Appendix 12: Whole farm systems analysis of Australian dairy farms greenhouse gas emissions

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Abstract

The Australian dairy industry contributes approximately 1.6% of the nation's greenhouse gas (GHG) emissions, emitting an estimated 9.3 million tonnes of carbon dioxide equivalents (CO_2e) per annum. This study examined 41 contrasting Australian dairy farms for their GHG emissions using the Dairy Greenhouse gas Abatement Strategies (DGAS) calculator, which incorporates Intergovernmental Panel on Climate Change and Australian inventory methodologies, algorithms and emission factors. Sources of GHG emissions included were pre-farm embedded emissions associated with key farm inputs (i.e., grains and concentrates, forages and fertilisers), carbon dioxide emissions from electricity and fuel consumption, methane emissions from enteric fermentation and animal waste management, and nitrous oxide emissions from animal waste management and nitrogen fertilisers. Enteric methane emissions were found to be approximately half of total farm emissions. Linear regression analysis showed that 95% of the variation in total farm GHG emissions could be explained by annual milk production. The estimated mean (± standard deviation) GHG emissions intensity was 1.04 ± 0.17 kg CO_2e/ kg of fat and protein corrected milk (FPCM). Stepwise multiple linear regression analysis showed that milk production per cow (kg FPCM/cow.lactation) explained 70% of the variation in milk GHG emissions intensity. Adoption of abatement strategies that reduce enteric methane production, while assisting in improving milk production per cow will have a positive impact on reducing the GHG emissions intensity of milk production in Australia.

Keywords*:* carbon dioxide, DGAS, farming system, grain feeding, methane, nitrous oxide, pre-farm emissions

Introduction

The dairy industry is one of Australia's major rural industries, ranked third behind beef and wheat, producing approximately 9.0 billion litres of milk from 1.6 million cows on 7,500 farms (Dairy Australia 2010a). South eastern Australia's climate and natural resources are generally favourable to dairying, with approximately 66% of milk production coming from coastal regions of Victoria, South Australia, New South Wales and Tasmania (Dairy Australia 2010b). The industry is also located in sub-tropical coastal northern New South Wales and Queensland, the south west of Western Australia and adjacent to major river systems in inland southern New South Wales and northern Victoria. Over the last two decades, farm numbers have declined by approximately 40%, however, with increases in herd sizes and milk production per cow, Australia's annual milk production has increased from 6.2 billion litres in 1990 to a peak of 10.8 billion litres by 2000. In the last decade, Australian milk production has remained relatively stable at 9 to10 billion litres (Dairy Australia 2010a).

The dairy industry is predominantly pasture-based, with approximately 70% of feed requirements coming from grazed pastures (Dairy Australia 2010a), although increases in farm intensification has largely been achieved through greater reliance on supplementary feeding and increase usage of nitrogen (N) fertiliser (Thorrold and Doyle 2007). Reliance on supplementary feed has allowed some farms to milk in excess of 1,000 cows and there has also been an increase in the establishment of feedlot dairies, particularly in traditional cropping regions (Dairy Australia 2010a). This intensification of the industry has also brought increasing focus on the environmental sustainability of dairying (Gourley 2004, Hart *et al*. 2004; Dougherty *et al,* 2008; Gourley *et al.* 2012a; 2012b; Gourley and Weaver 2012) with greenhouse gas (GHG) emissions becoming another area of importance when assessing environmental impacts of dairying (De Klein and Eckard 2008).

In 2009, Australia's agricultural sector accounted for approximately 15% of the nations' GHG emissions, the second largest contributor, behind stationary energy (DCCEE 2011a). The livestock industries of dairy, beef and sheep farming contribute approximately 10, 47 and 19% of these agricultural emissions, respectively (DCCEE 2011a). Although direct emissions from agricultural operations (e.g. methane (CH_4) emissions from cows or nitrous oxide (N_2O) emissions from animal waste and N fertiliser use) will not be subject to the price on carbon emissions in Australia (DCCEE 2011b), agriculture will have the option of providing emission offsets to other sectors (DCCEE 2010) through the Carbon Farming Initiative (CFI) . The CFI is the proposed mechanism for assisting agricultural farmers and land managers to obtain carbon offset credits by sequestering carbon or by reducing/avoiding GHG emissions (DCCEE 2011c). If farmers and land managers chose to undertake a CFI approved project, rigorous methodologies will need to be adhered to (e.g. proof of the abatement being measurable and verifiable, permanent removal of GHG emissions, abatement is additional to 'business as usual' farm practices etc) before farmers and land managers will be allocated carbon offset credits. These credits can then be tradable so that other sectors of the economy (e.g. stationary energy companies) can offset a portion of their GHG emissions (DCCEE 2011c). However, before agriculture can begin to reduce their GHG emissions to provide offsets for other sectors, there is a critical need to evaluate farm emissions, determine the sources of these emissions and their corresponding contribution and quantify the key management factors influencing emissions across differing farming systems.

There have been assessments of either real or simulated beef and sheep enterprises for their GHG emissions profile (e.g. Kopke *et al.* 2008; Biswas *et al.* 2010; Peters *et al.* 2010; Browne *et al.* 2011). However, to date there have been few assessments of dairy farm GHG emissions across the various dairying regions of Australia, operating under different levels of farm intensity and management practices. The Victorian Department of Primary Industry have assessed the GHG emissions of between 57 and 73 dairy farms from northern, south eastern and south western Victoria for the last four years (2006/07 to 2009/10; English 2007; English *et al.* 2008; Gilmour *et al.* 2009, 2010) using the National Greenhouse Gas Inventories (NGGI) methodology (DCCEE 2009). However, they did not include any of the pre-farm embedded emissions associated with key farm inputs and so could not be considered as a whole farm systems approach. Beldman and Daatselaar (2010) followed NGGI methodology and included pre-farm embedded emissions but only assessed three dairy farms (Western Australia, northern and south eastern Victoria). Christie *et al.* (2011) assessed 60 dairy farms' GHG emissions using the NGGI methodology, with the inclusion of pre-farm embedded emissions. However, all farms were located in a single region (Tasmania) and therefore exploring regional differences and their influence on GHG emissions was not possible. Therefore, to date there has been limited assessment of dairy farm GHG emissions following the NGGI methodology, including pre-farm embedded emissions, across the various dairying regions of Australia, operating under different levels of farm intensity and management practices.

The aim of this study was to estimate total farm GHG emissions of 41 Australian dairy farms from diverse geographical locations, varying herd and farm sizes, levels of milk production per cow and per hectare, and reliance on irrigation and supplementary feeding. This study also aimed to ascertain any regional differences in terms of three functional units; GHG emissions intensity per unit of milk produced, per cow and per hectare. In addition, this study examined the influence of key farm variables on these three abovementioned functional units.

Materials and methods

Farm selection and dataset

This study was designed to estimate the GHG emissions across the breadth of the Australian dairy industry and to enable a comparison of contrasting dairy systems. To achieve this, forty-one Australian dairy farms were selected using a stratified-random process taking into consideration key criteria of (i) geographical location, (ii) litres of milk per grazed hectare, (iii) grazed hectares, and (iv) proportion of grazed hectares that were irrigated (Gourley *et al.* 2012b). Farms selected were representative of the local industry and varied in terms of milking herd size and farm size, level of milk production per cow, level of grain and other supplementary feeding and fertiliser inputs (Table 1). This farm selection process resulted in a diversity of locations and farming systems to provide an industry-wide assessment of the current GHG emissions at a range of scales (e.g. range of milking herd sizes, farm areas, stocking rates, level of milk production per cow and level of supplementary feeding). Ten farms were located in south eastern Victoria, nine farms in New South Wales, five farms in Western Australia, four farms in Queensland and Tasmania and three farms in South Australia, south western Victoria and northern Victoria.

Farms were visited five times throughout the 12-month study period (February 2008 to February 2009) with visits identified as being T0 (summer 2008) at the commencement and T1 (autumn 2008), T2 (winter 2008), T3 (spring 2008) and T4 (summer 2009) occurring at the 3rd, 6th, 9th and 12th month stage of the study period. To establish an inventory of supplementary feeds present on the farm during the study period, the amount of conserved forage, grain and other feeds present at visit T0 and T4 were determined. Any home-grown conserved feed or purchased supplementary feed present at T0 and consumed within the study period was included in diet intake estimations. Any home-grown conserved feed or purchased supplementary feed present at T4 was excluded from the diet calculations as it was not consumed within the study period. This resulted in a closed system where the feed inventory was reflective of the conserved and purchased feed consumed within the study period. All feed purchased during the 12 month study period was classified as an import for pre-farm embedded emissions estimations, irrespective of whether it was or was not consumed during the study period.

At each visit, stock numbers present on the milking platform (i.e. area where generally only the milkers and bulls are located but could also include some or all of the rising 1 and 2 year olds and non-lactating mature cows) and any runoff/outblock or leased areas (i.e. area where the rising 1 and 2 year olds and non-lactating mature cows are generally located in addition to areas where supplementary feeds are grown, harvested and transported to the milking area) were recorded. For farms with one or two calving periods per annum, the maximum milking herd size from the five visits was used as the milking herd size for GHG emissions estimations. For farms with year round calving, the milking herd and non-lactating mature cow herd were added together to provide a seasonal milking herd size for each visit. The milking herd size for GHG emissions estimations for year round calving herds was taken as the second highest figure recorded during the five seasonal farm visits. This eliminated a potential over estimation of the milking herd size for year round calving herds. The number of 1st lactation cows was used as the herd size for the rising 1 and 2 year old heifers. Some farms retained bulls year round while others only had bulls present during the breeding season (i.e. 1-2 visits). An average bull herd size was calculated based on bulls being present year round. The live weight for the milking herd for each farm was based on the breed of cattle; 450kg for Jerseys, 550kg for Holstein-Friesians and 500kg for all other breeds and Holstein-Friesian crossbreds (Dairy Australia 2003). For any herds with two or more breeds, a mean herd weight was calculated taking into consideration the number of milkers from each breed. The live weight of the rising 1 and 2 year olds were assumed to be 35 and 75% of the milking herd live weight (Dairy Australia 2003), respectively, while the bulls were assumed to be 650kg, irrespective of breed. Live weight gain was set at 0.7 kg/day for the rising 1 and 2 year olds (Dairy Australia 2003) and at 0 kg/day for the bulls and mature cows (assuming that any loss of condition post calving is gained in mid to late lactation and so over the 12 month study period, the net weight gain is zero).

Daily grazed pasture and supplementary feed dry matter (DM) intakes for the milking herd were provided by the farmer at each visit. A sample of each feed source (pastures and supplements) fed to the milking herd on the day of each visit was collected, prepared and analysed for various feed quality parameters by George Weston Technologies (Enfield, NSW, Australia). The key feed quality parameters obtained and used in this study were Crude Protein (CP%) and Metabolisable Energy (ME; MJ ME/kg dry matter (DM)). For this study, the dry matter digestibility (DMD%) was calculated from the obtained ME values using the following equation:

DMD % = (ME + 1.037) / 0.1604 (Minson and McDonald 1987)
(1)

The DM intake (kg DM/day), DMD% and CP% for each component of the diet (pasture and supplementary feeds) was entered into DGAS to calculate a seasonal mean DMD% and CP% for the milking herd. The milking herd's diet DMD and CP % was calculated based on the dietary information collated during visits T1 (autumn 2008), T2 (winter 2008), T3 (spring 2008) and T4 (summer 2009) and used throughout DGAS (as required) to estimate CH_4 and N_2O emissions. Total dry matter (DM) intake (t DM/cow.lactation) and pasture consumption (t DM consumed/ha) were estimated using the Pasture Consumption and Feed Conversion Efficiency Calculator (Heard and Wales 2009 and used in the stepwise multiple linear regression analysis. No diet information (quality or quantity) was collected for rising 1 and 2 year olds or the bulls. This study assumed the mean annual DMD and CP was 70% and 18%, respectively, for all non-milking stock classes.

Monthly milk volume, mean butterfat % and mean protein % was provided by the various milk companies supplied by the participating farms. Mean annual butterfat% and protein % was calculated by summing the quotient of monthly milk volume by its corresponding milk component and dividing by total annual volume. To compare milk production between farms, fat and protein corrected milk (FPCM) was used to correct milk volume to a standard of 4.0% fat and 3.3% protein. This is a standard used for comparing milk with different fat and protein contents and is a means of evaluating milk production of different dairy breeds on a common basis (FAO 2010). The annual fat and protein correct milk (FPCM) was calculated as:

FPCM (kg) = raw milk (kg; litres x 1.03 (Sevenster and de Jong 2008)) x (0.337 + (0.116 x fat content (g/ 100g milk)) + (0.06 x protein content (g/ 100g milk)) (FAO 2010)
(2)

There was no direct assessment of electricity and diesel consumption. Electricity consumption for milk harvesting was estimated at 0.67 kWh/cow.day (adapted from Genesis Now 1997) whilst electricity for irrigation was estimated at 200 or 275 (kWh/ML) for flood and spray delivery, respectively (adapted from NSW Department of Primary Industries 2003). Diesel consumption (litres; adapted from Christie *et al.* 2011) was estimated as:

Diesel (l) = 25.5 x milk production (t MS/farm) + 5,500
(3)

Greenhouse gas emissions estimation

The farm system boundary for this study was defined by the GHG emissions associated with milk production up to the point of transportation from the farm, including pre-farm embedded emissions. All areas used for dairy related activities, including the milking platform and runoff/outblock or leased areas for raising young stock and growing pastures and crops for forage conservation were included in the total farm area. The DGAS (version 1.3) calculator was used to estimate GHG emissions using a global warming potential of 1, 21 and 310 to convert CO_2, CH_4 and N_2O emissions into CO_2 equivalent (CO_2e) emissions, respectively (DCCEE 2009). The DGAS calculator incorporates the Australian NGGI methodology (DCCEE 2009) to estimate on-farm emissions (CH_4, N_2O and CO_2 from energy). In addition, the DGAS calculator also incorporates calculations of CH_4, N_2O and CO_2 emitted in the production/manufacturing of key farm inputs (i.e. supplementary feeds and fertilisers). The NGGI methodology complies with rules that conform to international guidelines adopted by the United Nations Framework Convention on Climate Change (DCCEE 2009). The NGGI methodology also conforms to the protocol required for the Australian Government to report the nation's annual anthropogenic sources and sinks as part of its commitments under the Kyoto Protocol (DCCEE 2009). The NGGI methodology has also been widely used to estimate GHG emissions from the agricultural sector (e.g. Petersen *et al.* 2003; Flugge and Schilizzi 2005; Keogh 2009; Biswas *et al.* 2010; Peters *et al.* 2010; Browne *et al.* 2011; Eady *et al*. 2011) and therefore is the most currently accepted approach for estimating GHG emissions for Australian dairy farms. All equations and constants relating to the GHG emissions estimations in this study are from the NGGI methodology (DCCEE 2009) unless stated otherwise.

Pre-farm embedded emissions

Simapro life cycle assessment software (Simapro 2006) was used to determine the CO_2e emissions associated with the production of key farm imports. The amount of N, P and K fertiliser applied during the study period was converted into equivalent amounts of urea (46% N), triple superphosphate (18% P) and potassium chloride (50% K) and multiplied by their corresponding emission factor of 0.89, 0.83 and 0.13 kg CO_2e/kg product, respectively. The amount of purchased grains/concentrates, hay and silage was multiplied by their corresponding emission factor. These emission factors were 0.20 kg CO_2e/kg DM for lucerne hay, 0.25 kg CO_2e/kg DM for pasture and cereal hay and silage, and 0.30 kg CO_2e/kg DM for grains/concentrates. All by-products such as canola meal, brewer's grain and molasses were assumed to have no carbon footprint as the carbon liability was assumed to lie with the primary process (i.e. cooking oil production, beer brewing and sugar refining for the abovementioned by-products). The pre-farm embedded emissions were presented in terms of GHG emissions (t CO_2e) from fertiliser, grain/concentrates and forage sources.

Calculating on-farm carbon dioxide emissions

Australian electricity is generated by a range of sources (*e.g.,* brown and black coal, natural gas, hydro, solar, wind). However, as most of the country is connected to a national grid, it is difficult to know where or how electricity is being generated for individual regions. We selected brown coal as the source of electricity for all farms, with an emission factor of 1.4 kg CO_2e/kWh, with an exception for Western Australia farms, where natural gas was selected with an emission factor of 0.5 kg CO_2e/kWh (DCCEE 2009). The extraction/refinement and consumption of diesel fuel by farm vehicles and machinery was equivalent to 3.4 kg CO_2e/litre (DCCEE 2009). The GHG emissions associated with transportation of key farm inputs was not taken into consideration in this study due to this information not being gathered from farmers during farm visits.

Calculating on-farm methane emissions

Methane is emitted on farm from two sources; enteric fermentation and animal waste. Enteric fermentation was estimated in DGAS from a series of methodologies, algorithms and emission factors from the NGGI report (DCCEE 2009), based on an approach developed by Blaxter and Clapperton (1965), incorporating research by Minson and McDonald (1987) and the Standing Committee on Agriculture (1990). Throughout the DCCEE (2009) methodology, the Australian dairy industry is divided into sub-categories for the estimation of GHG emissions, with these sub-categories reported as subscript letter in the equations. The subscript I represents the various states of Australia (i.e. Queensland, Victoria, Western Australia etc), the subscript j represents the dairy cattle stock class (i.e. milking cows, heifers < 1 year of age, bulls > 1 year of age etc0 and the subscript k represents the four seasons of the year (i.e. spring, summer etc). To estimate enteric CH_4 production, daily DM intake (I_{ijk}; kg DM/head.day) is calculated as:

$$I_{ijk} \text{ (kg DM/head.day)} = (1.185 + 0.00454 \times W_{ijk} - 0.0000026 \times W_{ijk}^2 + 0.315 \times LWG_{ijk})^2 \times MR + MI \quad (4)$$

Where W_{ijk} = live weight (kg)

LWG_{ijk} = live weight gain (kg/day)

MR = metabolic rate; 1.1 for mature cows and 1.0 for all other stock

MI = additional intake required for milk production (kg DM/head.day; equation 5)

The additional intake required for milk production (MI_{ijk}; kg DM/head.day) is calculated as:

$$MI_{ijk} \text{ (kg DM/head.day)} = MP_{ijk} \times NE / (k \times q \times 18.4) \quad (5)$$

Where MP_{ijk} = milk production (kg/head.day)

NE = 3.054 MJ (net energy/kg milk)

k = 0.60 (efficiency of use of metabolisable energy for milk production)

q = metabolisability of the diet (0.00795 * DMD_{ijk}x 100 – 0.0014; dry matter digestibility of diet expressed as a fraction of DM

18.4 = gross energy content of feed (((MJ/kg DM; SCA 1990) where this value is the assumed value for all feeds (DCCEE 2009))

Intake relative to that required for maintenance for each stock class (L_{ijk}) is calculated as:

$$L_{ijk} = I_{ijk} / (1.185 \times 0.00454 \times W_{ijk} - 0.0000026 \times W_{ijk}^2 + (0.315 \times LWG_{ijk})^2 \quad (6)$$

Where LWG is set to zero

The percentage of gross energy intake (GEI_{ijk};%) that is yielded as enteric CH_4 (Y_{ijk}) is calculated as:

$$Y_{ijk}\% = 1.3 + 0.112 \times DMD_{ijk} \times 100 + L_{ijk} \times (2.37 - 0.050 \times DMD_{ijk} \times 100) \quad (7)$$

Where DMD_{ijk} = dry matter digestibility of diet expressed as a fraction of DM

The total daily production of enteric CH_4 (M_{ijk} enteric CH_4; kg CH_4/head.day) is calculated as:

$$M_{ijk} \text{ enteric } CH_4 \text{ (kg } CH_4\text{/head.day)} = (Y_{ijk} / 100) \times (GEI_{ijk} / F) \quad (8)$$

Where $GEI_{ijk} = I_{ijk} \times 18.4$

F = 55.22 (MJ/kg CH_4; Brouwer 1965)

From this, total enteric CH_4 production (Gg CH_4/annum) is calculated as:

$$\text{Total enteric } CH_4 \text{ production (Gg } CH_4\text{/annum)} = \sum (M_{ijk} \times N_{ijk} \times 365) \times 10^{-6} \quad (9)$$

Where N_{ijk} = number of dairy cattle per state (i), stock class (j) and season (k)

Methane from animal waste was estimated using a series of methodologies, algorithms and emission factors from the NGGI report (DCCEE 2009), based on research by Williams (1993) and IPCC (1997) guidelines. Methane production (kg CH_4/head.day) from manure management requires the calculation of volatilise solids (VS) excreted per head per day, based on DM intake and DMD calculated as:

$$VS_{ijk} \text{ (kg/head.day)} = I_{ijk} \times (1 - DMD_{ijk} \times 100) \times (1 - A) \quad (10)$$

Where I_{ijk} = dry matter intake (kg /head.day)

DMD_{ijk} = dry matter digestibility of diet expressed as a fraction of DM

A = ash content expressed as a fraction (assumed to be 8% of faecal DM)

From this, daily animal waste CH_4 production ($M_{ijk;}$ waste CH_4; kg CH_4/head.day) is calculated as:

$$M_{ijk} \text{ waste } CH_4 \text{ (kg } CH_4\text{/head.day)} = VS_{ijk} \times B_o \times MCF \times \rho \quad (11)$$

Where B_o = emission potential (0.24 m^3/ kg VS)

MCF = integrated methane conversion factor (%; DCCEE (2009) defaults of 2.75 for WA; 4.57 for QLD & NT; 6.5 for NSW, ACT, TAS & VIC; and 10.07 for SA)

ρ = density of methane (0.662 kg/m^3)

From this, total animal waste CH_4 production (Gg CH_4/annum) is calculated as:

$$\text{Total animal waste } CH_4 \text{ (Gg } CH_4\text{/annum)} = \sum (M_{ijk} \times N_{ijk} \times 365) \times 10^{-6} \quad (12)$$

Where N_{ijk} = number of dairy cattle per state (i), stock class (j) and season (k)

Calculating on-farm nitrous oxide emissions

Nitrous oxide emissions associated with animal faeces, urine and waste were estimated using methodologies, algorithms and emission factors that reflect Australian conditions (DCCEE 2009), based on research by the Australian Standing Committee on Agriculture (1990) and Freer et al. (1997).

The crude protein intake (CPI_{ijk}; kg/head.day) is calculated as:

$$CPI_{ijk} \text{ (kg/head.day)} = I_{ijk} \times CP_{ijk} \times 100 \quad (13)$$

Where I_{ijk} = DM intake (as calculated in equation 4 above)

CP_{ijk} = crude protein of the diet expressed as a fraction of DM

The amount of N excreted in faeces (F_{ijk}; kg/head.day) is calculated as:

$$F_{ijk} \text{ (kg/head.day)} = \{0.3 \times (CPI_{ijk} \times (1-[(DMD_{ijk} \times 100 + 10) / 100])) + 0.105 \times (ME_{ijk} \times I_{ijk} \times 0.008) + (0.0152 \times I_{ijk})\} / 6.25 \quad (14)$$

Where DMD_{ijk} = dry matter digestibility of diet expressed as a fraction of DM

ME_{ijk} = Metabolisable energy (MJ/kg DM; calculated as 0.1604 x DMD_{ijk} – 1.037; Minson and McDonald 1987))

1 / 6.25 = factor for converting CP into N

The amount of N that is retained by the animal (NR_{ijk}; kg/head.day) in milk and body tissue is calculated as:

$$NR_{ijk} \text{ (kg/head.day)} = \{(0.032 \times MP_{ijk}) + \{0.212 - 0.008 \times (L_{ijk} - 2) - [(0.140 - 0.008 \times (L_{ijk} - 2)) / (1 + \exp(-6 \times (Z_{ijk} - 0.4)))]\} \times (LWG_{ijk} \times 0.92)\} / 6.25 \quad (15)$$

Where MP_{ijk} = milk production (kg/head.day)

L_{ijk} = intake relative to maintenance (as calculated in equation 6 above)

Z_{ijk} = relative size (live weight / standard reference weight for each stock class)

LWG_{ijk} = live weight gain (kg/day)

Therefore N excreted in urine (U_{ijk}; kg/head.day) is calculated by subtracting NR_{ijk}, F_{ijk} and dermal protein loss from total N intake such as:

$$U_{ijk}\ (\text{kg/head.day}) = (CPI_{ijk} / 6.25) - NR_{ijk} - F_{ijk} - [(1.1 \times 10^{-4} \times W_{ijk}^{0.75}) / 6.25 \quad (16)$$

Where W_{ijk} = live weight (kg/head)

From this, total faeces (AF_{ijk}; Gg N/annum) and urinary (AU_{ijk}; Gg N/annum) N excreted is calculated as:

$$AF_{ijk}\ (\text{Gg N/annum}) = \sum F_{ijk} \times N_{ijk} \times 365 \times 10^{-6} \quad (17)$$

$$AU_{ijk}\ (\text{Gg N/annum}) = \sum U_{ijk} \times N_{ijk} \times 365 \times 10^{-6} \quad (18)$$

Where N_{ijk} = number of dairy cattle per state (i), stock class (j) and season (k)

The direct and indirect N_2O emissions from faeces and urine voided onto pastures directly and from stored/spread faeces and urine is estimated using the total faeces (AF_{ijk}) and total urine (AU_{ijk}) from equations 17 and 18, respectively, with the emission factors and equations presented in Table 2. The DCCEE (2009) methodology defines the percentage of faeces and urine allocated to one of four manure management systems depending on the location of the farm. In NSW/ACT, Tasmania and Victoria, 92% of annual faeces and urine is deposited onto pastures during grazing, 6% is stored in a lagoon system, 1.5% is spread daily, and 0.5% is stored as a liquid/slurry. In Queensland, 90% of annual faeces and urine is deposited onto pastures during grazing, 7% is spread daily and 3% is stored in a lagoon system. In Western Australia, 92% of annual faeces and urine is deposited onto pastures during grazing, 6% is spread daily and 2% is stored in a lagoon system. In South Australia, 88.5% of annual faeces and urine is deposited onto pastures during grazing, 10% is stored in a lagoon system, 1% is spread daily and 0.5% is stored as a liquid/slurry.

Nitrous oxide emissions associated with N fertilisers were estimated using methodologies, algorithms and emissions factors (Table 2) that reflect Australian conditions based on research by Galbally *et al.* (2005). The study did not differentiate between N fertiliser applied to pastures or crops, and given the slightly higher emission factor for pastures compared to crops (0.004 cf 0.003, respectively), this study assumed that all N fertiliser was applied to pasture.

Farming classification

Farms were classified according to their farming system as described by Dairy Australia (2011a). The farming systems (FS) classification is defined as FS1 (grazed pasture year-round with supplementary forage fed in paddocks and low grain feeding (< 1 t DM/cow.lactation)), FS2 (grazed pasture year-round, with supplementary forage fed in paddocks and medium to high grain feeding (> 1 t DM/cow.lactation)), FS3 (grazed pasture year-round with supplementary forages and other feeds fed as a partial mixed ration on feedpad as required and low to high grain feeding), FS4 (grazed pastures for < 9 months of the year with a partial mixed ration fed on feedpad area as required and low to high grain feeding) and FS5 (zero grazing of milking herd, fed total mixed ration year round and housed indoors). This study consisted of 11 FS1 farms, 20 FS2 farms and 10 FS3 farms. While this study did not assess the GHG emissions of farms classified as either FS4 or FS5, nationally less than 10% of the farms are identified as being FS4 or FS5 (Dairy Australia 2011b), therefore supporting the conclusion that the results from this study are reflective of the majority of Australian dairy farms.

Statistical Analysis

Statistical Program for the Social Sciences Statistics (SPSS 2008) was used to for all statistical data analysis. Multiple regression analysis was used to describe the influence of annual milk production, milking herd size and total farm area on total farm GHG emissions. A stepwise multiple linear regression (SMLR) analysis between GHG emissions intensities and individual key farm variables was undertaken using the farm variables of milk production per cow (kg FPCM/cow), milk production per ha (t FPCM/ha), stocking rate (number of milkers/ha of milking platform), pasture consumption (t DM consumed/ha), total feed intake (t DM/cow.lactation), feed conversion efficiency (FCE; kg of FPCM/kg DM intake), proportion of grain in the milking herd diet and N fertiliser application rate (kg N/ha). The influence of farming system and region on the GHG emissions intensity of milk production (kg CO_2e/kg FPCM), cow intensity (t CO_2e/cow) and farm area intensity (t CO_2e/ha) were analysed separately using a one-way analysis of variance (ANOVA) procedure. In addition, a cumulative distribution function of the GHG emissions intensity of milk production for each farming system was constructed using the NORMDIST (value, mean, standard deviation, TRUE) function in Microsoft Excel 2007 (Microsoft Corporation 2007).

Results

Farm greenhouse gas emissions

The mean ± standard deviation total farm GHG emissions, as estimated by the DGAS calculator, was 2,255 ± 1,756 t CO_2e/annum ranging between 411 and 9,416 t CO_2e/annum (Table 3). There was substantial variation in the regional mean total farm GHG emissions, between a low of 1,184 t CO_2e/annum in Queensland and a high of 4,450 t CO_2e/annum in South Australia (Table 3), as a result of varying milking herd sizes, farm areas and level of milk production per cow.

The mean estimated GHG emissions intensity of milk production was 1.04 ± 0.17 kg CO_2e/kg FPCM. The mean estimated GHG emissions intensity of milk production for Tasmania was 1.30 kg CO_2e/kg FPCM, which was significantly ($P<0.05$) higher than all other regions, with the exception of Queensland (Table 3). The mean estimated GHG emissions intensity per cow was 6.34 ± 0.77 t CO_2e/cow.annum, with no significant ($P>0.05$) regional differences (Table 3). The mean estimated GHG emissions intensity per hectare was 7.74 ± 3.80 t CO_2e/ha.annum, with Tasmania and south eastern Victoria being significantly ($P<0.05$) higher than New South Wales, Western Australia and Queensland (Table 3).

There was a positive linear relationship between total farm GHG emissions and either annual milk production or milking herd size for the whole dataset as shown by the high coefficient of determination in equations 19 and 20. Therefore at whole of industry assessment, milk production or number of milking cows could be used as a suitable surrogate for estimating total GHG emissions. However, on a per farm basis, the GHG emissions intensity of milk production varied between 0.76 and 1.68 kg CO_2e/kg FPCM while the GHG emissions intensity per cow also varied between 4.78 and 8.59 t CO_2e/cow (Figure 1). This substantial variation between farms limits the acceptability of a single emission factor (milk production or milking cow number) to be used as a surrogate for quantifying on farm emissions. Area was not a suitable surrogate for estimating total GHG emissions as shown by low coefficient of determination in equation 21 and the large variation in GHG emissions intensity per hectare (Figure 1c).

$$\text{Total farm GHG emissions (t } CO_2\text{e/annum)} = 0.89 \times \text{annual milk production (t FPCM)} + 258.34;\ R^2 = 0.95 \quad (19)$$

$$\text{Total farm GHG emissions (t } CO_2\text{e/annum)} = 6.46 \times \text{milking herd size} - 41.81;\ R^2 = 0.97 \quad (20)$$

Total farm GHG emissions (t CO_2e/annum) = 3.97 x total farm area (ha) + 911.73; R^2 = 0.30

(21)

The contribution of the various GHG emission sources, as a percentage of total farm GHG emissions, for each state is presented in Table 4. Enteric CH_4 was the biggest source of total farm GHG emissions, with an overall mean of 55.5%, with regional means varying between 49.8 and 57.8% (Table 4). On-farm CO_2 from electricity and diesel consumption and indirect N_2O emissions from animal waste, at 9.6 and 8.4% respectively, were the next two largest sources (Table 4).

Stepwise multiple linear regression analysis

The SMLR analysis showed that milk production per cow (kg FPCM/cow.lactation) was the only significant (P<0.05) key farm variable influencing the GHG emissions intensity of milk production (kg CO_2e/kg FPCM) and accounted for 0.70 of the variation (Table 5). The SMLR analysis showed that milk production per cow (kg CO_2e/kg FPCM) alone could explain 0.64 of the variation in emissions intensity per cow (t CO_2e/cow.annum). The addition of percentage of the milking herds' diet consisting of grain to the model could only account of an additional 0.04 of the variation (Table 5). The SMLR analysis showed that milk production per hectare (t FPCM/ha.annum) alone could explain 0.88 of the variation in GHG emissions intensity per unit area (t CO_2e/ha.annum). The addition of milk production per cow (kg FPCM/cow.lactation) and nitrogen fertiliser application rate (kg N/ha.annum) could only account for an additional 0.09 of the variation (Table 5). Milk production per cow was the only common variable influencing the three intensities, with increased milk production per cow decreasing milk and area GHG emissions intensity, while it increased the cow GHG emissions intensity (Table 5).

Influence of farming system on greenhouse gas emissions intensity

The FS1 group exhibited a significantly (P<0.05) higher GHG emissions intensity of milk production, at 1.23 kg CO_2e/kg FPCM, compared to the FS2 and FS3 groups, at 0.98 and 0.97 kg CO_2e/kg FPCM, respectively (Table 6). The FS2 group exhibited a significantly (P<0.05) higher GHG emissions intensity per cow, at 6.78 t CO_2e/cow.annum, compared to the FS1 and FS3 groups, at 5.79 and 6.08 t CO_2e/cow.annum, respectively (Table 6). There was no significant (P>0.05) difference in GHG emissions intensity per unit area, at 8.21, 7.67 and 7.37 t CO_2e/ha.annum for the FS1, FS2 and FS3 groups, respectively (Table 6).

The cumulative distribution function of the GHG emissions intensity of milk production for the three farming systems groups showed little variation between FS2 and FS3, with 95% of the farms in FS2 having a GHG emission intensity of milk production between 0.77 and 1.12 kg CO_2e/kg FPCM compared to between 0.86 and 1.09 kg CO_2e/kg FPCM for the FS3 group. In contrast, there was a substantially higher variation for FS1, with 95% of the FS1 farms having a GHG emissions intensity of milk production between 1.04 and 1.60 kg CO_2e/kg FPCM (Figure 2).

Discussion

To date, few studies have been undertaken to estimate the GHG emissions associated with dairy production in Australia. This study was unique in that farms were selected from throughout all the dairying regions of the country, as opposed to a single region (English 2007; Christie *et al.* 2011), actual farm data, as opposed to hypothetical data, was used to estimate GHG emissions (Basset-Mens *et al.* 2005; Browne *et al.* 2011), farms were selected across a range of farming systems varying from predominantly pasture- based with no or low grain supplement through to relatively high levels of grain inputs and accurate seasonal feed quality values, as opposed to annual average 'textbook' values, were used to estimate GHG emissions (Beukes *et al.* 2011). All these factors contributed to the range of results achieved in this study which has allowed further exploration of the dataset to determine factors which influence the GHG emissions associated with milk production for the Australian dairy industry across varying farming systems.

In assessing the GHG emissions of 41 Australian dairy farms, total annual milk production was shown to account for 95% of the variation in estimated total farm GHG emissions. Given the correlation between milk production, daily intakes and enteric methane emissions, it is not surprising that using an inventory assessment would find such a relationship. In experimental studies measuring daily intakes, enteric CH_4 production and milk production, the positive relationship between enteric CH_4 emission production and milk production per cow has seen been shown (Ulyatt *et al.* 2002a, 2002b; Lovett *et al.* 2005; O'Neill *et al.* 2011). Boadi *et al.* (2004), in reviewing several studies, showed that the emission intensity of milk production varied between 11.4 and 28.3 L CH_4/kg milk; equivalent to between 0.31 and 0.76 kg CO_2e/kg milk from enteric methane from a variety of measured studies. The results of this study were not dissimilar to the Boadi *et al.* (2004) review, as they varied between 0.39 and 0.88 kg CO_2/kg FPCM from enteric CH_4 and included enteric CH_4 emissions from all stock, not just the milking herd as was the case for the other studies.

It is clear that while the relationship between total milk production and total farm GHG emissions suggests that milk production alone could be a suitable surrogate for estimating GHG emissions for national inventory purposes, using a single emissions factor, such as total annual milk production, to estimate any given individual farm's GHG emissions, has the potential to either substantially under or over estimate individual farms' GHG emissions. When total annual milk production was used with equation 19 to estimate total farm GHG emissions, less than half of the farms' total farm GHG estimation was within 10% of their DGAS-estimated total farm GHG emissions. At the two extremes, one farm's total farm GHG emissions was under-estimated by 30% while another farm's total farm GHG emissions was over-estimated by 41%. In addition, the GHG emissions intensity of milk production, on an individual farm basis, varied between 0.76 and 1.68 kg CO_2e/kg FPCM. Exploring reasons as to the variation in the GHG emissions intensity of milk production is critical and may assist in exploring potential mitigation strategies for maintaining total farm GHG emissions while increasing total annual milk production.

Results from this study were congruent to studies from other countries. In a study comparing 10 dairy farms in Ireland, Casey and Holden (2005) reported a range of between 0.92 and 1.51 kg CO_2e/kg milk, while Basset-Mens *et al.* (2005) found that the typical New Zealand dairy farm emitted 0.72 kg CO_2e/kg milk. Results from 23 conventional and organic farms in Sweden ranged between 0.90 and 1.04 kg CO_2e/kg milk (Cederberg and Flysjö 2004), while results from Germany comparing 18 farms found that the GHG emissions ranged between 1.0 and 1.3 kg CO_2e/kg milk (Haas *et al.* 2001). In two more recent studies, the GHG emissions of Oceania (dominated by the Australian and New Zealand dairy industries) was estimated at approximately 1.1 to 1.2 kg CO_2e/kg milk (FAO 2010; Hagemann *et al.* 2011), reaffirming that results from our study were comparative to other international studies. However, comparing the results of this study with results from other studies can be difficult given the impact hat different methodologies, emissions factors and assumptions can have on the estimations. For example, the direct N_2O emissions from N fertilisers applied to pastures is 0.4% in Australia (DCCEE 2009). This is considerably lower than the IPCC emission factor of 1.25% as is used in many European studies (e.g. Casey and Holden 2005; Lovett *et al.* 2006) or 1.0% as is used in New Zealand studies (e.g. Beukes *et al.* 2011; Flysjö *et al.* 2011). The direct N_2O emission factors for animal waste are also lower in Australia compared to other countries, with the result that direct N_2O emissions will be lower than indirect N_2O emissions for Australian dairy GHG emission studies.

There was a significant ($P<0.05$) regional difference in the GHG emissions intensity of milk production, however, caution needs to be taken when extrapolating the result of the small number of farms in this study to the whole of industry for any particular region. The mean GHG emissions intensity of milk production for the four Tasmanian dairy farms in this study was 1.30 kg CO_2e/kg FPCM compared to a mean of 1.04 kg CO_2e/kg FPCM when 60 Tasmanian dairy farms were assessed for their GHG emissions intensity (Christie *et al.* 2011). All four Tasmanian farms in this study had low levels of grain feeding (mean of 0.46 t DM/cow.lactation compared to an overall study mean of 1.29 t DM/cow.lactation), exhibited low milk production per cow (mean of 4,329 kg FPCM/cow.lactation compared to an overall study mean of 6,265 kg FPCM/cow.lactation) and were classified as FS1. Based on a recent survey of 80 Tasmanian dairy farm operators (Dairy Australia 2011b), 66% of farms were identified as FS1, 29% as FS2 and 5% as FS3. If one or two of the four Tasmanian farms in this study were an FS2 or FS3 as opposed to FS1, it is possible that the Tasmanian mean GHG emissions intensity of milk production may have been lower. For this reason, a comparisons of the farming system across all regions, was considered the preferable method than a regional comparison.

The cumulative distribution function for the three farming systems showed substantially wider variation in the GHG emissions intensity of milk production for the FS1 farms compared to substantially less variation between the FS2 and FS3 farms. One of the major differences between the three farming systems was in the level of milk production per cow, with the FS1 group producing on average 4,823 ± 902 kg FPCM/cow.lactation compared with 7,055 1,241 and 6,271 ± 654 kg FPCM/cow.lactation for the FS2 and FS3 groups, respectively. Given that the allocation of farms to farming systems classifications was partially based on the level of grain feeding, grain feeding was always lower for the FS1 group with a mean of 0.62 t DM/cow.lactation compared to 1.78 and 1.06 t DM/cow.lactation for the FS2 and FS3 groups, respectively.

It is well established that increasing the level of grain/concentrate in the diet improves milk production (Tessmann *et al.* 1991; Kellaway and Porta 1993; Robaina *et al.* 1998; Stockdale 1999). In addition, it is also well established that increasing the proportion of grain/concentrate in the diet reduces the proportion of dietary energy converted into CH_4 (Moe and Tyrrell 1979; Johnson and Johnson 1995; Boadi *et al.* 2004) and reduces enteric CH_4 emissions per unit of milk production (Johnson *et al.* 2002; Lovett *et al.* 2005, 2006). In addition, improving milk production per cow was found to be the only significant ($P<0.05$) key farm variable in the SMLR analysis to influence the GHG emissions intensity of milk production, with a reduction of 0.102 kg CO_2e for every additional 1000kg of FPCM produced per cow. Therefore it is clear from this study that management practices that increase milk production per cow will reduce the GHG emissions intensity of milk production and that this is a key target area for lowering the emissions intensity of milk production for the Australian dairy industry. However, focusing on improving milk production per cow is likely to result in higher milk production per farm, unless stocking rates and adjusted accordingly to produce similar levels of milk production from fewer animals. It is also important to note that increasing the consumption of home grown forage per hectare, and not milk production per cow, has been show to be a strong determinant of business success in grazing-based dairy production systems (O'Brien 1994; Savage and Lewis 2005; Chapman *et al.* 2008, 2009).

While there was no significant ($P>0.05$) difference in the GHG emissions intensity per unit of area across the three farming systems, there was significant ($P<0.05$) regional differences. Tasmania and south eastern Victoria were significantly ($P<0.05$) higher in farm area GHG emissions than New South Wales, Western Australia and Queensland. When farms were ranked according to stocking rate (i.e. number of milkers per hectare of milking area), 10 of the highest 15 farms were located either in Tasmania or south eastern Victoria. As stocking rate increases, there is greater CH_4 production per unit of land, thus resulting in higher farm area GHG emissions figures. Some of the lowest stocking rates were in New South Wales, Western Australia and Queensland, further confirming that even though stocking rate was not identified as one of the key farm variables in the area GHG emissions intensity SMLR analysis, stocking rate still appears to be a contributing factor when comparing regional average farm area GHG emissions.

The empirical methodologies used in this study are the only currently IPCC acceptable methods to account for farm GHG emissions at a regional and national scale. However, these emissions can only be considered as an estimate. Given that over half of all emissions were derived from enteric CH_4, any variation in the methodology used to calculate this source of emission is likely to have the biggest influence on total farm emissions. The Australian methodology for estimating CH_4 emissions use a Blaxter and Clapperton (1965) derived equation, using herd live weight, daily live weight gain (for growing stock) , diet DMD and milk production figures. In this study using farm and seasonal-specific, laboratory derived feed quality data was a vast improvement for estimating GHG emissions, compared to using potentially inaccurate generic 'textbook' averages. However, these were snap-shot assessments of the diet quality on the day that each farm was visited and as such may not accurately reflect the diet quality for the milking herd for each season or more importantly, for the whole study period.

It is also important to note that there are potentially seasonal influences on CH_4 emissions from pastures with similar feed quality. In a study by Ulyatt *et al.* (2002a), sheep were fed a diet with a DMD of 82.0% in mid spring (September) and mid winter (June). Methane emissions varied between the two seasons at 30.6 and 27.9 g CH_4/day, respectively. When converted to digestible DM intake (DDMI) to remove the variation in daily feed intakes between the two study periods, the results were 24.7 and 18.5 g CH_4/kg DDMI, respectively. In the same Ulyatt *et al.* (2002a) study, dairy cows were fed a diet with 82% DMD in early spring, resulting in a CH_4 emission of 27.3 g CH_4/kg DDMI. Even when the diet quality for the dairy cow study was reduced to 75.5 and 68.4% DMD in late spring (November) and early autumn (March), respectively, CH_4 emissions were not significantly ($P<0.05$) different at 18.2 and 18.0 g CH_4/kg DDMI. The Ulyatt *et al.* (2002a) study showed that diets with the same DMD% resulted in varied CH_4 emissions both within and between ruminant species. However it is important to know what other contributing factors, other than DMD%, could have resulted in differing enteric CH_4 production. If these factors can be identified and incorporated into our current methodologies, this would assist in strengthening the accuracy of enteric CH_4 emission estimations.

Palliser and Woodward (2002) compared measured CH_4 emissions from lactating dairy cows (Woodward *et al.* 2002) with estimated CH_4 emissions from one mechanistic (Baldwin 1995) and three empirical models (Blaxter and Clapperton 1965; Moe and Tyrell 1979; Kirchgessner *et al.* 1995). They found that the empirical Blaxter and Clapperton (1965) model consistently over predicted CH_4 emissions. While the mechanistic model was found to be a better estimate of CH_4 emissions, variations between measured and predicted CH_4 emissions were still present with this model (Palliser and Woodward 2002).

Ellis *et al.* (2010) further confirmed this when they compared the observed CH_4 emissions from 206 data points derived from 16 different studies with the estimated CH_4 emissions from nine CH_4 prediction equations. These nine CH_4 emissions equations varied in their level of detail required, with some only needing daily gross energy intake to estimate CH_4 emissions (e.g. the IPCC (1997) Tier II equation) while others required substantially greater data to estimate CH_4 (e.g. the Moe and Tyrell (1979) equation requires non-structural carbohydrate, hemicellulose and cellulose figures). The general conclusions drawn from the authors was that while some equations predict CH_4 emissions better than others, all equations had some degree of difficulty describing the variation present in observed CH_4 values and prediction accuracy appeared to be low.

Although agriculture is currently excluded from the carbon tax (or the subsequent emissions trading scheme) that the current Australian government is legislating (DCCEE 2011b), agriculture is considered an important component in meeting Australia's GHG emission targets. To facilitate this, the Australian government has legislated the Carbon Farming Initiative (DCCEE 2011c) to provide a mechanism and financial incentive to assist agriculture in adopting practices that can provide emission offsets in one of two ways; by removing or avoiding emissions (e.g. the capture and destruction, or abatement of enteric CH_4 from livestock) or by removing carbon from the atmosphere and storing it in trees or soil (e.g. farming in a manner to increase soil carbon). Collecting accurate on-farm information so as to undertake a 'business-as-usual' GHG emissions assessment will be the critical first step in this process. This study has shown significant variation in GHG emissions intensity of milk production exists between and within farming system and as such a single emission factor for milk production is not appropriate for estimating total farm emissions. It is also apparent that the current Australian inventory methodology for estimating GHG emissions may have some limitations, although finding the balance between simplicity of data collection and overall accuracy of emissions estimation will continue to be an issue given that on-farm emission measuring is unlikely to ever be practical. However, with on-going field research validating and improving the algorithms and emission factors currently used to estimate Australian dairy GHG emissions, this will further strengthen our ability to estimate on-farm GHG emissions.

Conclusion

The work presented in this paper is the first known case study of the estimation of the GHG emissions of Australian dairy farms across a range of regions, levels of milk production per cow and per hectare, and reliance on inputs such as supplementary feeding and fertilisers. While the results of this study indicated that adopting a more intensive dairy farming system, with higher inputs from grain and other supplements to increase milk production per cow, resulted in reducing the GHG emissions intensity of milk production, care needs to be taken that increasing milk production per cow is not at the detriment of reproductive performance, resulting in more replacement animals being required, or to the detriment of business success as developing a farming system that is more intensive could potentially diminish our international competitive advantage of producing milk at a low cost in addition to reducing the resilience of the farming system in a changing climate.

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Table 1. The mean (minimum and maximum in parenthesis) value for each farm, herd and milk production data required to estimate greenhouse gas emissions.

Farm		**Herd**		**Milk production**	
Farm area- total (ha)	338.6 (67.3 – 1,045.6)	Milking herd size (number of cows)[A]	355 (62 – 1,350)	Milk production (000's litres/year)	2,183 (373 – 1,1248)
Farm area- milking platform (ha)	191.7 (52 – 460)	Milking herd average live weight (kg)	534 (453 – 550)	Milk production (000's kg MS/year)	160 (26 – 780)

Farm area- irrigated (ha)	63.2 (0 – 329)	Heifer herd size (number of rising 1 and 2 yr olds)	72 (14 -190)	Milk production (000's kg FPCM/year)	2,254 (374 – 1,1067)
Farm area- non-irrigated (ha)	128.6 (3 – 460)	Replacement rate (%)	22.1 (3.9 – 36.1)	Milk production (000's kg FPCM/cow.lactation)	6.27 (3.25 – 9.87)
Electricity (000's kWh/year)	145.8 (27.2 – 1,023.1)	Mature bulls herd size	7 (0 – 40)	Milk production (000's kg FPCM/ha)[C]	12.67 (3.20 – 36.05)
Diesel (000's L/year)	9.6 (6.2 – 25.4)	Number of bulls per 100 milkers	2.0 (0 – 6.6)	Milk production (000's kg FPCM/ha)[d]	7.62 (1.41 – 18.08)
N fertilizer (000's kg N/year)	23.4 (0.0 – 154.3)	Stocking rate (cows/ha)	2.0 (0.6 – 4.4)	Annual mean butterfat (g/100 g milk)	4.10 (3.65 – 5.13)
P fertilizer (000's kg P/year	4.4 (0.0 – 25.1)	Pasture consumption (t DM/ha)[B]	6.5 (0.1 – 14.1)	Annual mean protein (g/100 g milk)	3.31 (3.09 – 3.83)
K fertilizer (000's kg K/year)	8.5 (0.0 – 64.4)	Concentrates (t DM/cow. lactation)	1.3 (0 – 2.9)		
S fertilizer (000's kg S/year)	4.1 (0.0 – 26.0)	Estimated total DMI (t DM/cow.lactation) [B]	5.8 (3.6 – 7.8)		
Purchased concentrates (t DM/year)	436.1 (19.9 – 2,336.6)	Dietary dry matter digestibility (%)	74.5 (68.9 – 78.9)		
Purchased forages (t DM/year)	233.4 (0.0- 1,788.7)	Dietary crude protein (%)	19.8 (14.4 – 24.4)		
Purchased other feeds (t DM/year)	132.7 (0.0 -2,375.9)	Feed conversion efficiency (litres of milk/kg DMI)	1.04 (0.55 – 1.56)		
		Percentage of grain in the milking herd diet	22.3 (0 – 57.4)		

[A] Cows milked for more than 2 months and contributing to annual milk production; [B] Pasture consumption (t DM/ha) and total dry matter intake (sum of home-grown pasture, conserved pasture, purchased forage, purchased grain/concentrates and purchased other feed sources (t DM/cow.lactation)), as estimated using the Pasture Consumption and Feed Conversion Efficiency Calculator (Heard and Wales, 2009); [C] Milk production per hectare based on milking platform only; [d] milk production per hectare based on total farm area

Table 2. Emission factors and equations to estimate direct and indirect nitrous oxide emissions from faeces, urine, stored and spread waste and nitrogen fertilisers (DCCEE 2009).

	Source	Equation and emission factors to estimate N_2O losses
Direct	Faeces excreted onto pastures	0.005 x faeces N x % faeces deposited onto pastures during grazing
	Urine excreted onto pastures	0.004 x urinary N x % urine deposited onto pastures during grazing
	Stored waste	0.001 x sum of faeces & urinary N x % faeces and urinary N stored in lagoons and as liquid/slurry[A]
	Spread stored waste	0.01 x (faeces & urinary N stored – N_2O lost during the storage phase – N_2O lost through volatilisation)
	N fertiliser applications	(0.004 x N fertiliser applied to pastures) and (0.003 x N fertiliser applied to crops)
Indirect	Volatilisation (faeces and urine)	0.01 x ((% faeces & urinary N deposited onto pastures x 0.2) + (% faeces & urinary N stored in lagoon x 0.35) + (% faeces & urinary N stored as liquid/slurry x 0.4) + (% faeces & urinary N spread daily x 0.07))
	Volatilisation (N fertiliser)	0.1 x 0.01 x sum N in fertiliser applied to pastures & crops
	Leaching/runoff (faeces and urine)	0.3 x 0.0125 x (faeces N + urinary N + spread and stored waste N)
	Leaching/runoff (fertiliser)	0.3 x 0.0125 x sum N in fertiliser applied to pastures & crops

[A] Faeces and urine stored and spread daily is also classified as stored waste, however this source of waste does not emit N_2O during the storage phase, only the spreading phase, and therefore is not a source of stored N_2O emissions.

Table 3. Regional means and ranges of total farm greenhouse gas emissions (t CO_2e/annum) and greenhouse gas emissions intensities (kg CO_2e/kg fat and protein corrected milk (FPCM); t CO_2e/cow; t CO_2e/ha).

	Number of farms	Total farm GHG emissions t CO_2e/annum		Greenhouse gas emissions intensity kg CO_2e/kg FPCM		t CO_2e/cow.annum		t CO_2e/ha.annum	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
NSW	9	1,723^{bc}	411 – 3,095	1.06^{b}	0.85 – 1.31	6.77^{a}	5.29 – 8.59	5.96^{b}	1.38 – 10.38
QLD	4	1,184^{c}	621 – 1,863	1.11^{ab}	0.95 – 1.36	6.17^{a}	4.78 – 6.98	4.79^{b}	1.48 – 7.01
SA	3	4,450^{a}	1,167 – 9,416	0.99^{b}	0.85 – 1.10	6.75^{a}	5.86 – 7.42	8.23^{ab}	2.22 – 15.39
TAS	4	3,645^{ab}	2,240 – 5,628	1.30^{a}	1.03 – 1.68	5.96^{a}	5.45 – 6.29	11.09^{a}	9.01 – 12.63
Nth VIC	3	2,521^{abc}	4,121 – 4,770	0.94^{b}	0.90 – 0.96	6.41^{a}	5.81 – 6.72	8.81^{ab}	5.03 – 11.01
SE VIC	10	1,993^{bc}	742 – 5,505	1.00^{b}	0.76 – 1.16	6.34^{a}	5.84 – 7.48	10.38^{a}	5.03 – 17.97
SW VIC	3	1,639^{bc}	883 – 3,014	0.93^{b}	0.78 – 1.05	5.82^{a}	5.34 – 6.25	6.39^{ab}	4.20 – 8.79
WA	5	2,373^{abc}	713 – 4,602	1.02^{b}	0.91 – 1.09	6.07^{a}	5.48 – 6.45	5.22^{b}	2.07 – 6.84
Mean	41	2,255	411 – 9,416	1.04	0.76 – 1.68	6.34	4.78 – 8.59	7.74	1.38 – 17.97

Superscript letters that differ within columns indicate values that are significantly different at $P = 0.05$

Table 4. Percentage (%) of total farm greenhouse gas emissions from each source for each dairy region, as estimated using the DGAS calculator.

Source of greenhouse gas emission	NSW	QLD	SA	TAS	Nth VIC	SE VIC	SW VIC	WA	Mean
Enteric CH_4 (%)	54.4	56.6	49.8	55.3	55.2	56.4	56.2	57.8	55.5
CO_2 from fuel & electricity (%)	11.5	10.8	12.7	10.9	8.6	8.8	8.1	5.5	9.6
Indirect N_2O from animal waste[A] (%)	8.2	7.5	7.5	9.3	7.6	8.9	7.6	9.2	8.4
Direct N_2O from animal waste[A] (%)	6.4	6.0	5.9	7.2	5.9	6.9	5.9	7.4	6.6
CO_2 from purchased grains/concentrates (%)	6.8	7.2	6.9	2.3	5.6	5.3	8.7	6.1	6.0
CH_4 from animal waste (%)	5.1	3.8	7.1	4.7	4.8	5.1	5.3	2.3	4.7
CO_2 from purchased fertilisers (%)	1.9	3.0	2.4	4.0	1.0	3.0	3.2	5.0	2.9
CO_2 from purchased forage (%)	3.0	0.1	5.0	1.2	10.1	1.6	0.9	0.5	2.4
Indirect N_2O from N fertilisers (%)	1.4	2.8	1.5	2.7	0.7	2.2	2.3	3.3	2.1
Direct N_2O from N fertilisers (%)	1.2	2.3	1.3	2.3	0.6	1.9	1.9	2.8	1.8

[A] Includes faeces and urine voided directly onto pastures during grazing and faeces and urine stored and spread onto pastures either daily or at a later time

Table 5. Models of stepwise multiple linear regression of the greenhouse gas emissions intensity expressed as milk intensity (kg CO_2e/kg fat and protein corrected milk; FPCM), cow intensity (t CO_2e/cow.annum) and area intensity (t CO_2e/ha.annum), where *b* is the unstandardized coefficient, *SE b* is the standard error of *b, β* is the standardized coefficient and R^2 is the coefficient of determination.

Milk intensity (kg CO_2e/kg FPCM)		*b*	*SE b*	*β*	R^2
Step 1	Constant	1.685	0.069		0.698
	Milk production (kg FPCM/cow.lactation)	-1.0E-04	-1.1E-05	-0.835***	
Cow intensity (t CO_2e/cow.annum)		*b*	*SE b*	*β*	R^2
Step 1	Constant	3.572	0.342		0.639
	Milk production (kg FPCM/cow.lactation)	4.4E-04	5.3E-05	0.799***	
Step 2	Constant	3.633	0.326		0.682
	Milk production (kg FPCM/cow.lactation)	3.8E-04	5.9E-05	0.677***	
	Grain feeding (% grain in milker diet)	0.016	7.2E-03	0.240*	
Area intensity (t CO_2e/ha.annum)		*b*	*SE b*	*β*	R^2
Step 1	Constant	0.974	0.461		0.875
	Milk production (t FPCM/ha.annum)	0.887	0.054	0.935***	
Step 2	Constant	5.300	0.631		0.951
	Milk production ((t FPCM/ha.annum)	0.985	0.036	1.038***	
	Milk production (kg FPCM/cow.lactation)	-8.1E-04	1.1E-04	-0.295***	
Step 3	Constant	4.581	0.593		0.963
	Milk production (t FPCM/ha.annum)	0.919	0.037	0.969***	
	Milk production (kg FPCM/cow.lactation)	-7.0E0.4	9.7E-05	-0.256***	
	Nitrogen fertiliser (kg N/ha.annum)	7.3E-03	2.1E-03	0.128**	

Significant contributions to the model at * $P < 0.05$, ** $P < 0.01$; ***$P < 0.001$

Table 6. The mean greenhouse gas emissions intensity (kg CO_2e/kg fat and protein corrected milk (FPCM); t CO_2e/cow.annum; t CO_2e/ha.annum) for each farming system group. (FS1 = pasture based with low grain feeding; FS2 = pasture-based with medium to high grain feeding and supplements fed in grazed paddocks; FS3 = pasture-based with low to high grain feeding and supplements fed on feedpad area as required).

	Greenhouse gas emissions intensity		
	kg CO_2e/kg FPCM	t CO_2e/cow.annum	t CO_2e/ha.annum
FS1	1.23[a]	5.79[b]	8.21[a]
FS2	0.98[b]	6.78[a]	7.67[a]
FS3	0.97[b]	6.08[b]	7.37[a]

Superscript letters that differ within columns indicate values that are significantly different at P = 0.05

Fig 1. The greenhouse gas emissions intensity of milk production (kg CO_2e/kg fat and protein corrected milk; A), per cow (t CO_2e/cow; B) and per hectare (t CO_2e/ha; C) for individual farms.

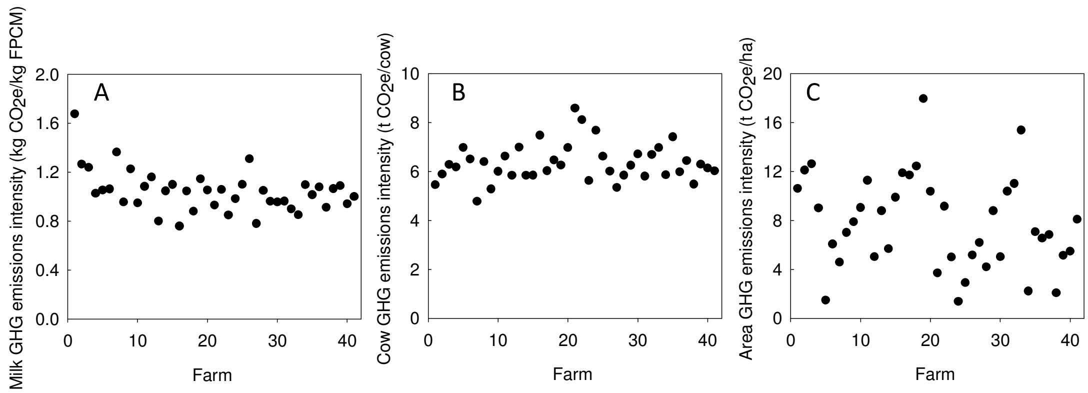

Fig 2. Cumulative distribution function of the greenhouse gas emissions intensity of milk production (kg CO_2e/kg fat and protein corrected milk) for the three farming systems groups (FS1 = pasture based with low grain feeding; FS2 = pasture-based with medium to high grain feeding and supplements fed in grazed paddocks; FS3 = pasture-based with low to high grain feeding and supplements fed on feedpad areas as required).