Appendix 10: A whole farm systems analysis of greenhouse gas emissions of 60 Tasmanian dairy farms

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Abstract

The Australian dairy industry contributes approximately 1.6% of the nation's greenhouse gas (GHG) emissions, emitting an estimated 8.9 million tonnes of CO_2 equivalents (t CO_2e) per annum (DCC, 2008). This study examined GHG emissions of 60 Tasmanian dairy farms using the Dairy Greenhouse gas Abatement Strategies calculator (DGAS), which incorporates International Panel on Climate Change (IPCC) and Australian inventory methodologies, algorithms and emission factors. Sources of GHG emissions including pre-farm embedded emissions associated with key farm inputs (*i.e.,* grains/concentrates, forages and fertilizers) and on-farm emissions from CO_2, CH_4 and N_2O are estimated by DGAS software. A detailed description of GHG calculations and functionality of DGAS software are provided. Total farm GHG emissions of 60 Tasmanian dairy farms, as estimated with DGAS, ranged between 704 and 5,839 t CO_2e/annum, with a mean of 2,811 t CO_2e/annum. Linear regression analyses showed that 0.93 of the difference in total farm GHG emission was explained by milk production. The estimated mean GHG emission intensity of milk of production was 1.04 kg CO_2e/kg fat and protein corrected milk (FPCM; ranged between 0.83 and 1.39 t CO_2e/t FPCM)) with a standard deviation of 0.13. Stepwise multiple linear regression analysis showed that feed conversion efficiency (kg FPCM/kg dry matter (DM) intake) and N based fertilizer application rate explained 0.60 of the difference in the GHG emissions due to milk production from these pastoral based dairy systems. The estimated mean per cow and per hectare emission intensity was 6.9 ± 1.46 t CO_2e/cow and 12.6 ± 4.37 t CO_2e/ha, respectively. Stepwise multiple linear regression analysis showed that DM intake per cow (t DM intake/cow/lactation) explained 0.86 of the variability in per cow GHG emissions intensity, while milk production per hectare (t FPCM/ha) explained 0.92 of the variability in per hectare GHG emission intensity. Given the influence that feed conversion efficiency and/or N based fertilizer application rates had on all GHG emissions intensities, it is clear that these factors should be key target areas to lower the intensity of emissions associated with dairying in Tasmania.

Keywords: Australia, carbon dioxide, DGAS, methane, nitrous oxide, pre-farm emissions

1. Introduction

Warming of the climate system is unequivocal, at least in the minds of most persons, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global sea levels (IPCC, 2007). Most of the observed increase in global temperatures is likely due to the observed increase in anthropogenic greenhouse gas (GHG) emissions (IPCC, 2007). It is estimated that global GHG emissions in 2005 totalled 40,950 million tonnes of CO_2 equivalents (Mt CO_2e), with Australia responsible for 553 Mt CO_2e, ~1.5% of world emissions (Climate Analysis Indicators Tool, 2009).

The stationary energy sector was the largest source of GHG emissions in Australia in 2008, accounting for approximately half of this total, with agriculture the second largest contributor, accounting for approximately 16% of the nations' GHG emissions (DCC, 2008). The livestock industries of dairy, beef and sheep farming contributed ~10, 47 and 19% of these agricultural GHG emissions, respectively (DCC, 2008). The major source of GHG emissions from these livestock industries was CH_4 from enteric fermentation. Nitrous oxide emissions were also generated from N based fertilizers and from animal deposition and manure management. In addition, there were indirect N_2O emissions associated with losses to the environment through atmospheric volatilisation and runoff/leaching of N based fertilizers and animal waste. The Dairy Greenhouse gas Abatement Strategy (DGAS) calculator was developed to model the CO_2, CH_4 and N_2O associated with dairying in Australia, using Intergovernmental Panel on Climate Change (IPCC) and Australian national inventory methodologies, algorithms and emission factors (DCC, 2009). While analysis of GHG emissions of dairy farm systems have been undertaken for the dairy industry of many countries, including Ireland (Casey and Holden, 2005), Sweden (Cederberg and Flysjö, 2004) and New Zealand (Basset-Mens et al., 2005), there has been a paucity of studies undertaken under Australian conditions to estimate the GHG emissions among dairy farms.

Dairying is a well-established industry in Australia. While the bulk of milk production occurs along the coastal areas of the south-east corner of the country (66% from Victoria, South Australia, New South Wales and Tasmania), 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 New South Wales and Victoria. In 2008/09, the dairy industry produced approximately 9.0 billion liters of milk from 1.7 million cows and 7,800 farms (Dairy Australia, 2009).

Our study determined GHG emissions, as estimated by the DGAS calculator, of 60 Tasmanian dairy farms. These farms were pasture based grazing systems with varying levels of milk production, grain feeding, N fertilizer application rates and reliance on irrigation water for pasture and crop production. This study also examined the relationship between GHG emission intensity and some key farm variables.

2. Materials and methods

2.1. Farm system boundary, global warming potentials and data collation

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, but included embedded pre-farm emissions. A global warming potential of 1, 21 and 310, respectively, was used to convert CO_2, CH_4 and N_2O emissions into CO_2e emissions (DCC, 2009), as these are the current global warming potentials for the Australian inventory. The farm and herd farm physical and key farm input data from 60 Tasmanian dairy farms (~12% of the state industry) for the 2006/07 milking year were collected during one-on-one farmer interviews. The mean and range of farm and herd input data for the 60 farms are in Table 1. Farms were located in the north-east and north-west of the state, and represented the diversity of the industry in terms of milk production per cow, milking herd size, level of grain feeding and N based fertilizer usage.

All areas used for dairy related activities, including the milking platform and run off areas for raising replacement stock and growing pastures and crops for forage conservation were included in total farm area. Milk production was reported as fat and protein corrected milk (FPCM), calculated as:

FPCM (kg) = raw milk (kg; calculated by multiplying liters by 1.03 (Sevenster and de Jong, 2008) × (0.337 + (0.116 × fat content (g/100 g milk)) + (0.06 × protein content (g/100 g milk)) (FAO, 2010).

2.2. Pre-farm embedded emissions

Simapro life cycle assessment software (Simapro, 2006) was used to determine the CO_2e emissions associated with production of key farm imports and the associated emission factor (EF) for each is in Table 2. As each farm applied varying blends of fertilizer, each was converted into kg of N, P, K and S and then converted into the equivalent amount of urea (0.46 N), single superphosphate (0.09 P and 0.11 S) and potassium chloride (0.50 K). The amount of each feed type and fertilizer was multiplied by their corresponding EF, with results presented in terms of GHG emissions (kg CO_2e) from fertilizer, grain/concentrates and other feed sources.

2.3. Calculating on-farm CO_2 emissions

In this study, on-farm CO_2 emissions were defined as those associated with electricity and diesel fuel consumption. Australian electricity is generated by a range of sources (*e.g.,* brown and black coal, natural gas, hydro, wind). However, as most of the country (including Tasmania) is connected to a national grid, it is difficult to know where or how the electricity is being generated. We selected the option with the highest EF (brown coal from Victoria) as the source of electricity, equivalent to 1.4 t CO_2e emitted for each 1000 kWh of electricity consumed (DCC, 2009). The extraction/refinement and consumption of diesel fuel by farm vehicles, machinery and irrigation pumps was equivalent to 3.4 t CO_2e emitted for every 1000 L of fuel consumed (DCC, 2009).

2.4. Calculating on-farm CH_4 emissions

Methane is emitted on-farm from two main sources, being enteric fermentation and manure management. Enteric CH_4 was estimated for four stock classes (*i.e.,* milking herd, growing one year olds, growing two year olds and mature bulls), using data for each stock class liveweight, liveweight gain, milk production and mean annual diet dry matter (DM) digestibility (DMD; g/kg DM intake). Enteric fermentation was calculated in DGAS from a series of methodologies, algorithms and emission factors in the Australian National Greenhouse Accounts National Inventory Report (DCC, 2009), based on research by Brouwer (1965), Blaxter and Clapperton (1965), Minson and McDonald (1987) and the Australian Standing Committee on Agriculture (1990).

Dry matter digestibility (g/kg DM) and crude protein (CP; g/kg DM) estimates were assigned to each feed source used, based on extensive results from the FeedTest® laboratory in Australia, as published in the Pasture Consumption and Feed Conversion Efficiency Calculator manual (Heard and Wales, 2009; Table 3). These estimates where used to determine mean annual DMD (g/kg DM) and CP (g/kg DM) of the diet for the milking herd. For all farms, the replacement herd and mature bull herd was assumed to have a diet with a DMD of 650 g/kg DM and CP of 180 g/kg DM. The Pasture Consumption and Feed Conversion Efficiency Calculator (Heard and Wales, 2009) was also used to determine annual pasture utilization for the milking platform (t DM/ha) and annual DM intake (t DM intake/cow/lactation) for the milking herd, taking into consideration a feed out wastage for grains/concentrates, forage and other feed sources.

Methane from manure management was calculated in DGAS using a series of methodologies, algorithms and emission factors (DCC, 2009), based on research by Williams (1993) and IPCC (1997) guidelines. In addition, an integrated CH_4 conversion factor was required, based on proportioning of animal waste to varying manure management regimes. For Tasmania, the manure management regime allocated 92% of waste voided onto pastures directly, 6% stored in a lagoon system, 1.5% spread on pastures daily and 0.5% stored as a liquid/slurry and applied later (DCC, 2009).

2.5. Calculating on-farm N_2O emissions

Four sources of N_2O emissions were estimated which were those associated with manure management, N based fertilizers, deposition of animal waste directly onto pastures during grazing and indirect N_2O emissions associated with the potential for N based fertilizers, and animal waste to be lost to the environment through leaching/runoff and volatilisation. The manure management regime allocation fractions for Tasmania, as described earlier (Section 2.4), were also used to calculate N_2O emissions associated with animal waste. Nitrogen based fertilizer N_2O emissions were calculated based on emission factors using research by Galbally et al. (2005), and the application rates of N based fertilizer. Nitrous oxide emissions associated with faeces and urine excretion were calculated, using methodologies, algorithms and emission factors that reflect Australian conditions (DCC, 2009), based on research by the Australian Standing Committee on Agriculture (1990) and Freer et al. (1997). The proportion of N based fertilizers and animal waste that is available for direct and indirect N_2O emissions and their corresponding EF is in Table 4.

2.6. Dairy Greenhouse gas Abatement Strategies calculator

The DGAS calculator was constructed as a Microsoft Excel Workbook and incorporates MS Forms for ease of use. The calculator has, at its core, five user forms and 13 worksheets. The first two forms are for farm and herd data entry for the baseline farm system. The farm data includes farm size (including proportion of farm area that is used to grow pastures and crops and proportion of farm area that is irrigated), location, annual rainfall, area of tree plantings, manure management system, electricity, diesel, fertilizer usage and purchased feed inputs. Herd data includes milk production and five livestock classes including animal numbers, liveweight, liveweight gain and dietary composition. The diet for the milking herd allows for seasonal variation in dietary composition while the diets of other livestock classes were fixed on an average annualized basis.

The third user form displays results of the baseline farm system, both as graphics and text. One functionality of DGAS is the opportunity to compare a baseline farm system with a hypothetical strategy farm system to ascertain impacts that GHG mitigation strategies have on farm GHG emissions. The last two forms are structured in a similar format to the first two, but allow for alterations to farm and/or herd data to assess implications of mitigation strategies on farm GHG emissions. The calculator then presents baseline and strategy farm results to assess impacts that adopting the mitigation strategy will have on both total farm and milk intensity GHG emissions. The 13 worksheets incorporate the methodologies, algorithms and emission factors to calculate the CO_2 emissions associated with the embedded pre-farm inputs, and the on-farm CO_2, CH_4 and N_2O emissions. These worksheets can be altered, if required, to reflect changes to the methodologies, algorithms and/or emission factors.

2.7. Statistical Analysis

Statistical Program for the Social Sciences Statistics (SPSS, 2008) was used to regress total farm GHG emissions against milk production, cow numbers and total farm area. A stepwise multiple linear regression (SMLR) analysis between three measures of GHG emissions intensity and individual key farm variables was undertaken using the statistical functions of SPSS Statistics. The three functional units of emissions intensity used were: emissions/kg of milk production (kg CO_2e/kg FPCM), emissions/milking cow (t CO_2e/cow) and emissions/unit of land (t CO_2e/ha). Key farm variables used in the SMLR analysis were milk production/cow (t FPCM/cow), milk production/hectare (t FPCM/ha), stocking rate (number of cows/ha of milking platform), pasture utilisation (t DM consumed/ha), total feed intake (t DM intake/cow/lactation), FCE (kg FPCM/kg DMI), proportion of grain in the milking herd diet and N fertilizer application rate (kg N fertilizer/ha).

Where the coefficient of determination of a linear regression is discussed, the result is reported as r^2. Where the coefficient of determination of a SMLR is discussed, the result is reported as R^2.

3. Results

The mean ± SD of farm GHG emission, as estimated by the DGAS calculator, was 2,811 ± 1,264 t CO_2e/annum. A positive linear relationship (Fig. 1) existed between total farm GHG emissions and milk production (equation 1), herd size (equation 2), and farm area (equation 3) as:

1. Total GHG emissions (t CO_2e/annum) = Fat protein corrected milk production (t FPCM) × 0.96 + 42.90; r^2 = 0.93 ($P < 0.001$)
2. Total GHG emissions (t CO_2e/annum) = Milking herd size (number of cows) × 5.94 + 373.75; r^2 = 0.75 ($P < 0.001$)
3. Total GHG emissions (t CO_2e/annum) = Total farm area (ha) × 7.68 + 993.95; r^2 = 0.41 ($P < 0.001$)

Estimated GHG emission intensity of milk production was 1.04 ± 0.13 kg CO_2e/kg FPCM, estimated GHG emissions intensity/cow was 6.9 ± 1.46 t CO_2e/cow, and estimated GHG emissions intensity/hectare was 12.6 ± 4.37 t CO_2e/ha.

The contribution of the various emission sources, as a proportion of total farm GHG emissions, is in Table 5. Enteric CH_4 was the biggest source of total farm GHG emissions. The next two largest sources were on farm CO_2 from electricity and diesel consumption and indirect N_2O emissions from N based fertilizers and animal waste.

The SMLR analysis showed that FCE (kg FPCM/kg DM intake) alone explained 0.55 of the difference in the emission intensity of milk production (kg CO_2e/kg FPCM) among farms (Table 6). Addition of N based fertilizer application rates to the model accounted for an additional 0.05 of the difference in the milk intensity among farms (Table 6). The model that most accurately predicted milk intensity GHG emissions was:

> (kg CO_2e/kg FPCM) = 2.03 + (-0.91 × FCE (kg FPCM/kg DM intake)) + (2.82E-04 × N based fertilizer application rate (kg N/ha)).

Increases in FCE decreased GHG emission intensity of milk production while increases in N based fertilizer application rates increased the GHG emission intensity of milk production (Table 6).

The SMLR analysis showed that DM intake (t DM intake/cow/lactation) explained 0.86 of the differences in per cow GHG emissions intensity (t CO_2e/cow) among farms (Table 6). Addition of

N based fertilizer application rates and milk production/ha improved prediction of per cow GHG emission intensity, although their addition could only account for an additional 0.03 of the difference (Table 6). Increases in DM intake and N based fertilizer application rates increased per cow GHG emission intensity while increases in milk production/hectare decreased per cow GHG emission intensity (Table 6).

The SMLR analysis showed that milk production/hectare (t FPCM/ha) explained 0.92 of the difference in per hectare GHG emissions intensity (t CO_2e/ha) among farms (Table 6). Addition of FCE and N based fertilizer application rates improved prediction of per hectare GHG emission intensity, although their addition could only account for an additional 0.03 of the difference (Table 6). Consistent with the milk intensity emissions model, increases in FCE decreased per hectare GHG emission intensity, while increases in milk production per hectare and N based fertilizer application rates increased per hectare GHG emission intensity.

4. Discussion

Results show that milk production was an accurate way of predicting total farm GHG emissions since milk production accounted for 0.93 of the difference in estimated total farm GHG emissions. While this suggests that milk production alone is a suitable surrogate for estimating farm emissions from pasture based systems, the GHG emissions intensity of milk production varied between 0.83 and 1.39 kg CO_2e/kg milk. Only 0.60 of difference in milk GHG emissions intensity was explained using the key farm variables in the SMLR, and it was most strongly influenced by FCE and the amount of N based fertilizer applied. Given the strong influence that FCE and/or N based fertilizer application rates had on the variability of all three GHG emissions intensities, it is clear that these factors should be key target areas for lowering the extent of GHG emissions associated with dairying in Tasmania.

Improvements in FCE could be achieved through several mechanisms, including feeding options, such as improved herbage quality and improvements in animal performance through breeding (Clark et al., 2007). In a review of studies from the USA, New Zealand and Europe, Grainger and Goddard (2007) examined the differences in intakes and FCE between Holstein-Friesian and Jersey cows, fed both total mixed ration diets and predominantly pasture based diets. Whilst Jersey DM intakes were always lower than those of Holstein Friesians, FCE was similar or higher for Jersey cows compared to the Holstein Friesians, for nine of 11 studies. Improved FCE has experimentally been shown to influence CH_4 production. Clark et al. (2007) found that ruminants with a higher FCE produced 0.1 to 0.2 less CH_4 (g/kg DM intake) than those with a lower FCE.

Improvements in efficiency of use of N based fertilizers generally result in lower N_2O emission from soils. The rate, source and timing of N fertilizers have all been shown to influence N_2O emissions (O'Hara et al., 2003). One example of reduced N_2O emissions from N based fertilizer applications is the use of nitrification inhibitors during times of the year when conditions are conducive to the formation of nitrate from ammonia (*e.g.,* wet winters and springs). Research studies in New Zealand have shown that seasonal N_2O emissions from N based fertilizers could be reduced by up to 80%, equivalent to approximately 30 to 45% on an annual basis, with use of nitrification inhibitors (de Klein et al., 2001; Smith et al., 2008; Luo et al., 2010).

Although the proportion of concentrate in the diet was not a significant predictor in the SMLR analysis of emission intensity, it is well established that increasing the level of grain/concentrate in the diet reduces the proportion of dietary energy converted to CH_4 (Blaxter and Clapperton, 1965). Lovett et al. (2006) found that increased grain feeding from 0.4 to 1.5 t

DM/cow/lactation resulted in a decrease in milk GHG emissions by 0.11 kg CO_2e/kg milk. Similar results were reported by Johnson et al. (2002), who increased the proportion of concentrate in the diet from 40 to 370 g/kg DM, and observed a corresponding reduction in CH_4 production from 1.62 to 1.38 kg CO_2e/kg milk.

In our study, the proportion of grain/concentrate in the diet varied between 0 and 390 g/kg DM (0.0 and 2.9 t DM/cow/lactation), and there was a positive linear relationship (data not shown) between the proportion of grain in diet and FCE, with a 10% increase in grain in the diet equating to a 9% increase in FCE. As shown, an improvement in FCE resulted in a decline in the GHG emissions intensity of milk production. While feeding a high level of grain per cow can be profitable in some circumstances, detailed analysis of farming system performance in southern Australia has shown that farm profitability is more closely related to the amount of pasture consumed on a per hectare basis (Beca, 2005; Savage and Lewis, 2005; Chapman et al., 2008).

Dairy farming in countries such as Ireland, New Zealand and Australia consumes a higher proportion of grazed pasture in the diet, which generally results in a lower cost of production, compared with production costs of confined farming systems such as those in Canada, the USA and some European countries. Dillon et al. (2005) assessed the relationship between milk production costs and the proportion of grazed pasture in the ration, and found that that for every 10% increase in grazed pasture in the ration, milk production costs were reduced by 2.7 euro cents/liter.

While pasture consumption may be a good indicator of business performance (Beca, 2005; Savage and Lewis, 2005; Chapman et al., 2008), the current study found that it provides no indication of associated GHG emissions (data not shown). As such, feeding higher proportions of grain in the diet, as a management practice to improve per cow production, with the intention of reducing the GHG emission intensity of milk production, has the potential to reduce Australia's competitive advantage of producing milk at a lower cost of production compared to some of its international competitors.

Increasing the level of grain feeding corresponded with an increase in DM intake and per cow milk production (data not shown). Emission of CH_4 represents loss of dietary energy (Johnson et al., 1997; Lassey et al., 1997), and the algorithms and equations used to determine DM intake are based on milk production. Therefore, increased milk production and DM intake, due to increased grain feeding, directly increases enteric CH_4 production and per cow GHG emissions. Thus increasing the level of grain feeding may lead to increased stocking rates, thereby increasing enteric CH_4 emissions per unit of land. Subsequently, although higher levels of grain feeding and corresponding high per cow production can reduce emissions due to milk production, these strategies will likely result in higher per farm, higher per cow and higher per unit of land GHG emissions.

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). A more recent study undertaken by the Food and Agriculture Organization of the United Nations (FAO, 2010), found that the global average of GHG emissions was estimated at 2.4 kg CO_2e/kg milk at the farm gate. However, there were substantial regional variations, ranging from a low of 1.0 to 1.5 kg CO_2e/kg milk for western industrialized regions (*e.g.,* USA, Eastern and Western Europe) to a high of ~7.5 kg CO_2e/kg milk for the sun-Saharan region of Africa (FAO, 2010). Oceania (dominated by the Australian and New Zealand dairy industries) was estimated at ~1.2 kg CO_2e/kg milk, reaffirming that results from our study were comparative to other international studies.

Comparing GHG emissions among countries is difficult and uncertain given the impact that different methodologies, emission factors and assumptions can have on the calculations. Some international studies allocate between 85 and 90% of total farm GHG emissions to milk production, with the balance allocated to meat production from cull cows, surplus heifers and bull calves (*e.g.,* Cederberg and Flysjö, 2004; Basset-Mens et al., 2005). However, other studies (*e.g.,* Haas et al., 2001) and the current study have allocated all farm GHG emissions to the primary product; milk. These differences in allocation of farm GHG emissions to milk and meat need to be considered when comparing results among studies.

There are also differences in methodologies and emission factors among countries. For example, in Australia the emission factor for direct N_2O emissions from fertilizers was reduced from the IPCC based 1.25% emission factor (IPCC, 2000), to 0.4% for pastures and 0.3% for crops (DCC, 2009). In New Zealand, an emission factor of 1.0% is used for direct N_2O emissions from N based fertilisers (New Zealand Ministry for the Environment, 2009). So, in effect, applying the same level of N based fertilizers in Australia, for example, would result in substantially lower direct N_2O fertilizer emissions than it would in New Zealand. While the comparison of results from farms from the same country can be useful in identifying potential areas of abatement, diligence should be shown when comparing results using differing empirical methodologies.

While the empirical methodologies used in our study are accepted methods to account for farm GHG emissions, they may not be a precise assessment of actual on farm GHG emissions. Errors in data collection can influence the outcome of inventory assessments of GHG emissions, especially in areas that have been shown to influence GHG emissions intensity. While milk production figures can generally be relatively accurately collected, based on the volume of milk sold to milk processors, DM intake is less accurately predicted and based on numerous assumptions. The algorithms and emission factors can also be a source of error. For example, whilst based on the estimated N_2O emissions under best management practices, allocation of a single emission factor for N fertilizer usage does not allow for the variations in soil types, rainfall patterns, or between the rate, source and timing of applications.

5. Conclusions

Results show that GHG emissions of 60 Tasmanian dairy farms, as estimated using the DGAS calculator, could be accurately explained using a regression equation based on annual milk production. For each kilogram of fat and protein corrected milk produced, there was a corresponding total farm GHG emission of 0.96 kg CO_2e. Results from this study were also comparative to studies in other countries, thus illustrating that the pasture dominant farming systems in Tasmania were as GHG efficient as other pasture-based farming systems in New Zealand, Ireland and Europe.

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and TIAR. The DGAS calculator is freely available and can be downloaded at http://www.dairyingfortomorrow.com.au/index.php?id=47 .

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Table 1. Key farm, herd and milk production input data required in the Dairy Greenhouse gas Abatement Strategies calculator to estimate greenhouse gas emissions (t CO_2e) and the mean (minimum and maximum in parenthesis) values for each of these key farm inputs for the 60 Tasmanian dairy farms.

Farm		Herd		Milk production	
Farm area- total (ha)	237 (57-576)	Milking herd size (number of cows)[a]	410 (147-870)	Milk production (000's kg FPCM/yr)	2,734 (521-5,753)
Farm area- irrigated (ha)	72 (0-280)	Milking herd average liveweight (kg)	526 (420-650)	Annual mean butterfat (g/100 g milk)	4.2 (3.3-5.5)
Farm area- non-irrigated (ha)	165 (0-576)	Rising 1 yr old replacement herd size	118 (28-320)	Annual mean protein (g/100 g milk)	3.4 (3.2-3.8)
Milking platform area (ha)	174 (57-375)	Rising 2 yr old replacement herd size	108 (0-255)	Milk production (kg FPCM/cow yr^{-1})	6,775 (3,304-9,642)
Electricity (000's kWh/yr)	202 (17-608)	Mature bulls herd size	9 (0-28)	Milk production (kg FPCM/ha yr^{-1})	12,332 (3,579-25,984)
Diesel (000's L/annum)	10.8 (0-43.1)	Stocking rate (cows/ha)	2.4 (1.1-4.1)		
N fertilizer (000's kg N/yr)	34.7 (1.5-138.9)	Total DMI (t DM/cow $lactation^{-1}$)[b]	5.9 (3.9-7.6)		
P fertilizer (000's kg P/yr)	8.1 (0.5-33.3)	Concentrates (kg/cow yr^{-1})	1,452 (0- 2,920)		
K fertilizer (000's kg K/yr)	13.8 (0-99.4)	Pasture utilisation (t DM/ha)[c]	9.3 (3.7-15.9)		
S fertilizer (000's kg S/yr)	7.4 (0.7-27.8)	Dietary dry matter digestibility (g/kg DM)	699 (676-716)		
Purchased concentrates (t DM/yr)	583 (0-1,560)	Dietary crude protein (g/kg DM)	191 (175-197)		
Purchased forage (t DM/yr)	195 (0-1,029)	Feed conversion efficiency (kg FPCM/kg DMI)[b]	1.1 (0.8-1.3)		
Purchased other feeds (t DM/yr)	56 (0-722)	Percentage of grain in the milking herd diet	23.3 (0-38.8)		

[a] Cows milked for more than 2 months and contributing to annual milk production; [b] Total dry matter intake from home-grown pasture, conserved pasture, purchased forage, purchased grain/concentrates and purchased other feed sources (t DM intake/cow/lactation), as calculated using the Pasture Consumption and Feed Conversion Efficiency Calculator (Heard and Wales, 2009); [c] Pasture utilisation (t DM consumed/ha), as estimated using the Pasture Consumption and Feed Conversion Efficiency Calculator (Heard and Wales, 2009).

Table 2. Greenhouse gas emission factors for the production of grain/concentrates, hay and silage and fertilizer as calculated using Simapro software (Simapro, 2006).

Key farm input	Emission factor (kg CO_2e/kg product)
Grain/concentrates	0.30
Pasture hay and silage	0.25
Cereal/Maize silage	0.25
Lucerne hay	0.20
Urea	0.89
Single superphosphate	0.23
Potassium chloride	0.13

Table 3. Dry matter digestibility and crude protein (g/kg dry matter) values used for each feed source fed to the milking herd for each of the 60 Tasmanian dairy farms.

Feed source	Dry matter digestibility (g/kg dry matter)	Crude protein (g/kg dry matter)
Home grown consumed pasture	700	200
Home grown conserved forage	650	180
Purchased forage	650	180
Grain	800	120-190[a]
Other feed source	600-750[b]	180-240[b]

[a] 22 farms fed grain with a crude protein of 120 g/kg dry matter while 38 farms fed a 70:15:15 grain/lupins/canola meal blend with a crude protein of 190 g/kg dry matter.

[b] Range of other feeds used so dry matter digestibility and crude protein based on each individual farm inputs.

Table 4. Proportion of N based fertilizers and animal waste that is available for direct and indirect N_2O emissions and their corresponding emission factor.

	Source	Proportion available for loss to the environment	Emission factor
Direct N_2O	N based fertilizer (irrigated pastures and crops)	1.0	0.4%
	N based fertilizer (non-irrigated pastures and crops)	1.0	0.3%
	Urine	1.0	0.4%
	Faeces	1.0	0.5%
	Stored manures	1.0	1.8%
Indirect N_2O - leached/runoff	N based fertilizers	0.3	1.25%
	Animal waste	0.3	1.25%
Indirect N_2O - atmospheric deposition	N -based fertilizers	0.1	1.0%
	Animal waste	0.07 to 0.4[a]	1.0%

[a] 0.07 for daily spread, 0.2 for voided directly onto pastures, 0.35 for stored in lagoons and spread later and 0.40 for liquid/slurry.

Table 5. Mean and range of individual greenhouse gas emissions sources, as a proportion of total farm greenhouse gas emissions for the 60 Tasmanian dairy farms as estimated by the DGAS calculator.

Greenhouse gas emission source	Mean	Range
Enteric CH_4	0.551	0.455 – 0.669
CO_2 from electricity and diesel	0.114	0.031 – 0.220
Indirect N_2O from N-based fertilizers and animal waste	0.109	0.088 – 0.143
Direct N_2O from animal waste[a]	0.074	0.060 – 0.099
CO_2 from purchased grain/concentrates	0.061	0 – 0.098
CO_2 from purchased fertilizers (N and non-N based)	0.036	0.002 – 0.076
Direct N_2O from N-based fertilizers	0.025	0.001 – 0.056
CO_2e from purchased forage	0.018	0 – 0.068
CH_4 from manure management	0.013	0.011 – 0.016

[a] includes N_2O emissions from manure management of stored manures (mean of 0.1%)

Table 6. Models of SMLR of the greenhouse gas emissions intensity expressed as milk intensity (kg CO_2e/kg FPCM), cow intensity (t CO_2e/cow) and area intensity (t CO_2e/ha), 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	2.01	0.12		0.55
	Feed conversion efficiency (kg milk/kg DMI)	-0.85	0.10	-0.74***	
Step 2	Constant	2.03	0.11		0.60
	Feed conversion efficiency (kg milk/kg DMI)	-0.91	0.10	-0.80***	
	Nitrogen fertilizer (kg N/ha)	2.82E-04	1.17E-04	0.21*	
Cow intensity (t CO_2e/cow)		*b*	*SE b*	*B*	R^2
Step 1	Constant	-0.60	0.41		0.86
	Total feed intake (t DMI/cow/lactation)	1.28	0.07	0.93***	
Step 2	Constant	-0.70	0.40		0.87
	Total feed intake (t DMI/cow/lactation)	1.25	0.07	0.90***	
	Nitrogen fertilizer (kg N/ha)	1.89E-03	7.28E-04	0.13*	
Step 3	Constant	-0.9	0.39		0.89
	Total feed intake (t DMI/cow/lactation)	1.36	0.08	0.98***	
	Nitrogen fertilizer (kg N/ha)	3.03E-03	8.18E-04	-0.20***	
	Area production (t FPCM/ha)	-0.05	0.02	-0.17*	
Area intensity (t CO_2e/ha)		*b*	*SE b*	*B*	R^2
Step 1	Constant	2.06	0.45		0.92
	Area production (t FPCM/ha)	0.85	0.03	0.96***	
Step 2	Constant	8.41	1.59		0.94
	Area production (t FPCM/ha)	0.94	0.04	1.05***	
	Feed conversion efficiency (kg milk/kg DMI)	-6.50	1.58	-0.17***	
Step 3	Constant	7.62	1.40		0.95
	Area production (t FPCM/ha)	0.86	0.04	0.96***	
	Feed conversion efficiency (kg milk/kg DMI)	-5.94	1.39	-0.15***	
	Nitrogen fertilizer (kg N/ha)	6.76E-03	1.59E-03	0.15***	

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

Fig. 1. Linear relationship between farm greenhouse gas (GHG) emissions (t CO_2e/annum), as estimated with the DGAS calculator, and milk production (a), milking herd size (b) and farm area (c).