areas of southeast Queensland. The dairy farms were identified as Farm 1, Farm 2, Farm 3 and Farm 4. The breed used on Farm 1 was Jersey, and on Farms 2 to 4 the Holstein breed was used. The numbers of cows on each farm were: Farm 1 – 220, Farm 2 – 460, Farm 3 – 850 and Farm 4 – 434. The target milk production was 7000 L on Farm 1 and 8000 L on farms 2 to 4. The animals at Farm 1 and Farm 4 were maintained in the dry lot housing system. However, the animals at Farm 2 and Farm 3 were not housed. On Farms 1 and 2, only corn silage was used as the roughage source. On Farms 3 and 4 numerous roughage sources were used: corn, barley and white sorghum silages, and grassy hay. Grazing was the normal management practice for most of the year on Farms 1, 2 and 3, whereas on Farm 4 cows were only grazed for 6 months. The average annual milk production of the herd is converted to energy-corrected milk using a standard milk fat content of 3.5% and milk protein content of 3.1%. An energy correction factor is determined as: $ECF = 0.327 + 0.1295\ (MF) + 0.072\ (MP)$, where ECF = energy correction factor; MF = milk fat content (%) and MP = milk protein content (%). The input details of all four farms are described in Table 3.

Results

Average daily methane, nitrous oxide, carbon dioxide and net GHG emission from the commercial dairy farms

The average daily CH_4, N_2O, CO_2 and total GHG emissions from Farms 1, 2, 3 and 4 are described in Table 4. Grazing

Table 3. Input details for the software for all four farms.

Input criteria	Input details: Farm 1	Farm 2	Farm 3	Farm 4
Type of animals	Jersey	Holstein	Holstein	Holstein
Total animals on farm	220	460	850	434
Age	1–4 years	1–4 years	1–4 years	1–4 years
< 1 year	50	155	310	120
1–2 years	70	125	170	134
2–4 year	100	180	370	180
Average body weight	430 kg	575 kg	575 kg	575 kg
Daily feed consumption (kg)				
< 1 year	5	7	7	7
1–2 year	7.5	10.5	10.5	10.5
2–4 year	10.5	14.5	14.5	14.5
Target milk production	7000 L	8000 L	8000 L	8000 L
Housing of animals	Dry Lot	None	None	Dry lot
Calving strategy	Random calving	Random calving	Calving in fall season	Random calving
Primary feed	Corn silage	Corn silage	Barley, corn and sorghum silage	Barley, sorghum and corn silage
Crude protein supplementation	–	Canola seed meal and urea	Soybean meal (48%) and urea	Soybean meal (48%) and canola seed meal
Less degradable protein	Brewers grain	–	Cotton seed and molasses	–
Protein content of diet (g/kgDM)	105–110	105–110	95	95
Energy supplement	Dry grain	Dry grain	Dry grain	Dry grain
Grazing	Old heifers and all lactating cows	All animals	All animals	All animals
Soil type	Clay loam	Clay loam	Clay loam	Clay loam
Grazing time	12 months	12 months	11 months	6 months
Annual pasture	900 t	1000 t	2000 t	500 t
Manure collection	Hand scraping with gutter cleaners	Scraper with bucket loading	Scraper with bucket loading	Scraper with bucket loading
Type of manure	Solid (20% DM)	Solid (20% DM)	Solid (20% DM)	Solid (20% DM)
N content of manure (lbs/ton)	11	11	11	11
N content of urine (g/L)	7	7	7	7
Field application method	Broadcast spreading	Broadcast spreading and irrigation	Band spreading	Broadcast spreading
Storage period for manure	Six months	Two months	Six months	Six months
Type of storage pit	Top-loaded earthen pit	Pond	Top-loaded earthen pit	Top-loaded earthen pit

DM: Dry Matter

Table 4. **Daily average of methane, nitrous oxide, carbon dioxide, and net greenhouse gas emissions on the four experimental farms.**

	Farm 1		Farm 2		Farm 3		Farm 4	
GHGs and sources	kg/cow	kg	kg/cow	kg	kg/cow	kg	kg/cow	kg
Methane								
Housed animals	0.134	15	0.085	21	0.083	42	0.993	191
Manure storage	0.004	0	0.001	0	0.001	1	–	–
Field-applied manure	0.000	0	0.000	0	0.000	0	0.001	0
Grazing animals	0.179	21	0.486	122	0.479	239	0.252	48
Total emission	0.318	37	0.573	143	0.564	282	1.245	239
Nitrous oxide								
Housing	0.006	1	–	–	–	–	–	–
Manure storage	0.000	0	0.001	0	0.001	0	0.011	2
Farmland	0.013	1	0.022	6	0.021	11	0.015	3
Total emission	0.019	2	0.023	6	0.022	11	0.026	5
Carbon dioxide								
Housed animals	6.447	741	2.692	673	2.577	1289	17.198	3302
Manure storage	0.012	1	0.033	8	0.032	16	–	–
Net fed production	−18.174	−2090	−25.410	−6353	−26.898	−13449	−34.882	−6697
Grazing animals	7.283	838	15.027	3757	14.379	7190	8.045	1545
Fuel combustion	0.527	61	0.801	200	0.722	361	1.793	344
Net emission	−3.904	−449	−6.858	−1714	−9.188	−4594	−7846	−1506
Total greenhouse gas (CO_2 eq)								
Housed animals	11.445	1316	4.809	1202	4.663	2332	45.315	8700
Manure storage	0.202	23	0.301	75	0.276	138	–	–
Net fed production	−14.292	−1644	−18.709	−4677	−20.586	−10,293	−30.403	−5837
Grazing animals	11.768	1353	27.184	6796	26.351	13,176	14.334	2752
Fuel combustion	0.527	61	0.801	200	0.722	361	1.793	344
Secondary sources	–	–	1.408	352	1.936	968	–	–
Not allocated to milk	−0.374	−43	−1.328	332	−1.004	−502	−2.501	−480
Net emission	7.991	919	14.466	3616	12.358	6179	28.188	5412

and housed cows contributed to the daily CH_4 emissions on Farms 1, 2 and 3 (Table 4). However, for Farm 4, the predominant contribution to average daily CH_4 emission was from the housed cows (Table 4). The highest total average daily CH_4 emission was from Farm 4 (1.25 kg/cow), and the lowest was from Farm 1 (0.32 kg/cow). Likewise, the highest contribution of daily N_2O was from the farmland in all four farms. A small amount of the daily N_2O emission was also contributed by housed cows and manure storage (Table 4). The highest total average daily N_2O emission was from Farm 4 (0.026 kg/cow), and the lowest was from Farm 1 (0.019 kg/cow). Negative values were obtained for the daily average CO_2 emission on all four farms as the positive contributions from housed cows, manure storage, grazing cows and fuel combustion are offset by the net feed production. Grazing and housed cows contributed to the daily net GHG emission for Farms 1, 2 and 3 (Table 4). However, for Farm 4, the predominant contribution to average daily net GHG emission was from the housed cows (Table 4). On an individual cow basis the highest daily net GHG (CO_2 eq) emission was from Farm 4, and the lowest was from Farm 1 (Table 4). The total average daily net GHG (CO_2 eq) emissions from Farms 1, 2, 3 and 4 were 7.99, 14.47, 12.36 and 28.19 kg/cow, respectively.

Average annual methane, nitrous oxide, carbon dioxide and net GHG emission from the commercial dairy farms

The average annual CH_4, N_2O, CO_2 and total GHG emission from Farms 1, 2, 3 and 4 are described in Table 5. The highest contribution of annual CH_4 was from the grazing cows on Farms 1, 2 and 3, while on Farm 4 it was from the housed cows. The highest total average annual CH_4 emission was from Farm 4 (434.5 kg/cow), and the lowest was from Farm 1 (116 kg/cow). Likewise, the highest contribution of annual N_2O was from the farmland on all four farms (Table 5). The highest total average annual N_2O emission was from Farm 4 (9.5 kg/cow), and the lowest was from Farm 1 (6.9 kg/cow). As with the daily average CO_2, negative values were obtained for the total annual CO_2 emission on all four farms because the positive contributions from housed cows, manure storage, grazing cows and fuel combustion are offset by the net feed production. Grazing and housed cows contributed to the annual net GHG emission on all four farms (Table 5). On an individual cow basis, the highest annual net GHG (CO_2 eq) emission was from Farm 4 and the lowest was from Farm 1 (Table 5). The total average annual net GHG (CO_2 eq) emissions from Farms 1, 2, 3 and 4 were 2916.6, 5280.0, 4510.5 and 10288.6 kg/cow, respectively.

Comparison of methane, nitrous oxide, net GHG emission and carbon footprints for all four commercial dairy farms

The levels of annual CH_4, N_2O and net GHG emission per cow on the Farms 1, 2, 3 and 4 are described in Figures 2, 3 and 4, respectively. On an individual animal basis, the highest CH_4 emission was recorded on Farm 4 while the lowest was on Farm 1 (Figure 2). Annual CH_4 emissions from Farm 2 and Farm 3 were similar

Table 5. **Annual average of methane, nitrous oxide, carbon dioxide, and net greenhouse gas emissions on the four experimental farms.**

	Farm 1		Farm 2		Farm 3		Farm 4	
GHG and sources	kg/cow	kg	kg/cow	kg	kg/cow	kg	kg/cow	kg
Methane								
Housed animals	49.0	5631	30.9	7730	30.5	15,229	362.4	69,585
Manure storage	1.4	158	0.5	121	0.5	234	–	–
Field-applied manure	0.2	19	0.2	43	0.0	1	0.2	46
Grazing animals	65.5	7530	177.5	44,373	174.8	87,396	91.8	17,630
Total emission	116.0	13,339	209.1	52,267	205.7	102,861	434.5	87,260
Nitrous oxide								
Housing	2.0	232	–	–	–	–	–	–
Manure storage	0.1	14	0.3	72	0.3	130	4.0	775
Farmland	4.7	545	8.2	2048	7.7	3865	5.5	1050
Total emission	6.9	790	8.5	2120	8.0	3995	9.5	3995
Carbon dioxide								
Housed animals	2353.2	270,614	982.4	245,602	940.7	470,350	6277.2	1,205,227
Manure storage	4.5	513	12.0	3001	11.7	5850	–	–
Net fed production	−6633.3	−76,2834	−9274.8	−2,318,692	−9817.8	−4,908,889	−12,732.1	−2,444,559
Grazing animals	2658.2	305,694	5484.8	1,371,199	5248.5	2,624,232	2936.5	563,800
Fuel combustion	192.4	22,125	292.4	73,105	263.5	131,706	654.6	125,682
Net emission	−1425.1	−163,887	−2503.1	−625,782	−3353.5	−1,676,754	−2863.8	−549,851
Total greenhouse gas (CO_2 eq)								
Housed animals	4177.3	480,385	1755.4	438,862	1702.1	851,072	16,539.8	3,175,650
Manure storage	73.9	8500	109.8	27,457	100.6	50,321	–	–
Net fed production	−5216.8	−599,928	−6829.0	−1,707,240	−7514.0	−3,757,004	−11,097.0	−2,130,625
Grazing animals	4295.2	493,944	9922.1	2,480,533	9618.3	4,809,142	5232.0	1,004,539
Fuel combustion	192.4	22,125	292.4	73,105	263.4	131,706	654.6	125,682
Secondary sources	–	–	513.9	128,484	706.6	353,321	–	–
Not allocated to milk	−136.7	−15717	−484.8	−121,194	−366.6	−183,317	−912.7	−175,237
Net emission	2916.6	335,405	5280.0	1,320,007	4510.5	225,5251	10,288.6	1,975,412

Cradle-to-farm gate carbon footprint including carbon dioxide from
Farm 1
-all important sources and sinks: 0.39 kg CO_2 eq/kg of energy-corrected milk sold
-engine emissions only: 0.55 kg CO_2 eq/kg of energy-corrected milk sold
Farm 2
-all important sources and sinks: 0.64 kg CO_2 eq/kg of energy-corrected milk sold
-engine emissions only: 0.88 kg CO_2 eq/kg of energy-corrected milk sold
Farm 3
-all important sources and sinks: 0.54 kg CO_2 eq/kg of energy-corrected milk sold
-engine emissions only: 0.88 kg CO_2 eq/kg of energy-corrected milk sold
Farm 4
-all important sources and sinks: 1.35 kg CO_2 eq/kg of energy-corrected milk sold
-engine emissions only: 1.60 kg CO_2 eq/kg of energy-corrected milk sold

(Figure 2). On an individual animal basis, the highest N_2O emission was predicted for Farm 4 while the lowest was predicted for Farm 1 (Figure 3). Annual N_2O emissions from Farms 2 and 3 are almost the same (Figure 3). On an individual animal basis, the highest net GHG emission was predicted for Farm 4 while the lowest was predicted for Farm 1 (Figure 4). Annual net GHG emissions on Farms 2 and 3 were similar (Figure 4).

The carbon footprints of all farms are depicted in Figure 4. On a comparative basis, for Farm 1

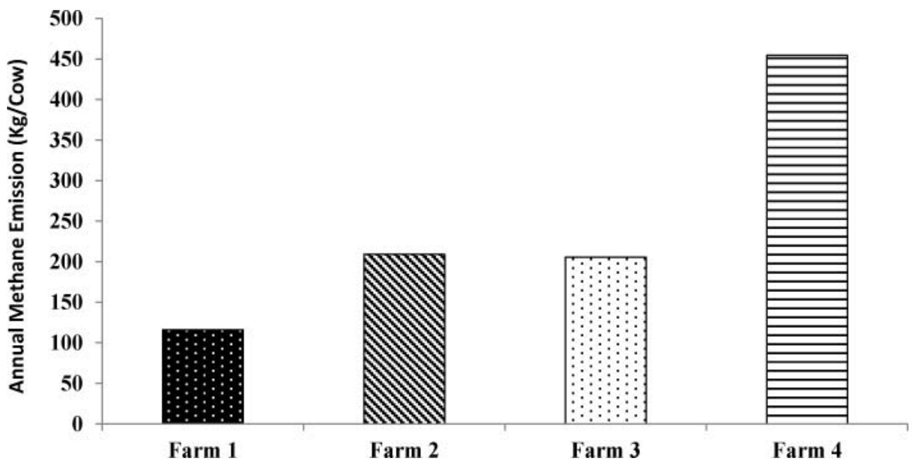

Figure 2. **Comparison of annual methane (kg/cow) emission on the four dairy farms.**
On an individual animal basis, the highest methane emission was recorded on Farm 4 while the lowest was recorded on Farm 1. Annual methane emissions on Farms 2 and 3 are almost the same.

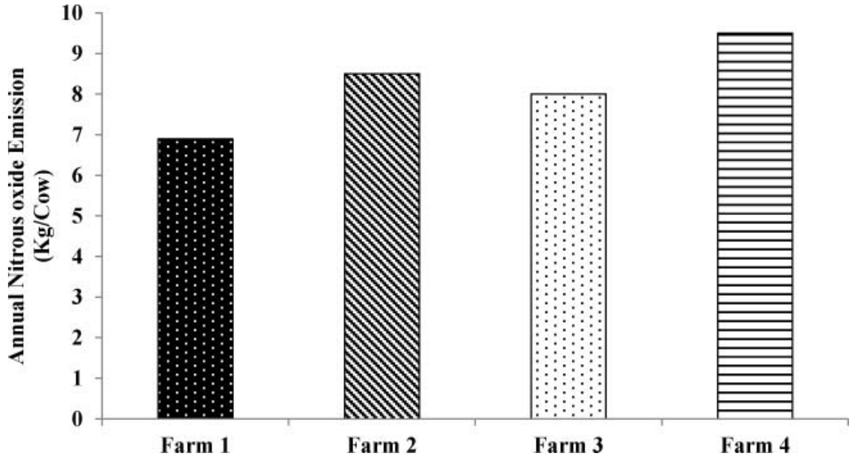

Figure 3. **Comparison of annual nitrous oxide (kg/cow) emission on the four livestock farms.**
On an individual animal basis, the highest nitrous oxide emission was recorded on Farm 4 while the lowest was recorded on Farm 1. Annual nitrous oxide emissions on Farms 2 and 3 are almost the same.

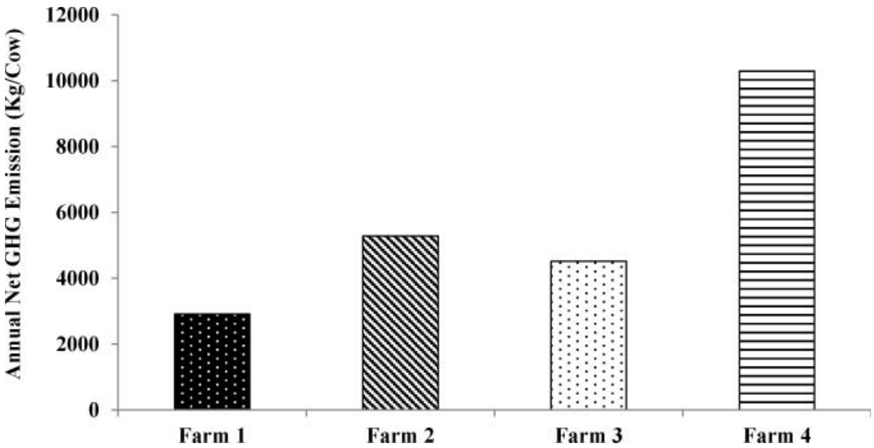

Figure 4. **Comparison of annual net greenhouse gas (kg/cow) emission on the four dairy farms.**
On an individual animal basis, the highest net GHG emission was recorded on Farm 4 while the lowest was recorded on Farm 1. Annual net GHG emissions on Farms 2 and 3 are almost the same.

(Figure 5a), Farm 2 (Figure 5b) and Farm 3 (Figure 5c) the highest contribution to carbon footprint was from animal emissions, whereas for Farm 4 (Figure 5d) the highest contribution came from manure emissions. On the basis of per kg of energy-corrected milk, the predicted amount of GHG produced from Farm 1 (Figure 5a), Farm 2 (Figure 5b), Farm 3 (Figure 5c) and Farm 4 (Figure 5d) was 0.39, 0.64, 0.54 and 1.35 kg CO2 eq, respectively. Further, engine emissions and secondary emissions during the production of farm inputs also contributed a few percentage points to the carbon footprints.

Seasonal distribution pattern of whole-farm daily methane and net GHG emission

The whole-farm daily CH_4 distribution pattern across the year for the four dairy farms is depicted in Figure 6. The daily CH_4 emissions from Farm 1 ranged from 35 to 40 kg/d. The highest daily CH_4 emission for Farm 1 was during spring while the lowest level was during winter. The daily CH_4 emissions for Farm 2 ranged from 125 to 155 kg/d. The highest daily CH_4 emissions for Farm 2 were during autumn and winter while the lowest was during summer. For Farm 3 daily CH_4 emissions were between 270 and 315 kg/d. The highest level of daily CH_4 emissions from Farm 3 was during the autumn and winter and the lowest level was during the spring and summer. The daily CH_4 emissions for Farm 4 were between 125 and 450 kg/d. The highest level of daily CH_4 emissions for Farm 4 were during summer and the lowest was during the autumn and winter.

The whole-farm daily net GHG distribution patterns across the year for all dairy farms is shown in Figure 7. The daily net GHG (CO_2 eq) emissions for Farm 1 were between 850 and 1550 kg/d over the span of a year. The highest level of daily net GHG (CO_2 eq) emissions for Farm 1 was during summer while the lowest levels were during autumn, winter and spring. The daily net GHG (CO_2 eq) emissions for Farm 2 were between 3000 and 3700 kg/d. The distribution pattern of daily

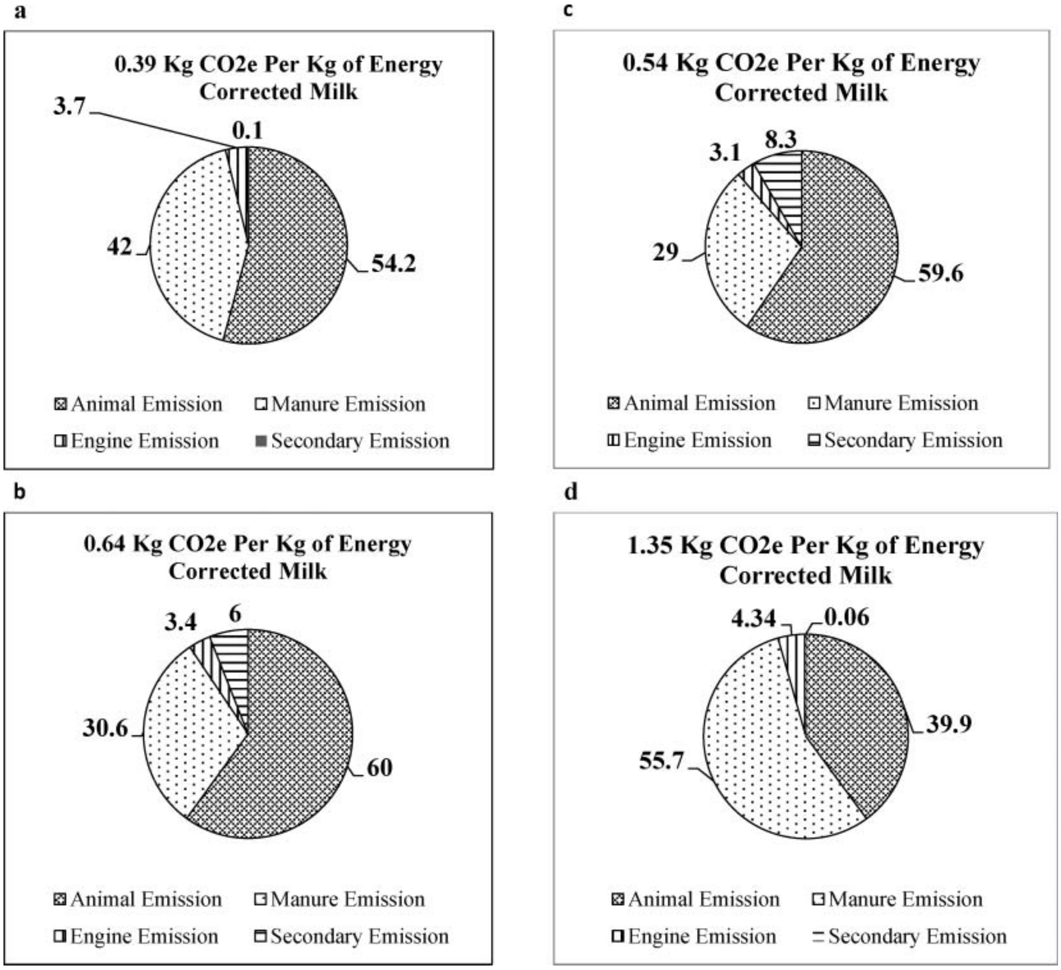

Figure 5. Carbon footprints of the four dairy farms on the basis of per kg energy-corrected milk
On a comparative basis, on Farm 1 (a), Farm 2 (b) and Farm 3 (c) the highest contribution to carbon footprint was from animal emissions, whereas on Farm 4 (d) the highest contribution came from manure emission. On the basis of per k kg of energy-corrected milk the amount of greenhouse gas produced on Farm 1 (a), Farm 2 (b), Farm 3 (c) and Farm 4 (d) was 0.39 kg, 0.64 kg, 0.54 kg and 1.35 k kg CO_2 eq, respectively.

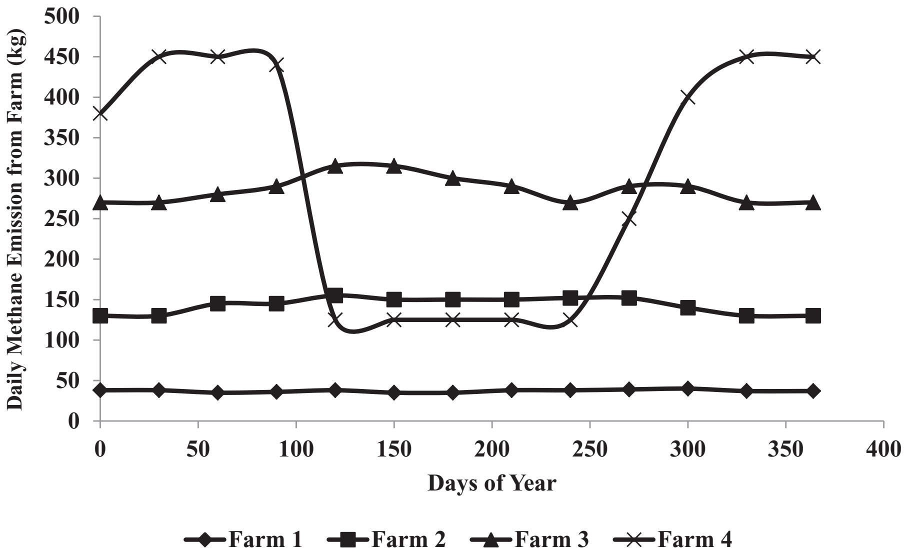

Figure 6. Comparison of whole-farm daily methane emissions (kg) from the four dairy farms, on different days of the year
The highest level of daily CH_4 emission (kg) on Farm 1, Farm 2, Farm 3 and Farm 4 was established during spring, autumn and winter, autumn and, and summer, respectively. The lowest level of daily CH_4 emission (kg) on Farm 1, Farm 2, Farm 3 and Farm 4 was established during winter, summer, spring and summer, and autumn and winter, respectively.

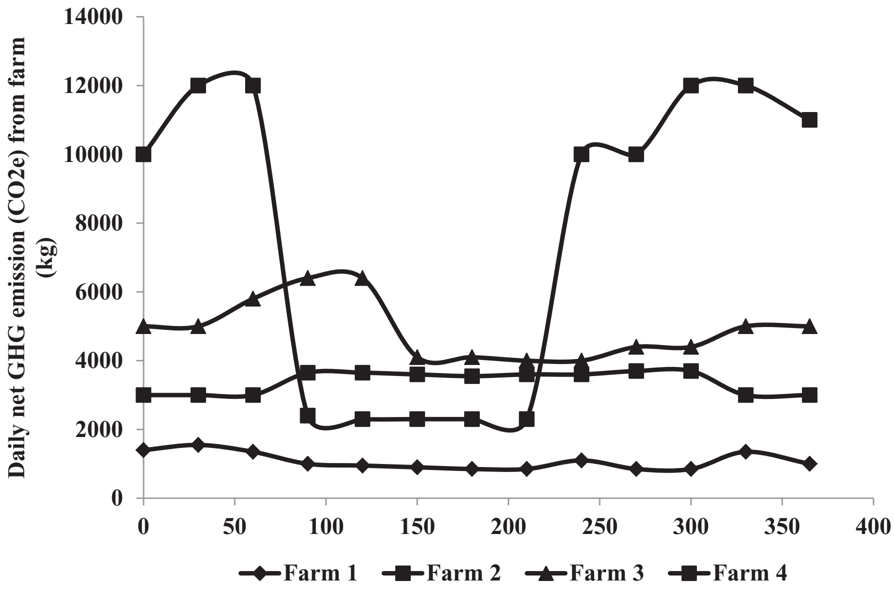

Figure 7. **Comparison of whole-farm daily net GHG emission (kg CO_2 eq) among the four dairy farms, on different days of the year**
The highest level of daily net GHG emission (kg) on Farm 1, Farm 2, Farm 3 and Farm 4 was established during summer; autumn, winter and spring; autumn; and summer, respectively. The lowest level of daily net GHG emission (kg) on Farm 1, Farm 2, Farm 3 and Farm 4 was established during autumn, winter and spring; summer; spring; and autumn and winter, respectively.

net GHG (CO_2 eq) emissions for Farm 2 showed a reverse trend compared to Farm 1. The highest levels of daily net GHG (CO_2 eq) emissions for Farm 2 were during autumn, winter and spring, and the lowest level was established during the summer. The daily net GHG (CO_2 eq) emissions for Farm 3 were between 4000 and 6400 kg. The highest level of daily net GHG (CO_2 eq) emissions for Farm 3 was during the autumn and the lowest level was during the spring. The daily net GHG (CO_2 eq) emissions for Farm 4 were between 2300 and 12,000 kg/d across different days of the year. The highest levels of daily net GHG (CO_2 eq) emissions for Farm 4 were during summer and spring and the lowest levels were during the autumn and winter.

Discussion

A dairy farm is a complex system with several interacting subsystems. Whole-farm models of dairy systems should therefore be able to give an accurate representation of the internal cycling of materials and their constituents as well as the exchange of materials and nutrients between the farming system and its environment [16]. Moreover, such models should reliably predict the effects of changes in management. Given the global scope of the assessment and the complexity of dairy systems, several hypotheses and generalizations have been used to overcome the otherwise excessive data requirements of the GHG assessment in the existing dairy production systems. These are the types of efforts which can help to quickly identify the appropriate mitigation strategies to find a solution for livestock-induced climate change.

The largest contributions to the GHG pool for the four farms assessed were CH_4 emissions. Each individual dairy farm will have a different emissions profile depending upon its farm system. Approximately 60 to 70% of a typical dairy farm's emissions arises from CH_4 produced by rumination [17]. Both average daily and annual CH_4 emissions were lowest on Farm 1 and highest on Farm 4. The differences could be attributed to the different feeding systems on these farms. There are studies indicating CH_4 emission depends on nutritional inputs [18,19]. The significantly lower predicted CH_4 emissions from Farm 1 as compared to other farms may be attributed to breed differences as generally Jersey cows produce less CH_4 as compared to Holstein cows [20,21]. Further, the target milk production also was lower for Farm 1 compared to the other farms, which would also explain the reduced CH_4 production from Farm 1 [22].

The primary differences in estimates of GHG produced from the farms could be attributed to differences in diet composition, and feeding and grazing patterns. The amount of CH_4 produced through enteric fermentation is impacted by various factors, including animal type and live weight, dry matter intake (DMI), digestibility of the feed, total dietary carbohydrates and digestibility of the carbohydrates [23,24]. Furthermore, CH_4 emissions are positively correlated with live weight, DMI and milk yield (MY). The lower CH_4 emission from Farms 1 and 2 compared to Farms 3 and 4 could be due to the differences in roughage composition. On Farms 1 and 2 only corn silage was fed, whereas on Farms 3 and 4 barley, sorghum and corn silage were used. Similar observations of corn silage-based reductions in CH_4 emissions from dairy cows were reported by Sejian *et al*. [25]. Thus, knowledge of the dietary components – not only of typical foodstuffs, but also of alternative foodstuffs that are under consideration for CH_4 emission reduction purposes – is an essential prerequisite for successful use of these models to compare the effects of different feeds on CH_4 production [26].

The high forage intake per unit of milk production for Farm 4 could be the reason for the very high CH_4 production from this farm compared to the other farms. It is not only the forage quantity, but also the forage quality that has a significant impact on enteric CH_4 emissions [25,27]. The higher carbon footprint per kg of milk production for Farm 4 compared to the other farms could be attributed to the extended grazing periods on the other farms. There are reports suggesting an extended grazing season reduces the carbon footprint of milk production [28,29]. However, the negative association of extended grazing on carbon footprint may only be moderate as the extended grazing may also increase N_2O emissions from manure excreted on pasture by grazing cattle [30].

The reason for varied CH_4 production among the farms could also be due to differences in the forage preservation, which has not been studied at length. The ensiling process results in fermentation of the forages, which can reduce digestion in the rumen and, ultimately, the CH_4 production [31,32]. Hence, future efforts are needed to include the dynamics of forage preservation modules in the IFSM. From these findings, it is evident that there are several promising strategies that may be developed to reduce CH_4 emissions through forage selection using the DairyGHG model, but these need further investigation, particularly at a whole-farm level. The results from the current study suggest that a comprehensive evaluation of the effect of forage quality on CH_4 emissions must consider diet composition and level of intake. The mechanistic representation of digestion and fermentation processes in this model offers a good opportunity to test the model's ability to predict CH_4 production compared to the existing simple regression equations [14].

The IFSM was effectively used to predict the N_2O emission through various sources in this study. The IFSM is a cost-effective and efficient method of estimating N_2O emissions from dairy farms and analyzing how management scenarios affect these emissions [33]. The major contributor to N_2O emissions from the farms assessed is the land used for grazing or holding cows. On Farms 1 and 4 the cows were housed and a considerable amount of the predicted N_2O emissions came from this source. The highest contribution of N_2O to the total emissions is mainly caused by the deposition of dung and urine in pastures, due to the long grazing time for the animals [6]. The higher N_2O emission from Farms 2, 3 and 4 relative to Farm 1 could be attributed to a large number of animals on these farms, and further all animals were grazed on other farms as compared to only older heifers and lactating cows being grazed on Farm 1. Chianese *et al*. [34] predicted an annual total of 681 kg of N_2O emission from a 100-Holstein cattle dairy farm using IFSM. Predictions of N_2O emission for the four farms studied here are considerably higher than what they reported [34], and could be attributed to the large number of animals on these farms. The N_2O level was directly proportional to the number of animals on each farm. Further, the higher N_2O emissions from all four farms would be influenced by soil type (clay loam) as generally N_2O emission are higher from clay loam soils compared to loam soils [34].

The CO_2 emission per unit product was the least contributor among the major GHGs to the net total GHG emission, which is in agreement with the findings reported by Chianese *et al.* [35] on dairy farms. Primary sources of CO_2 emissions on dairy farms are soil, plant and animal respiration, with smaller contributions from microbial respiration in manure. Animals and manure handling provide additional sources of CO_2 emission from dairy farms [17]. These emission sources are offset by that assimilated in crop growth, with about 50% more CO_2 assimilated than is emitted from the farm [35]. The Food and Agriculture Organization (FAO) [5] also reported that CO_2 plays a minor role in on-farm emissions, representing on average 5 to 10% of the total emissions. Further, it is an established fact that CO_2 emissions are highest in the temperate zones, where milk production levels are highest and high energy is used for feed production,as in US-based systems [35]. In a sub-tropical environment like Southern Queensland, where the studied farms were located, the emission of CO_2 should therefore be less, and moreover the targeted milk production also was less, which indicates again that less machinery is used on these farms. This could be the reason for the negative effect of CO_2 on the overall GHG emissions from these farms. Agriculture in general and dairy farms in particular are not considered to be an important global source of CO_2 [3]. This is the reason the CO_2 is sometimes ignored when assessing GHG emissions from dairy farms [3,36]. In the overall farm balance, the CO_2 released is largely offset by the CO_2 assimilated in plant material [35]. However to obtain credibility in the prediction of net GHG from a farm, it is essential to include the CO_2 predictive module in IFSM. By including CO_2 emissions, a farm balance of C can be established to ensure a more accurate assessment of all C flows and losses from the dairy farm [35].

Generally, compared to other published prediction model research, the IFSM used in this study predicted comparatively less net GHG emission for the four farms [4,5]. In Canada, Mc Geough *et al*. [4] using an Life Cycle Assessment (LCA) model reported a GHG intensity of 0.92 kg of CO_2 eq/kg of fat- and protein-corrected milk yield, which was much higher than the values reported for Farms 1–3 in the current study. This primary difference in net GHG emission between these studies could be attributed to the low target milk production in this study and, moreover, the above predictions were based on complete life cycle assessment as compared to partial life cycle assessment in the current study. However, Chianese *et al*. [35] reported that the estimated whole−farm net annual GHG emission using the same IFSM model ranged from 0.50 to 1.2 kg CO_2 eq kg^{-1} of milk produced, which was more or less similar to the range reported in the current study among Farms 1, 2 and 3. The net GHG emission on an individual animal basis was much lower on Farm 1 as compared to other farms. This could be attributed to the breed difference in CH_4 emission [20,21]. This shows that genetic differences and differences in total diet consumed between animals in CH_4 production should also be explored in current animal breeding programs in the tropics.

In the current study, the highest net GHG emitted per kg energy-corrected milk was recorded on Farm 4 with 1.35 kg CO_2 eq. On the other farms it was well below 1 kg CO_2 eq. Rotz *et al*. [33], using partial life cycle assessment, predicted carbon footprints of 0.37 to 0.69 kg of CO_2 eq units/kg of energy-corrected milk, depending upon the milk production level and the feeding and manure handling strategies used. This range of carbon footprint was similar to that reported on Farms 1–3 in the current study. O'Brien *et al*. [30] reported that the mean certified carbon footprint of milk from grass-based Irish dairy farms was 1.11 kg of CO_2 eq/kg of fat- and protein-corrected milk, but varied from 0.87 to 1.72 kg of CO_2/kg of fat- and protein-corrected Milk in an extensive system of rearing. In another study, O'Brien *et al*. [37] concluded that the top-performing herds in Irish, UK and US dairy systems have carbon footprints of 27 to 32% lower than average dairy systems. This could be the reason for the low carbon footprint on Farm 1 due to its top-performance herd as compared to other farms in the study.

As per the LCA model of the FAO [5], the amount of net GHG emitted from a livestock farm was 2.4 kg CO_2 eq per kg energy-corrected milk. This shows that the net GHG emissions from all four farms are well below the global average reported by the FAO. However, the primary difference here is that the DairyGHG model is a partial LCA model, accounting only for milk production, and does not take into account the processing and transport of milk – compared to the complete LCA model of the FAO that involves all of these processes. All four farms in the study were following a semi-intensive system of rearing with both grazing and in-house feeding. The LCA [5] predicted the global average of 1.78 kg CO_2 eq. per kg energy-corrected milk in the semi-intensive systems of dairy farms. In comparison to this level, all four farms in the study reported lower net GHG emissions. This shows that all four farms were following effective production systems, directing most of the consumed feeds toward production of milk.

The daily CH_4 and total GHG distributions differed with different seasons on all four farms. Especially for daily CH_4 the peak emission was observed in different seasons on the four farms. However, the highest total GHG emission was recorded during summer on both Farm 1 and Farm 4, while on Farm 2 and Farm 3 it was recorded during the autumn season. In a US-based simulation using the same DairyGHG model, the peak daily CH_4 and total GHG emission coincided with the summer season [17]. Among the dairy farms in the current study, only on Farm 4 were both daily CH_4 and total GHG emission found to be at peak during summer season. There are reports suggesting peak CH_4 emission during hot summer months [38,39]. Further, Verge *et al*. [40] reported similar findings of higher carbon footprints on Canadian dairy farms, to the level 1.12 kg of CO_2 eq/L of milk, and attributed these to differences in climatic conditions and dairy herd management. The erratic peak distribution pattern of both CH_4 and total GHG emission during autumn, spring and winter seasons on Farms 2 and 3 is indicative of an effective management system being in place for these farms during the summer season.

Conclusion

The expanded IFSM was shown to predict both CH_4 and N_2O emissions that were consistent with reported values from specific experiments and previously estimated whole−farm emissions. Further, the study indicated that the Jersey dairy farm emitted less GHG as compared to Holstein per unit of feed consumed and on an individual basis. In addition, the lowest carbon footprint per kg energy-corrected milk was recorded on Farm 1. This shows an effective production system supported with appropriate management practices on Farm 1 as compared to the other three farms. In addition, the results from this study will advance the examination of diet-related CH_4 emission mitigation strategies and regulatory policies. Knowing how much each of the various sources of dairy farm emissions contributes to the total farm emission is important to help determine where and how to invest time and effort to reduce them. Quantifying the accurate GHG emission rate in dairy farms is very crucial if the scientific community wishes to target a solution to global warming through the livestock sector. Along that line, this study is a step forward in finding a solution to livestock-related climate change.

Geolocation statement

The experiment was conducted in Gatton which is situated in the Lockyer Valley of South East Queensland, Australia.

Acknowledgements

The authors express their sincere thanks to Dr. Brad Granzin, Executive Officer, Subtropical Dairy Program Ltd, Regional Manager, Dairy Australia Regional Development Program and Dr. Belinda Haddow, Regional Extension Co-ordinator, South East Queensland, Subtropical Dairy Program Ltd for their valuable help in establishing a link with the experimental dairy farms. The authors also sincerely thank Dr. Allan C. Rotz from Pennsylvania State University for providing the software, and other technical inputs from time to time which helped us troubleshoot the problems we faced while validating the model for the existing Australian conditions.

Disclosure statement

The authors declare that there is no conflict of interest for this particular manuscript.

References

1. Chianese DS, Rotz CA, Richard TL. Whole-farm greenhouse emissions: a review with application to a Pennsylvania dairy farm. *Appl. Eng. Agric*. 25, 431–442 (2009).
2. Gerber PJ, Steinfeld H, Henderson B et al. *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy (2013).
3. FAO Food and Agricultural Organization. *Livestock's Long Shadow-Environmental Issues and Options*. Food and Agriculture Organisation of the United Nations, Rome, Italy (2006).
4. Mc Geough EJ, Little SM, Janzen HH, McAllister TA, McGinn SM, Beauchemin KA. Life-cycle assessment of greenhouse gas emissions from dairy production in Eastern Canada: a case study. *J. Dairy Sci*. 95, 5164–5175 (2012).
5. FAO- Food and Agricultural Organization. *Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment*. Food and Agricultural Organization of the United Nations, Animal Production and Health Division, Rome, Italy (2010).
6. Crosson P, Shalloo L, O' Brien D et al. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. *Anim. Feed Sci. Technol.* 166, 29–45 (2011).
7. Beukes PC, Gregorini P, Romera AJ. Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. *Anim. Feed Sci. Technol.* 166–167, 708–720 (2011).
8. Del Prado A, Crosson P, Olesen JE, Rotz CA. Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems. *Animal* 7, 373–385 (2013a).
9. Del Prado A, Chadwick D, Cardenas L, Misselbrook T, Scholefield D, Merino P. Exploring systems responses to mitigation of GHG in UK dairy farms. *Agric. Ecosyst. Env.* 136, 318–332 (2010).
10. O'Brien D, Shalloo L, Grainger C, Buckley F, Horan B, Wallace M. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. *J. Dairy Sci.* 93, 3390–3402 (2010).
11. Del Prado A, Mas K, Prado G, Gallejones P. Modelling the interactions between C and N farm balances and GHG emissions from confinement dairy farms in northern Spain. *Sci. Total Environ*. 465, 156–165 (2013b).
12. Patra A.K. Recent advances in measurement and dietary mitigation of enteric methane emissions in ruminants. *Front. Vet. Sci.* 3, 39 (2016).
13. Sejian V, Lal R, Lakritz J, Ezeji T. Measurement and prediction of enteric methane emission. *Int. J. Biometeorol.* 55, 1–16 (2011a).
14. Chianese DS, Rotz CA, Richard TL. Simulation of methane emissions from dairy farms to assess greenhouse gas reduction strategies. *T. ASABE* 52, 1313–1323 (2009a).
15. Christie K, Rawnsley R, Donaghy D. *Final Report to Dairy Australia on the Investigation and Analysis into Greenhouse Gas Abatement Strategies, Modelling and Decision Tools for the Australian Dairy Industry*. Tasmanian Institute of Agricultural Research, University of Tasmania, Tasmania, Australia (2008).
16. Schils RLM, Olesen JE, Prado AD, Soussana JF. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livest. Sci.* 1, 240–251 (2007).
17. Sejian V, Rotz A, Lakritz J, Ezeji T, Lal R. Modeling of greenhouse gas emissions in dairy farms. *J. Anim. Sci. Adv*. 1, 12–20 (2011b).
18. Sedorovich DM. Greenhouse gas emissions from agroecosystems: simulating management effects on dairy farm emissions. Unpublished PhD diss. The Pennsylvania State University, Department of Agricultural and Biological Engineering, University Park, PA (2009).
19. Grainger C, Beauchemin KA. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166–167, 308–320 (2011).
20. King EE, Smith RP, St-Pierre B, Wright ADG. Differences in the rumen methanogen populations of lactating jersey and holstein dairy cows under the same diet regimen. *App. Environ. Microbiol.* 77(16), 5682–5687 (2011).
21. Capper JL, Cady RA. A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. *J. Dairy Sci.* 95, 165–176 (2012).
22. Yan T, Mayne S, Porter MG. Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. *Int. Congr. Ser.* 1293, 123–126 (2006).
23. Wilkerson VA, Casper DP, Mertens DR. The prediction of methane production of Holstein cows by several equations. *J. Dairy Sci.* 78, 2402–2414 (1995).
24. Monteny GJ, Bannink A, Chadwick D. Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ.* 11, 163–170 (2006).
25. Sejian V, Lakritz J, Ezeji T, Lal R. Forage and Flax seed impact on enteric methane emission in dairy cows. *Res. J. Vet. Sci.* 4, 1–8 (2011).
26. Palliser CC, Woodward SL. Using models to predict methane reduction in pasture fed dairy cows. *Proceedings Integrating Management and Decision Support. Coordinated by Susan M. Cuddy (CSIRO, Australia). Parte 1*, vol. 482, pp 162–167 (2002).
27. Ulyatt MJ, Lassey KR, Shelton ID, Walker CF. Seasonal variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand. *New Zealand J. Agric. Res.* 45, 217–226 (2002).
28. Robertson LJ, Waghorn GC. Dairy industry perspectives of methane emissions and production from cattle fed pasture or total mixed rations in New Zealand. *Proc. N Z. Soc. Anim. Prod.* 62, 213–218 (2002).

29. Schils RLM, Verhagen A, Aarts HFM, Šebek LBJ. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. *Nutr. Cycl. Agroecosyst.* 71(2), 163–175 (2005).
30. O'Brien D, Brennan P, Humphreys J, Ruane E, Shalloo L. An appraisal of carbon footprint of milk from commercial grass-based dairy farms in Ireland according to a certified life cycle assessment methodology. *Int. J. Life Cycle Assess.* 19, 1469–1481 (2014a).
31. Boadi D, Benchaar C, Chiquette J, Masse D. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci*. 84, 319–335 (2004).
32. Knapp JR, Laur GL, Vadas PA, Weiss WP, Tricarico JM. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci*. 97, 3231–3261 (2014).
33. Rotz CA, Montes F, Chianese DS. The carbon footprint of dairy production systems through partial life cycle assessment. *J. Dairy Sci.* 93, 1266–1282 (2010).
34. Chianese DS, Rotz CA, Richard TL. Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. *T. ASABE* 52, 1325–1335 (2009b).
35. Chianese DS, Rotz CA, Richard TL. Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies. *T. ASABE* 52, 1301–1312 (2009c).
36. IPCC- Intergovernmental Panel on Climate Change. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK (2001).
37. O'Brien D, Capper JL, Gamsworthy PC, Grainger C, Shalloo L. A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. *J. Dairy Sci.* 97(3), 1835–1851 (2014b).
38. DeRamus HA, Clement TC, Giampola DD, Dickison PC. Methane emissions of beef cattle on forages: efficiency of grazing management systems. *J. Environ. Qual.* 32, 269–277 (2003).
39. Sirohi S, Michaelowa A. Sufferer and cause: Indian livestock and climate change. *Climatic Change* 85, 285–298 (2007).
40. Verge XPC, Maxime D, Dyer JA, Desjardins RL, Arcand Y, Yanderzaag A. Carbon footprint of Canadian dairy products: calculations and issues. *J. Dairy Sci*. 96(9), 6091–6104 (2013).

Websites

101. IPCC- Intergovernmental Panel on Climate Change. Changes in atmospheric constituents and in radiative forcing. Chapter 2 in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf (2007).
102. EIA. *Emissions of Greenhouse Gases in the United States*. U.S. Department of Energy, Energy Information Administration, Washington, D.C. (2007). Available at:www.eia.doe.gov/oiaf/1605/ggrpt/index.html.
103. Rotz CA, Corson MS, Chianese DS, Coiner CU. *The Integrated Farm System Model: Reference Manual*. USDAARS Pasture Systems and Watershed Management research unit, University Park, Pa (2009). www.ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.
104. Australian Department of Climate Change. *Australian Greenhouse Emissions Information System*. (sourced 10/7/2008;http://www.ageis.greenhouse.gov.au/GGIDMUserFunc/QueryModel/Ext_QueryModelResults.asp#resultStartMarker) (2008).