Whole Farm Systems Analysis of Climate Change Impacts on the Southern Grazing Industries – (a sub-project under CCASALI)
Executive summary

This sub project (B.SBP.0071) of the SLA 2030 program was segmented into two broad theme areas. These were climate change assessments and analysis for the Southern Australian livestock industries and greenhouse gas emission (GHG) assessments and mitigation options for the Australian dairy industry. The Key findings are as follows:

- Simulation modelling of perennial ryegrass production has indicated that annual pasture production is likely to increase under most climate scenarios in the cool temperate (Tasmania) pastoral regions with increases in pasture growth occurring during winter and early to mid spring.
- To capture the associate increases in pasture production in the cool temperate dairy regions of Tasmania, it was shown that adapting changes to stocking rate and calving date could improve dairy farm profitability.
- Although the more temperate regions of SW and SE Victoria were found to be generally resilient to 1°C increases in daily temperature with minimal (10%) rainfall decline, further changes are likely to reduce annual pasture growth.
- Incorporating deeper rooted and heat tolerant plant traits in the current pasture base were shown to be effective in moderating the pasture production decline in the SW and SE regions of Victoria, highlighting that the breeding of new cultivars of perennial ryegrass should be focused on these traits and that adopting alternative species into the feedbase that already possess these traits, e.g. tall fescue, should be considered.
- In the more temperate dairy regions of SE and SW Victoria, adaptations to calving date and stocking rate were unlikely to negate the effects of climate change suggesting that further changes to the farm system are required to maintain profitability.
- One hundred dairy farms throughout Australia have been assessed for their farm’s GHG emissions. Data analysis of these 100 dairy farms has shown that 94% of the variation in total farm GHG emissions is explained by milk production alone, although the GHG emission intensity of milk production varied between 0.83 and 1.39 kg CO$_2$e/ kg fat and protein corrected milk (FPCM).
- The mean intensity of emissions associated with milk production was 1.04 kg CO$_2$e/kg FPCM. Milk production per cow, feed conversion efficiency and the amount of nitrogen based fertiliser applied were the key farm variables most influencing the GHG emission intensity of milk production.
- Adoption of abatement strategies that reduce enteric methane production, while assisting in improving milk production per cow and those focused on improving the efficiency of nitrogen usage on farm will have a positive impact on reducing the GHG emissions intensity of milk production in Australia.
- Several modifications and improvements have been made to the Dairy Greenhouse gas Abatement Strategies (DGAS calculator) as result of changes to the national inventory methodology and from user feedback. Webinars and face-to-face training in the use of the DGAS calculator has been undertaken regularly throughout the project for Dairying for Tomorrow co-ordinators, private consultants, milk factory and government department field officers.
- In collaboration with the University of Melbourne, the team has developed a MS Office Excel spreadsheet Carbon Offset Scenarios Tool (COST) calculator for the Australian dairy industry to explore the viability of a range of mitigation options that could be included as Carbon Farming Initiative (CFI) offsets. This spreadsheet tool allows for the exploration of key
questions such as the price of carbon required to make a strategy profitable and costs of implementing these strategies.
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Project objectives and activities
There were three main objectives of this specific sub-project and all were completed by the end of the project (Table 1). Many of the activities within each objective were undertaken in collaboration with University of Melbourne (UoM) project staff members. Where TIA staff members were the lead author, the activities are reported in this Final Report. However, where University of Melbourne staff members were the lead-author, these activities are reported in their Final Report.

Table 1. Project objectives and activities undertaken within this project

<table>
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<th>Objectives</th>
<th>Activities undertaken</th>
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| Biophysical modelling simulations that address the key regional questions of climate change impacts on current dairy grazing systems in a future environment, adaptation options and new farming systems; keeping in mind mitigation options given an emissions constrained environment; | ❖ Biophysical modelling of 3 dairy regions (SE Victoria (Ellinbank), SW Victoria (Terang) and NW Tasmania (Elliott)) using a direct scaling approach:  
  • Adapting to increases in mean daily temperature by increasing the heat tolerance of perennial ryegrass (Appendix 1)  
  • Effects of deficit rainfall and rooting depth of perennial ryegrass on pasture production in South East Australia (Appendix 2)  
  • Modelling pasture based dairy systems to a changing climate in a carbon constrained world (Appendix 3)  
  • An historical analysis of the changes in pasture production and growing season in three dairy regions of South East Australia (Appendix 4)  
  • Pasture growth to lift under climate change (Appendix 5)  
  ❖ Biophysical modelling of 5 dairy/ extensive agriculture regions of Tasmania (Cressy, Flowerdale, Ouse, Ringarooma and Woolnorth) using the Climate Futures for Tasmania climate scenarios data approach  
    • Frequency of wet and dry soil conditions for Tasmanian dairy regions under future climate scenarios (Appendix 6)  
    • Timing of autumn breaks and length of springs in Tasmanian dairy regions under future climate scenarios (Appendix 7)  
    • Frequency of wet and dry soil conditions for Tasmanian beef and sheep regions under future climate scenarios (Appendix 8)  
    • Timing of autumn breaks and length of springs in Tasmanian beef and sheep regions under future climate scenarios (Appendix 9) |
| Further development of climate change adaptation and mitigation modelling capability for the dairy industry | ❖ Estimation of the GHG emissions of 60 Tasmanian dairy farms using the Dairy Greenhouse gas Abatement Strategies (DGAS) calculator (Appendix 10, 11 & 12)  
❖ Estimation of the GHG emissions of 41 Australian dairy farms using the DGAS calculator (Appendix 13, 14 & 15)  
❖ Improvements to the DGAS calculator aligning with changes to the national methodology and from user feedback (Appendix 16)  
❖ Development of the Carbon Offset Scenarios Tool (COST) calculator to assess dairy abatement strategies and their profitability with the Carbon Farming Initiative (Appendix 17) |
|———|———|
| A better informed industry and producer population of the opportunities and risks associate with climate change through the publication and communication of research results | ❖ 2 published scientific papers (one with UoM as 1st author)  
❖ 15 conference publications (four with UoM as 1st author)  
❖ 2 conference presentations  
❖ 1 draft scientific publication  
❖ 2 popular press publications  
❖ 6 workshops/field days held presenting climate change adaption to in excess of 250 farmers, public and private consultants and advisors and government representatives  
❖ 5 training workshops/webinars associated with DGAS user training of 50+ Dairying for Tomorrow co-ordinators, public and private consultants and advisors  
❖ On-going support to DGAS users (farmers, Dairying for Tomorrow co-ordinators, public and private consultants and advisors) |
Background

Climate change will impact on the Australian grazing industries both through policies to mitigate climate change (e.g. the Carbon Farming Initiative), and the physical impact of warmer temperatures, increased atmospheric CO$_2$ concentrations and changed rainfall patterns on pasture production. For producers, regionally specific information will be required to make informed decisions, as outcomes will be determined by multiple and complex interactions between climatic and edaphic factors.

Biophysical models are the only means that we currently have available to decipher these interactions and provide simulations of likely future outcomes at a regional level. This project is collaborative in its approach to addressing the climate adaptation and GHG mitigation options for the dairy industry and southern grazing industries within the *Climate Change Adaptation in the Southern Australian Livestock Industries (CCASALI)* program. This sub project (B.SBP.0071) was undertaken by Tasmanian Institute of Agriculture (TIA) modelling scientist Dr. Richard Rawnsley and Ms. Karen Christie in collaborative approach with modelling scientists from the University of Melbourne (Associate Professor Richard Eckard, Dr. Brendan Cullen and Dr. Matthew Bell) as part of sub project (B.SBP.0072).

The two sub projects have utilised the most recently available and acceptable climate projection data (e.g. OzClim [http://www.csiro.au/ozclim/home.do](http://www.csiro.au/ozclim/home.do) and Climate Futures for Tasmania, [https://dl.tpac.org.au/](https://dl.tpac.org.au/)) and used a direct scaling approach to examine the sensitivity of agricultural production to scaled changes in key climate variables. These climate scenarios have been utilised in conjunction with a range of biophysical, farm system and GHG accounting models to address specific regional impacts of climate change, various adaptation options, GHG emissions and the interacting dynamics between adaptation and mitigation for a range of farming systems.

The two sub project teams have participated in regional consultations with the larger CCASALI team, industry and producers to present the modelling outcomes and foster regionally specific feedback. This approach has allowed the sub projects to formulate key questions which have been prioritised by the program steering committee and participating parties. The typical questions posed to the modelling team have focused on both adaptation and mitigation and are listed below:

- What are the likely impacts of climate change in 2030 and 2070 on pasture growth, species composition and water balance, relative to a historical baseline?
- What are the specific adaptation options for extensive/intensive grazing systems?
- What are the climate thresholds for adaptation within and between farming systems?
- Are high temperatures going to have the greatest effect on the length of our growing season and how best to adapt to this? What breeding or species selection is required?
- What are the potential impacts of an emissions constrained policy environment on dairy production systems?
- What is the Whole Farm Systems impact and abatement from currently available GHG mitigation strategies?
- What level of abatement can be achieved through best management practices alone?
- What level of GHG abatement is required for additional abatement activities to be economically viable?
What is the impact of future climate scenarios on the balance between productivity and total greenhouse gas emissions from pasture based dairy systems in SE Australia?

The modelling team possess the skills and capabilities to combine and develop models/tools to address the complex interactions between adaptation and mitigation for temperate grazing systems and the project has focused on establishing improved capacity across a range of industry RD&E providers through training, whilst communicating directly with industry and producers the finding, model developments and project outputs.

Project activities and major findings

This project was undertaken by TIA staff Richard Rawnsley and Karen Christie. Throughout the project, the TIA team also worked collaboratively with staff from the University of Melbourne (Richard Eckard, Brendan Cullen and Matthew Bell). This report focuses on the collaborative work led by TIA staff, with reference to collaborative work led by University of Melbourne staff where relevant. The project was segmented into two broad theme areas. These were climate change assessments and analysis for the Southern Australian livestock industries and greenhouse gas emission assessments and mitigation options for the Australian dairy industry. Within each of these, the outputs were broadly grouped into five main areas:

- Conference papers/publications
- Published and submitted papers
- Presentations, workshops, popular press and field days
- Enhanced modelling software development and training
- Other activities

1) Climate change adaptation
   a) Conference papers/publications

Four conference papers were published in the Proceedings of the Climate Change Research Strategy for Primary Industry (CCRSPI) Conference; Melbourne, February 2011. In addition, one verbal presentation and two posters were also presented from this work at the CCRSPI conference. In the paper titled *Adapting to increases in mean daily temperature by increasing the heat tolerance of perennial ryegrass* (Appendix 1), historical climate data (1971-2008) for three dairying regions of South East Australia (Elliott (NW Tasmania), Ellinbank (SE Victoria) and Terang (SW Victoria)) was used in combination with the biophysical model DairyMod to ascertain the impact of increasing daily temperatures and carbon dioxide concentrations on pasture production. Five climate data sets for each region were created by direct scaling the historical baseline climate data (1971 to 2008; actual temperatures with current carbon dioxide (CO₂) concentration of 380 ppm) by 1, 2, 3, 4 and 5°C with corresponding atmospheric carbon dioxide concentrations of 435, 535, 640, 750 and 870 ppm, respectively. The highest mean annual pasture production for Elliott, Ellinbank and Terang occurred when temperatures/carbon dioxide concentrations were increased by 3°C/640 ppm, 1°C/435 ppm and 2°C/535 ppm, respectively. Exposure to periods of extreme high temperatures and its impact on pasture production was also reviewed. Increasing the high temperature tolerance of perennial ryegrass was able to alleviate the negative effects on annual pasture up to 5°C of warming at Terang
and up to 4°C warming at Ellinbank. This highlights the relative benefit of exploring and introducing more heat tolerant perennial ryegrass cultivars to the regions used in this study.

In the paper titled *Effects of deficit rainfall and rooting dept of perennial ryegrass on pasture production in South East Australia* (Appendix 2), historical climate data (1971-2008) for three dairying regions of South East Australia (Elliott, Ellinbank and Terang) was used in combination with DairyMod to ascertain the impact that altering the rooting depth of perennial ryegrass would have on annual pasture production. Rooting depths of 30cm (baseline), 40cm, 50cm, 60cm and 70cm were explored using the baseline (1971-2008) rainfall. In addition, the abovementioned rooting depths in combination with rainfall deficits of between 50 and 90% of the baseline rainfall were explored. There was a positive linear relationship between rooting depth and annual pasture production for each rainfall deficit scenario, with the greatest benefit of extended rooting depth observed over the spring, and lesser extent summer, months. However, there was no benefit of additional pasture production through extended rooting depths in autumn and winter. In addition, at Ellinbank, extending rooting depth to 50cm was able to overcome a 20% restriction in rainfall. However, this was not the case at the other two locations where a 60cm rooting depth was still unable to overcome a 20% reduction in annual rainfall. This indicated that although the adaptation of increasing rooting depth for our temperate pasture species may be considered a very favourable adaptation strategy for adapting to a drier future climate, the ability to alleviate the impacts under significant rainfall decline is limited.

In the paper titled *Modelling pasture based dairy systems to a changing climate in a carbon constrained world* (Appendix 3), DairyMod was used to model a Tasmanian dairy farm system with either a baseline scenario (climate data for 1979-2009) or a future scenario (2°C increase in daily minimum and maximum temperatures, increase of carbon dioxide concentration to 535 ppm and a 10% reduction in daily rainfall). Various farm system adaptation options were implemented on the future scenario dairy system (e.g. increasing stocking rate or removal of concentrate supplementary feeding). The impact of each scenario was then compared to the baseline farm system in terms of changes in annual pasture production, milk production, farm gross margin and GHG emissions. This modelling analysis has shown that the cool temperate dairy regions of Tasmania are well buffered against predicted climate changes and that within farm system adaptations appear more likely with the producers continuing to focus on milk production per ha and pasture consumption per ha as key determinants of business success. The adaptation of increasing stocking rate and or lower concentrate feeding to capture the high level of pasture production being achieved with a warmer environment, resulted in an a higher GHG emissions intensity of milk production, highlighting that in this environment there is an emerging conflict between how dairy farms may adopt to a changing climate and those strategies for mitigating the GHG emission associated with milk production.

In the paper titled *An historical analysis of the changes in pasture production and growing season in three dairy regions of South East Australia* (Appendix 4), historical climate data (1960-2009) for three dairying regions of South East Australia (Elliott, Ellinbank and Terang) was used in combination with DairyMod to examine changes to annual and seasonal pasture production, the commencement, duration and reliability of the growing season and the duration of wet and dry periods. There was no evidence that the commencement period for wet and dry periods has altered over the last 50 years at any of the three regions. However, in the most recent years (2000 to 2009), there has been a period of unusually low number of wet days and unusually high number of dry days at all three regions.
In 2012, two papers have been accepted for the 16th ASA Conference to be held in October at Armidale, NSW. The first paper is titled *Frequency of wet and dry soil conditions for Tasmanian dairy regions under future climate scenarios* (Appendix 6). DairyMod was used in combination with climate data generated from the Climate Futures for Tasmania project ([https://dl.tpac.org.au/](https://dl.tpac.org.au/)) out to the year 2100 for two dairy regions of Tasmania (Flowerdale and Ringarooma). The number of wet days per annum (soil moisture content is above field capacity) and dry days per annum (all readily available water is exhausted from the soil profile) for each region, based on six general circulation models (GCMs), was determined for four climate periods (years 1971 to 2000, 2001 to 2030, 2031 to 2060 and 2061 to 2090). By years 2061 to 2090, the mean number of wet days, as an average of the six GCMs, at Flowerdale and Ringarooma is predicted to decline by 8.5 and 4.5 days per annum, respectively, when compared to the baseline period of years. In contrast, the mean number of dry days, as an average of the six GCMs, at Flowerdale and Ringarooma is predicted to increase by 7.5 and 4.8 days per annum, respectively, when compared to the baseline period of years.

The second paper for the 16th ASA Conference is titled *Frequency of autumn breaks and length of springs in Tasmanian dairy regions under future climate scenarios* (Appendix 7). DairyMod was used in combination with climate data generated from the Climate Futures for Tasmania project out to the year 2100 for two dairy regions of Tasmania (Flowerdale and Ringarooma). The frequency of early and late autumn breaks and frequency of short and long springs were determined for four climate periods (years 1971 to 2000, 2001 to 2030, 2031 to 2060 and 2061 to 2090) based on six GCMs. Comparing the mean change between the baseline period of years 1971 to 2000 and the future climate period of years 2061 to 2090, the frequency of early autumn breaks was predicted to increase from 27% to 33% for Flowerdale and from 26% to 34% for Ringarooma. The frequency of late autumn breaks was predicted to decline from 31% to 16% for Flowerdale and from 34% to 17% for Ringarooma. The frequency of short springs was predicted to decline from 14% and 16% for Flowerdale and Ringarooma, respectively, to < 1% for both regions. The frequency of long springs was predicted to remain relatively stable at ~ 32% for both regions.

In 2012, two papers have been submitted to the Grasslands Society of Southern Australia Inc 53rd Annual Conference to be held in July at Launceston, Tasmania. These two papers were co-authored with Peter Ball; TIA’s Extensive Agriculture Centre Industry Development and Extension Leader. The studies followed a similar format to those discussed previously to be presented at the ASA conference. However, the two extensive agricultural regions of Cressy and Ouse were explored with the implications to beef and sheep farms explored as opposed to dairy. The first paper titled *Frequency of wet and dry soil conditions for Tasmanian beef and sheep regions under future climate scenarios* (Appendix 8) found that by years 2061 to 2090, the mean number of wet days, as an average of the six GCMs, was predicted to decline by 2.8 days per annum when compared to the baseline period (years 1971 to 2000) at Cressy. In contrast, at Ouse, the mean number of wet days, as an average of the six GCMs, was predicted to increase by 0.1 days per annum when compared to the baseline period. By years 2061 to 2090, the mean number of dry days, as a mean of the six GCMs, was predicted to decline by 0.2 and 4.5 days per annum at Cressy and Ouse, respectively, when compared to the baseline period.

The second paper titled *Timing of autumn breaks and length of springs in Tasmanian beef and sheep regions under future climate scenarios* (Appendix 9) found that when comparing the mean change between the baseline period (years 1971 to 2000) and the future climate period (years 2061 to 2090), the frequency of early autumn breaks was predicted to increase from 18% to 28% at Cressy
and from 19% to 29% at Ouse. The frequency of late autumn breaks was predicted to decline from 39% to 26% at Cressy and from 39% to 23% at Ouse. The frequency of short springs was predicted to decline from 29% to 19% at Cressy and from 22% to 13% at Ouse. The frequency of long springs was predicted to decline from 22% to 20% at Cressy and from 27% to 18% at Ouse.

b) Presentations, workshops, popular press and field days

The TIA team have presented climate change research from this project at various conferences, field days, workshops and in popular press. These include:

- Climate change modelling outcomes on annual pasture production for NE (Ringarooma) and NW (Mawbanna) Tasmania, March 2010. Total attendees were 66 farmers, public and private advisors and consultants.

- Modelling Climate Change for Tasmanian Dairy Regions at the Dairy Climate Forum, December 2010. Total attendees were 20 public and private advisors and consultants.

- An historical analysis of the changes in pasture production, growing season and the number of wet and dry days in three dairy regions of South East Australia at the Climate Change Research Strategy for Primary Industries: Melbourne, Victoria, February 2011. Total conference attendees were approximately 300 public and private researchers, advisors, consultants and government representatives.

- Whole farm system analysis of the GHG emissions of Australian dairy farms at the Climate Change Research Strategy for Primary Industries: Melbourne, Victoria, February 2011. Total conference attendees were approximately 300 public and private researchers, advisors, consultants and government representatives.

- Modelling approaches to adapting pasture based dairy systems to a changing climate in a carbon constrained world at the Dairy Science Symposium; Ellinbank, Victoria, March 2011. Total attendees were 55 extension and researcher officers from the Victorian DPI.

- Agriculture, Greenhouse Gas and Carbon Farming: Burnie, November 2011. Total attendees were 60 representing local council, public and private advisors and consultants.

- Pasture growth to lift under climate change. Publication in the Australian Dairyfarmer magazine, November 2011 (Appendix 5). Target audience includes all Australian dairy farmers, public extension and research officers, milk factory field officers, private consultants and advisors.

- Australian dairy farm greenhouse gas emissions. Publication in the Australian Dairyfarmer magazine, November 2011 (Appendix 14). Target audience includes all Australian dairy farmers, public extension and research officers, milk factory field officers, private consultants and advisors.

- Modelling the effects of climate change on Tasmanian dairy production systems to the Fonterra Supplier Forum meeting; Burnie, November 2011. Total attendees were 34 dairy field officers and Fonterra staff.

- Climate projections and modelling climate influences on dairy production to a group of 15 Victorian dairy farmers and rural bankers; TIA Dairy Research Facility, March 2012.
2) Greenhouse gas emission assessments and mitigation options

a) Published and submitted papers

A major output of this project was two peer reviewed journal papers assessing dairy GHG emissions. The first was a paper titled *A whole farm systems analysis of greenhouse gas emissions of 60 Tasmanian dairy farms* and was published in the Animal Feed Science and Technology journal in 2011 (Appendix 12). The study found that the GHG emissions intensity of milk production was 1.04 kg CO$_2$e/ kg fat and protein corrected milk (FPCM; varied between 0.83 and 1.39 kg CO$_2$e/ kg FPCM). Linear regression analysis showed that 93% of the difference in total farm GHG emissions was explained by annual milk production and that feed conversion efficiency (kg milk/kg dry matter intake) and nitrogen (N) fertiliser application rate ( kg N/ha) could explain 60% of the difference in the GHG emissions intensity of milk production. The GHG emissions intensity per cow and per hectare was also examined. Given the strong influence that feed conversion efficiency and/or N based fertiliser application rates had on the GHG emissions intensity of milk production, these factors should be key research target areas for lowering the GHG emissions associated with dairying in Tasmania. Of interest also was that the results from this study were 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.

The second paper titled *Whole farm systems analysis of Australian dairy farms greenhouse gas emissions* was submitted for publication in the Animal Production Science journal in early 2012 (see Appendix 15 for the submitted draft paper) and with minor revisions, will be published in 2012. The study assessed the GHG emissions of 41 Australian dairy farms and found that the GHG emissions intensity of milk production was 1.04 kg CO$_2$e/ kg FPCM (varied between 0.76 and 1.68 kg CO$_2$e/kg FPCM). Linear regression analysis showed that 95% of the difference in total farm GHG emission was explained by annual milk production and that milk production per cow (kg fat and protein correct milk/cow lactation) could explain 70% of the difference in the GHG emissions intensity of milk production. The GHG emissions intensity per cow and per hectare was also examined as well as the influence of regional and farming system on milk, cow and area GHG emissions intensity. While the results of this study suggest that milk production alone could be a suitable surrogate for estimating GHG emissions for national inventory purposes, the GHG emissions intensity of milk production, on an individual farm basis, was shown to vary by over 100%. It is clear that using a single emissions factor, such as milk production alone, to estimate any given individual farm’s GHG emissions, has the potential to either substantially under or over estimate individual farms’ GHG emissions. Enteric methane emissions were found to be responsible for over half the total farm emissions associated with milk production in Australia and milk production per cow was found to be the key driver influencing the GHG emissions intensity of milk production. As such, implementing management practices that reduce enteric methane production whilst also improving milk production per cow, will have a positive impact on reducing the GHG emissions intensity of milk production in Australia.

b) Conference papers/ publications

The findings reported in the above-mentioned two papers were also communicated through several conference papers and as a conference presentation. Two conference papers titled *DGAS: software for modelling and managing greenhouse gas emissions for Australian dairy farms* and *A whole farm systems analysis of the greenhouse gas emissions of 60 Tasmanian dairy farms* were published in the...
Proceedings of the 4th International Greenhouse Gases and Animal Agriculture Conference; Banff, Canada, October 2010 (Appendix 10 and 11).

A conference paper titled A whole farm systems analysis of the greenhouse gas emissions of Australian dairy farms was published in the Proceedings of the Climate Change Research Strategy for Primary Industry (CCRSPI) Conference; Melbourne, February 2011 (Appendix 13), with a verbal presentation of this research study at the CCRSPI Conference by Karen Christie.

c) Presentations, workshops, popular press and field days

The results of the GHG emissions assessment of the Australian dairy industry was also published in The Australian Dairyfarmer magazine (November 2011; Appendix 14). In addition, the results were also made public to various advisers/consultants (e.g. Dairying for Tomorrow co-ordinators, Victorian and New South Wales Dairy Extension Officers) to use in their presentations to farmer groups as relevant.

d) Enhanced modelling software development and training

Throughout the duration of the project Karen Christie ran webinars and face-to-face training in the use of the Dairy Greenhouse gas Abatement Strategies (DGAS calculator). Participants included Dairying for Tomorrow co-ordinators, private consultants, milk factory and government department field officers in December 2009, September and November 2010, and in June and November 2011. In addition there has been on-going assistance/training of individuals as required (e.g. famers, public and private advisers/consultants). Total training and assistance would be to in excess of 50 people over the duration of the project.

Throughout the duration of this project, there have been several modifications and improvements to DGAS (Appendix 16). These changes were due to changes to interpretation of the national inventory methodology and from user feedback. Some of the most significant changes have included the introduction of the abatement strategy of applying a nitrification inhibitor to reduce direct and indirect nitrous oxide emissions from animal waste, the alteration of pre-existing abatement strategies to align with recent advances in research findings (e.g. reducing the reduction of methane production from 5.6 to 3.5% for each 1% increase in dietary fat in the diet), the alteration of the emission factors for indirect N\textsubscript{2}O emissions from leaching/runoff and the development of a series of questions to ascertain the impact of individual farm management practices on the methane and nitrous oxide emissions associated with waste management. These changes were documented in the User Manual for DGAS version 1.4 which is available, with DGAS version 1.4, to the public via the Dairying for Tomorrow website (http://www.dairyingfortomorrow.com.au/index.php?id=47).

e) Other activities

Throughout this project the priorities for the dairy industry in terms of mitigating their GHG emissions has changed. In 2010, the Australian Federal Government proposed a cap-and-trade emissions trading scheme called the Carbon Pollution Reduction Scheme (CPRS). Due to a lack of bipartisan support, the CPRS was not legislated. However, a new emissions trading scheme, the Clean Energy Future Plan, was legislated in 2011 and will be implemented in 2012. One component of the Clean Energy Future Plan was a shift in the focus from agriculture being a sectoral source of GHG emissions, and thus requiring ‘taxing’ of a proportion of their GHG emissions (as proposed with the CPRS), to agriculture being a sector of the economy that could implement practices that achieve mitigation and gain financial incentive to do so. To facilitate this, the Carbon Farming Initiative (CFI)
was the proposed mechanism within the Clean Energy Bill for assisting agricultural farmers and land managers to obtain carbon offset credits by sequestering carbon on-farm or by reducing/avoiding on-farm GHG emissions. These carbon credits could then be tradable, allowing for other high carbon polluting industries (e.g. electricity companies) to offset their GHG emissions.

In 2011 the TIA project team were approached by this projects’ Dairy Australia steering committee member to assist Dairy Australia in developing a list of standard practices for the Department of Agriculture, Fisheries and Forestry (DAFF) in formulating farm practices that could be included as methodologies that qualify for the ‘Additionality’ requirements in the CFI. These farm practices were broadly grouped into the 3 broad themes of nutrients and effluent, pasture management and herd and dairy shed practices. In addition, the TIA project team developed the MS Office Excel spreadsheet Carbon Offset Scenarios Tool (COST) calculator and expanded the three abovementioned themes and potential mitigation options provided to DAFF into four theme areas. These were herd and breeding management, diet management, feedbase management and waste management. Within each theme area, mitigation strategies were identified and at the time of finalising the final report, seven individual mitigation strategies had been identified and incorporated into the COST calculator (Appendix 17). However, several more have been identified (e.g. improved reproductive performance, manure digesters to reduce the amount of stored animal waste in lagoons) and these will be incorporated into the COST calculator into the future. In addition, as science progresses and/or the CFI encourages the development of new technologies to reduce and/or remove on-farm GHG emissions, these too will be incorporated into the COST calculator.

f) Other activities in collaboration with member of the University of Melbourne modelling team

In addition to the above-mentioned conference papers/proceedings, the TIA team have also been co-authors on several other papers with members of the University of Melbourne team. These include:

Implications of project findings

In the cool temperate regions, such as Tasmania, the current feedbase of perennial ryegrass pastures are well suited to the current environment. Biophysical modelling using future climate projections has indicated that pasture production will most likely increase in most regions. This is primarily due to the current pastures species being limited by relatively low temperatures and so the future climate projections for increased warming, increased atmospheric CO\(_2\) concentrations and minimal changes in precipitation will provide a more favourable environment for pasture growth. Increased pasture production in early spring and mid to late autumn should provide livestock managers with greater confidence. To adapt to these changes, within systems adaptations may need to be implemented to capture the benefits of this change in seasonal pasture growth patterns. These adaptations include changes to calving dates, stocking rates, and winter nitrogen fertiliser management etc for the dairy industry or increased capacity for autumn lambing/calving or earlier weaning strategies for the extensive agriculture industry. Modelling has indicated that these adaptations will result in improved profits above ‘business as usual’ (BAU). However, modelling has also indicated that summer feed deficits will remain into the future so reliance on irrigation and/or summer forage crops and the potential for greater forward purchasing of supplementary feeds will continue into the future. The severity and frequency of extended wet periods is projected to slightly decline over time for most regions of Tasmania thus indicating that no new adaptation options will be required beyond current practices that are already in place. However, there appears to be some projected increase in the number of dry days into the future for most Tasmanian regions examined. Therefore within farming system adaptation options such as deeper rooted pasture species or the implementation of irrigation may be required into the future.

In the temperate regions of southern Australia, modelling has shown that the current feedbase of perennial ryegrass will become limited by temperature increases and/or the availability of soil moisture into the future. Modelling has shown that modifying the feedbase with pasture species that possess greater high temperature tolerance and/or have deeper root systems to capture soil moisture will be able to alleviate some of the impact of increased temperatures and/or reduced precipitation out to 2050. Therefore, modifying the feedbase will be more critical in these regions, given that changes within the current feedbase will not be sufficient to overcome increases in mean daily temperatures of more than 2°C or declines in annual rainfall by more than 20% compared to the current baseline climate.

One hundred Australian dairy farms were assessed for their GHG emissions with the GHG emission intensity of milk production averaging 1.04 kg CO\(_2\)e/kg FPCM. Total annual milk production was shown to be a good surrogate for predicting total farm GHG emissions. However, there was substantial variation between farms with the GHG emission intensity of milk production varying between 0.76 and 1.68 kg CO\(_2\)e/kg FPCM. Enteric methane emissions were > 50% of total farm GHG emissions and so the key driver of the GHG emissions intensity of milk production being milk production per cow is not surprising. Key mitigation areas include improved feed conversion efficiency in livestock and improvements in the efficiency of N fertiliser usage.

Modelling analysis has shown that the potential CFI income from adopting currently possible dairy mitigation options is in the vicinity of ~ 1% of total milk production income. Therefore on farm adoption of CFI offset mitigation options are unlikely unless other non-GHG emissions aspects of the mitigation option, e.g. increases in milk production, can provide significant financial gain.
Future RD&E needs

One of the major outcomes of this project is a clear need to demonstrate/extend adaptations options, whether they are changes within the current feedbase system, a modification of the current feedbase system or a change in farming system. Whole of farm systems evaluation will strongly assist in providing a greater level of validation to the whole of system models currently available and highlight the potential adaptation opportunities within or across farming systems. The extension/demonstration of adaptation options should be regionally specific. For example whole of farm system evaluation of modifying the current feedbase to adapt to future climates should be undertaken in regions in which this project have clearly shown that a modified feedbase will strongly alleviate projected climate change and therefore result in improved resilience and farm profitability.

There is also a corresponding need to research the component level physiological/agronomical factors associated with modifying the feedbase. There is general reluctance to shift to a modified feedbase as the knowledge underpinning a changing feedbase is not as great as the knowledge for the current feedbase, and therefore there is uncertainty about how best to move to a modified feedbase amongst producers. In regions that have been clearly shown that a modified feedbase is required then developing the “local know how” is viewed with high importance.

Another area highlighted is the need to have the ability to effectively and efficiently quantify CFI offset methods across a broad spectrum of farming systems for the livestock industries. The current COST calculator has begun this process for the dairy industry. Seven individual mitigation strategies had been identified and incorporated into the COST calculator which efficiently and effectively evaluates the adoption of these strategies on the farm GHG emission profile and potential farm profit under the proposed CFI. However, it is envisaged that several other strategies need to be added to the calculator. For example, improved reproductive performance through extended lactations could result in reduced total farm GHG emissions as less stock are required for a similar level of milk production. In addition, the current COST calculator focuses on the impact of various diet management strategies as they influence enteric methane production only. However, many of the current mitigation strategies could also alter the crude protein concentration of the diet and therefore influence animal waste nitrous oxide emissions. Therefore incorporating the COST calculator into DGAS is seen as a critical next step to not only strengthen the mitigation strategies already included in DGAS but also allow for a full farm systems approach to explore the impact of mitigation strategies on total farm GHG emissions and any associated change to business profit under the proposed CFI. In addition, developing a similar calculator to examine the implications of mitigation options for both beef and sheep industries is viewed as an important need for agricultural managers to have confidence in implementing CFI-adopted mitigation options on farm.
# Budget reconciliation

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Appendix 1: Adapting to increases in mean daily temperature by increasing the heat tolerance of perennial ryegrass

Published in the Climate Change Research Strategy for Primary Industries (CCRSPI) Conference Proceedings; February 2011, Melbourne, VIC, Australia

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Abstract

Climate projections for Australia suggest that there will be a general increase in daily temperatures of 0.4 to 1.8°C by 2030 and 2.2 to 5°C by 2070 (CSIRO and BoM, 2007). Climate change impact modelling based on future climate scenarios, created by direct scaling of historical climate data, can be used to examine the effect of increased temperature on pasture production and potential adaptation approaches, while maintaining the inherent climate variability. The biophysical model DairyMod (Johnson et al. 2008) was used to simulate mean annual pasture yields for the three Australian dairying regions of Elliott (North West Tasmania), Ellinbank (South East Victoria) and Terang (South West Victoria), which heavily rely on perennial ryegrass (Lolium perenne L.) to support dairy production.

Five climate files for each region were created by direct scaling the historical baseline climate file (1971 to 2008) by 0, 1, 2, 3, 4 and 5°C with corresponding atmospheric CO₂ concentrations of 380, 435, 535, 640, 750 and 870 ppm, respectively. The highest mean annual yield for Elliott, Ellinbank and Terang resulted from scaling to 3°C/640 ppm (a 27.2% increase above the baseline climate data), 1°C/435 ppm (1.7% increase) and 2°C/535 ppm (10.1% increase), respectively. At Elliott, increases in temperature with corresponding increases atmospheric CO₂ concentration increased annual pasture yields. At Ellinbank and Terang, increasing temperature and CO₂ concentrations to and above 2°C/535 ppm and 4°C/750 ppm respectively, resulted in lower annual yields than those produced using the baseline climate data.

The effect of exposure to periods of extreme high temperatures on the growth of perennial ryegrass was then explored using nine variations of high temperature tolerance, in conjunction with the scaled increases in temperature and atmospheric CO₂ concentrations described above. Three onset and full temperature combinations (28/35°C, 29/36°C and 30/37°C) were examined across three critical T-sums (20, 35 and 50°C). The onset temperature represents the temperature at which a reduction in plant function commences due to heat stress, the full temperature represents the upper temperature at which plant function ceases, and the critical T-sum represents the recovery period required following exposure to heat stress. Increasing the high temperature tolerance of perennial ryegrass was able to alleviate the negative effects on annual pasture up to 5°C of warming at Terang and up to 4°C warming at Ellinbank. This highlights the relative benefit of exploring and introducing more heat tolerant perennial ryegrass cultivars to the regions used in this study.

References


Appendix 2: Effect of deficit rainfall and rooting depth of perennial ryegrass on pasture production in South East Australia.

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Abstract

The biophysical model DairyMod (Johnson et al. 2008) was used to simulate the annual and seasonal production of perennial ryegrass (Lolium perenne L.) pastures for the three dairying regions of Elliott (North West Tasmania), Ellinbank (South East Victoria) and Terang (South West Victoria). Five rooting depth treatments were assessed; a baseline rooting depth of 30 cm, and then increments of 10 cm to a maximum of 70 cm. Six differing rainfall scenarios were implemented; a baseline rainfall scenario (current rainfall pattern for the period 1971 to 2008) and five deficit increments between 0.5 and 0.9 of the baseline rainfall. Mean annual and seasonal pasture production (kg DM/ha) figures for each rooting depth/rainfall treatment was calculated for the period 1971 to 2008.

There was a positive linear relationship between rooting depth (cm) and annual pasture production (kg DM/ha.year) for each rainfall scenario. The greatest benefit of increasing rooting depth was observed over the spring period, and to a lesser extent summer, in all regions. There was very little benefit of increased rooting depth in autumn and winter when the winter-dominant rainfall patterns of these regions was sufficient for maintaining growth, especially if rainfall deficits were minimal. Increasing the rooting depth from 30cm to 50cm was able to alleviate the impact of a 20% decline in rainfall on mean annual pasture production at Ellinbank. However, this increase in rooting depth was not able to overcome a 20% rainfall deficit at the other two regions, with an 8.8 and 0.9% decline in mean annual pasture production for Terang and Elliott, respectively. At all three regions, when the rainfall deficit exceeded 20%, a doubling of the rooting depth to 60cm was not able to alleviate the effects on mean annual pasture production. This indicates that although the adaptation of increasing rooting depth may be considered a very favourable adaptation strategy for adapting to a drier future climate, the ability to alleviate the impacts under significant rainfall decline is limited.

Shallow rooted perennial temperate pastures, such as perennial ryegrass, are currently considered the main forage source for dairy cattle in temperate regions of SE Australia. However, a changing and variable climate may lead to alterations to the current the forage base. Further work is required to analyse the adoption of these forage combinations at whole of farm system level and under agreed climate projection scenarios for the differing regions.

References

Appendix 3: Modelling approaches to adapting pasture based dairy systems to a changing climate in a carbon constrained world

Published in the CCRSPI Conference Proceedings; February 2011, Melbourne, VIC, Australia

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Abstract

The temperate regions of Australia support over 80% of the nation’s milk production, (Dairy Australia, 2009). Perennial ryegrass (Lolium perenne L.) is commonly sown in a mixed sward with white clover (Trifolium repens L.) and is the dominant pasture specie in many of these regions (Mason, 1993; Fulkerson and Doyle, 2001). In such pasture-based systems, consumption of home-grown herbage is a key determinant to business success (Beca, 2005; Chapman et al., 2008). Increasing pasture productivity, through improved production and consumption, has been highlighted as an important objective for the dairy industry into the future (Dairy Australia, 2010).

Modelling the pasture production under future climate scenarios for the cool temperate dairy regions of Tasmanian has shown that pasture production is likely to increase between 15 and 30% (Cullen et al. 2009, Holz et al. 2010). The average per cow production of Tasmanian dairy farms is 5,000 L/cow (Dairy Australia, 2009), with on average less than 20% of the cows diet coming from purchased grain concentrates or by products (Barlow, 2008) and average annual nitrogen fertiliser applications exceeding 200kg N/ha (TIAR, 2010). These dairy farm systems are classified as farm system 1 (FS1) and are characterised by being predominantly pasture based with less than 30% purchased supplementary feeding. Climate change projections for Tasmania’s dairy regions has highlighted that the current forage base is quite resilient to future climate scenarios and that adaptations are likely to be within system adaptations with the industry continuing to focus on milk production per ha and pasture consumption per ha as key determinants of business success. Cullen et al. (2010) showed that increasing stocking rate and changes in calving date are profitable adaptive response to a warming climate in these regions, however, there is an emerging conflict between the most profitable approaches to adapting to changing climate and that of mitigation of greenhouse gases (GHG) in a carbon-constrained world. The GHG emissions intensity of milk production of FS1 farms have been shown to be higher than those of dairy farm systems with higher levels of concentrate feeding and higher per cow production (Christie et al. 2009). For these predominantly pasture based systems there is an urgent need to develop agreed approaches to examining adaptation strategies and their influences on total farm GHG emissions, the emission intensity of milk production and farm profitability.

References


TIAR, 2010. Impact Dairy Business of the Year Award field day. Tasmanian Institute of Agricultural Research, Burnie, Australia.
Appendix 4: An historical analysis of the changes in pasture production, growing season and the number of wet and dry days in three dairy regions of South East Australia

Published in the CCRSPI Conference Proceedings; February 2011, Melbourne, VIC, Australia

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Abstract

The production of high quality perennial ryegrass (*Lolium perenne* L.) is a strong determinant of business success for pasture-based dairy systems in Australia (Beca, 2005; Chapman *et al.*, 2008). There is concern regarding the influence of a changing and variable climate on these systems, with evidence that the global climate has changed over the past century and that the risk of extreme events and abrupt changes in climatic patterns is increasing (NRMMC 2006). It is important to quantify these changes and their effects in order to identify and explore potential system adaptations. For pasture-based dairy systems in South East Australia, seasonal and annual pasture production, the commencement, length and reliability of the growing season and the duration of wet and dry periods are all significant factors that influence management decisions and profitability.

Using the biophysical pasture simulation model DairyMod (Johnson *et al.* 2008), the current study quantified the changes and variability of these factors, by undertaking a historical analysis (1960 - 2009) across three dairy regions in South East Australia: Terang (South West Victoria, Mediterranean climate); Ellinbank (Gippsland, Victoria, temperate climate); and Elliott (North West Tasmania, cool-temperate climate).

A significant linear relationship between year and commencement date of the growing period at Elliott (*P* = 0.04) and Terang (*P* = 0.01) indicated that for every 10 year period, between 1960 and 2009, the commencement date of the growing period for these regions was 1.5 days earlier. There was no evidence that the commencement date of the wet and dry periods has changed over the last 50 years. However, during the last 4 to 5 years, all three sites have experienced an unusually low number of days in the year when soil moisture content has exceeded field capacity, and an unusually high number of days when the readily available water in the root profile has been exhausted.

Although unpredictable to date (i.e. there was no significant (*P* > 0.05) linear relationship between year and the number of days for the wet and dry periods at any of the sites over the last 50 years), the observation that the length of wet periods may be decreasing and length of dry periods may be increasing, has important implications for farm management decision-making.

References


Appendix 5: Pasture growth to lift under climate change

Published in the Australian Dairyfarmer magazine; November 2011

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Dairy systems in south eastern Australia may be facing a warmer and drier future, but a recent modelling research has shown that dairy producers in some areas could maintain or even increase pasture production under a changing climate.

It is well established that pasture consumption is a key index of dairy farm business success. Climate change is a feature of the 21st century and pasture production is heavily reliant on the climate. Projected climatic changes will alter the pattern of pasture growth requiring dairy farmer to adapt their grazing systems. Using biophysical models, researchers from the Tasmanian Institute of Agricultural Research and the University of Melbourne have been studying what dairy systems might look like at a regional level under a future climate.

The research has focused on the production of perennial ryegrass and white clover under future climate scenarios and examined adaptation options at both a biophysical and farm system level.

Annual and seasonal pasture growth was predicted by inputting projections of future rainfall and temperature – based on three future climate change scenarios – into the grazing systems models DairyMod and SGS Pasture Model. The future climate scenarios were developed for each site by adjusting baseline climate data (from the period 1971–2000) with climate change projections based on a high greenhouse gas emission scenario in 2030, and mid- and high-emission scenarios in 2070.

Researchers found that although higher temperatures and reduced rainfall are likely to result in a contraction of the spring growing season by a few weeks, warmer temperatures in winter and early spring, and higher levels of atmospheric carbon dioxide concentrations will elevate pasture growth rates enough to offset most, and in some cases all, of the decline later in the season (Fig 1).
Figure 1. Mean monthly pasture growth rates under a baseline (1971-2000) and three future climate scenarios at Ellinbank.

The research also highlighted that the use of deeper rooted perennials and higher temperature tolerant plants were able to alleviate the impact of a warmer and drier on pasture production. Incorporating deep rooted and heat tolerance traits into pasture species may involve breeding new cultivars of perennial ryegrass or changing to species such as tall fescue that already have these traits.

At a farm system level, the capacity to adapt stocking rate and calving time to future climates was explored. The impact of climate change on pasture production and farm gross margin at three sites; Terang (south-west Victoria, Mediterranean climate); Ellinbank (Gippsland, Victoria, temperate climate); and Elliott (north-west Tasmania, cool-temperate climate) were modelled under a range of climate by stocking rate by calving date scenarios. In the cool temperate region where pasture production was expected to increase in most climate scenarios adapting calving pattern and stocking rate resulted in significant increases in gross margins. No benefit or a decrease in gross margin were simulated in the Mediterranean and temperate regions suggesting that further changes to the farm system are required to maintain profitability in these regions.

While maintaining or improving pasture consumption is considered critical to the underlying competitive advantage of the dairy industry it is also important that these climate change adaptation strategies do not conflict with climate change mitigation. For example, the logical response of producers to warmer winter conditions will be to increase nitrogen fertiliser application, resulting in greater nitrous oxide emissions. The greenhouse gas emissions intensity of milk production of predominately pastured based dairy farms have been shown to be generally higher than those of dairy farm systems with higher levels of concentrate feeding and higher per cow production. For these predominantly pasture based systems the research teams are exploring climate change adaptation strategies that are not only resilient to a changing climate but also reduce emission intensity of milk production and improve farm profitability.

For further information contact: Richard Rawnsley (Richard.Rawnsley@utas.edu.au) or Brendan Cullen (bcullen@unimelb.edu.au)

This project is supported by funding from Dairy Australia, Meat and Livestock Australia, the Tasmanian Institute of Agricultural Research, the University of Melbourne and the Australian Government Department of Agriculture, Fisheries and Forestry under its Australia’s Farming Future Climate Change Research Program.
Appendix 6: Frequency of wet and dry soil conditions in Tasmanian dairy regions under future climate scenarios

Submitted for publication in the 16th Australian Society of Agronomy (ASA) Conference Proceedings; October 2012, Armidale, NSW, Australia

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Abstract

Durations of wet and dry periods are significant factors that influence pasture management on dairy farms. Historical and future simulated daily climate data for two dairy regions of Tasmania (Flowerdale and Ringarooma) was accessed from the ‘Climate Futures for Tasmania’ project and used to simulate a perennial ryegrass sward growing on a clay loam soil. The simulated soil moisture content to depth of 400mm was used as the criteria for determining number of wet (soil moisture > 160mm) and dry (soil moisture < 120mm) days per annum. The mean number of dry and wet days for each region for six general circulation models (GCMs; CSIRO-Mk3.5, ECHAM5, GFDL 2.0, GFDL 2.1, MIROC3.2 and UKHad), was computed for the baseline period (years 1971 to 2000) and three future climate periods (years of 2001 to 2030, 2031 to 2060 and 2061 to 2090). By years 2061 to 2090, the mean number of wet days at Flowerdale and Ringarooma is predicted to decline by 8.5 and 4.5 days per annum, respectively. In contrast, the mean number of dry days for Flowerdale and Ringarooma is predicted to increase by 7.5 and 4.8 days, respectively. While there was little change in the mean number of wet and dry days when averaged over each GCM, there was substantial variation between GCMs for any particular period and region. This paper discusses the implication of these results and also highlights the influence of inter-annual climate variability on dairy farming systems.

Key Words

Climate Futures for Tasmania, climate change, field capacity, readily available water, Flowerdale, Ringarooma

Introduction

Climate is an important driver of pasture production and the intra-annual variability in climate results in different patterns of pasture production needs to be managed to meet feed demands on dairy farms. In recent decades, South Eastern Australia has experienced a decline in total annual rainfall (Australian Bureau of Meteorology 2008), with the most substantial reduction occurring in autumn (Gallant et al. 2007). General Circulation Models (GCMs) provide the best estimates for assessing potential changes to the climate on a global scale however projections of climate change are not evenly distributed over the globe. This necessitates that local or regional climate projections are required to quantify local or regional climate impacts (Corney et al 2010). The Climate Futures for Tasmania (CFT) project generated climate projections specific to Tasmania through a dynamical downscaling approach (Grose et al. 2010). This downscaling approach increased the spatial resolution from 2° to 3° grid cells (~200 to 300km) in the GCMs down to a 0.1° grid (~10km) for Tasmania, thus capturing regional and sub-regional differences allowing the projected climate change impacts to be quantified on a local scale (Corney et al 2010).

Extended periods of both wet and dry soil conditions can strongly influence the managerial operations of a pasture based dairy system. For example, extended periods of wet soil moisture conditions can result in pugging of pasture, increased lameness and an increase incidence of mastitis, whilst extended dry soil conditions often results in lower pasture production, reduced pasture persistence and an increased reliance on purchased feed. This study examined the changes in the
frequency of wet and dry days per annum for two dairy regions of Tasmania out to 2090 using climate projection data from the CFT project.

Methods

Daily climate data developed from the CFT project (https://dl.tpac.org.au/) was accessed for Flowerdale (41.0°S, 145.6°E) and Ringarooma (41.3°S, 147.7°E). For both regions, six down-scaled A2 emissions scenario GCM files (CSIRO-Mk3.5, UKHad, ECHAM5, GFDL 2.0, GFDL 2.1 and MIROC3.2) were used, in combination with the biophysical model DairyMod (Johnson et al. 2008), to simulate a rain-fed perennial ryegrass pasture sward using a generic clay loam soil. Each GCM predicts varying increases or decreases in mean annual rainfall for future climate periods for Flowerdale (Figure 1a) and Ringarooma (Figure 1b) compared to its corresponding baseline period. The simulated soil moisture content to depth of 400mm was used as the criteria for determining number of wet (soil moisture > 160mm) and dry (soil moisture <120mm) days per annum. The number of wet days represents when the soil is above field capacity and the number of dry days represents the point where water in the soil profile is no longer readily available to the pasture sward, and evapotranspiration falls below its potential rate. The mean number of dry and wet days for each region, averaged across the six GCMs, was computed for the baseline period (years 1971 to 2000) and three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090). In addition, a ten-year moving mean number of wet and dry days and the associated coefficient of variation (CV%) for each region and GCM were calculated (mean of years 1971 to 1980 = 1980 value).

Results

Wet days

The mean number of wet days, averaged over the six GCMs, was predicted to decline by 8.5 days per annum at Flowerdale and 4.5 day per annum at Ringarooma (Table 1). While there was little variation in the mean number of wet days between GCMs during the baseline period, each GCM predicted varying changes in the number of wet days per annum for three future climate periods. At Flowerdale, five of the six models predicted a reduction in the mean number of wet days per annum by years 2061 to 2090 when compared to the baseline period of years (Table 1). The only exception was the UKHad model with a predicted increase in the mean number of wet days per annum by years 2061 to 2090 when compared to the baseline period of years (Table 1). At Ringarooma, all models predicted either no change (i.e. ECHAM model) or a decline in the mean number of wet days per annum by years 2061 to 2090 when compared to the baseline period of years (Table 1).
Table 1. Mean annual number of wet days (soil moisture > 160mm) per annum for Flowerdale and Ringarooma using six general circulation models for a baseline period (year 1971 to 2000) and change in the number of wet days for three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090) compared to the baseline period.

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There was substantial inter-annual variability in the number of wet days both within GCMs over time and between GCMs during the same timeframe (only limited data shown). The CSIRO-Mk3.5 model predicted a decline in the moving ten-year mean number of wet days per annum over time for Flowerdale (2.0 days per decade decline; Figure 2a). In contrast, the UKHad model predicted only a very small reduction in the moving ten-year mean number of wet days per annum over time (< 0.01 days per decade decline; Figure 2b). However, for both regions, it appears that there will be trend towards increasing year-to-year variability in the number of wet days, as evidenced by the increase in coefficient variation of the ten year moving mean.
Figure 2. Moving ten-year average number of wet days (solid line), defined as soil moisture > 160mm in the top 400mm of soil profile, and its associated variability (CV%, dashed line), from years 1980 to 2090 for Flowerdale using the CSIRO-Mk3.5 (a) and UKHad (b) general circulation models.

**Dry days**

The mean number of dry days, averaged over the six GCMs, was predicted to increase by 8.0 days per annum for Flowerdale and 7.2 days per annum for Ringarooma in the period of years 2031 to 2060 (Table 2). There was little variation in the number of dry days between GCMs during the baseline period. However, post the baseline period, there was substantially more variation between the climate models. For example, the CSIRO-Mk3.5 model resulted in Ringarooma having, on average, an additional 19.5 dry days per annum in the period of years 2061 to 2090 compared to the baseline period of years while the ECHAM model predicted a decline of 1.4 dry days per annum in the period of years 2061 to 2090 compared to the baseline period of years (Table 2).
Table 2. Mean annual number of dry days (soil moisture < 120mm) per annum for Flowerdale and Ringarooma using six general circulation models for a baseline period (years 1971 to 2000) and change in the number of dry days for three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090) compared to the baseline period.

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There was also substantial inter-annual variability in the number of dry days both within GCMs over time and between GCMs during the same timeframe (only limited data shown). For example, Figure 3 shows the moving ten-year mean number of dry days per annum for Ringarooma using the CSIRO-Mk3.5 and ECHAM models. The CSIRO model showed a trend towards an increase in the moving ten-year mean number of dry days per annum (2.0 days per decade increase; Figure 3a). In contrast, the ECHAM model showed a trend towards a decline in the moving ten-year mean number of dry days per annum (0.1 days per decade decline; Figure 3b). The variability in the moving ten-year mean number of dry days per annum was also predicted to decline for the CSIRO-Mk3.5 model but increase for the ECHAM model over time.
Figure 3. Moving ten-year average number of dry days (solid line), defined as soil moisture < 120mm in the top 400mm of soil profile, and its associated variability (CV%, dashed line), from years 1980 to 2090 for Ringarooma using the CSIRO-Mk3.5 (a) and ECHAM (b) general circulation models.

Conclusion

This study concluded that while there was substantial variation between GCMs, over time there will be an increase in the number of dry days per annum when available water in the soil profile will limit pasture production for the two Tasmanian dairy regions examined in this study. In addition, inter-annual variability in the number of wet and dry days will continue to occur and may increase in the future. There is currently no conclusive evidence to suggest that for the two dairy regions of Tasmania examined in this study that adaptation strategies for managing extended dry or wet periods are going to be any more imperative into the future beyond how imperative they are today. Managing extended dry periods could include the adoption of deeper rooted pasture species into the feedbase or the implementation of irrigation, whilst managing extended wet periods could include improvements to on-farm drainage or the provision of infrastructure to support a standoff area for herd. There will also be a need to quantify the whole of farm biophysical and business performance when adopting such potential adaptation strategies.

References


This study was supported by funding from Dairy Australia, Tasmanian Institute of Agriculture and the Australian Government Department of Agriculture, Fisheries and Forestry under its Australia’s Farming Future Climate Change Research Program.
Appendix 7: Timing of autumn breaks and lengths of springs in Tasmanian dairy regions under future climate scenarios
Submitted for publication in the 16th ASA Conference Proceedings; October 2012, Armidale, NSW, Australia
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Abstract
The timing of autumn breaks and the length of the spring growing season are considered two times of the year where pasture growth can be most variable. Daily climate data for two dairy regions of Tasmania (Flowerdale and Ringarooma) was accessed from the ‘Climate Futures for Tasmania’ project and used to simulate a perennial ryegrass sward using the biophysical pasture model DairyMod. The mean frequency of early and late autumn breaks and frequency of short and long spring seasons for a baseline period (years 1971 to 2000) and three climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090) was predicted for each region using climate projections from six general circulation models. Comparing the mean change between the baseline period and the future climate period, years 2061 to 2090, the frequency of early autumn breaks was predicted to increase from 27% to 33% for Flowerdale and from 26% to 34% for Ringarooma. The frequency of late autumn breaks was predicted to decline from 31% to 16% for Flowerdale and from 34% to 17% for Ringarooma. The frequency of short springs was predicted to decline from 14% and 16% for Flowerdale and Ringarooma, respectively, to < 1% for both regions. The frequency of long springs was predicted to remain relatively stable at ~32% for both regions. The results of this study indicate that for both regions of Tasmanian, earlier autumn breaks and a reduction in the frequency of short springs will result in a more reliable growing season. This paper discusses the implications of these results and possible adaptation options.

Key Words
Climate Futures for Tasmania, Flowerdale, Ringarooma, autumn breaks, spring seasons

Introduction
Climate is an important driver of pasture production and the intra-annual variability in climate results in differing patterns of pasture production which needs to be managed to meet feed demands on dairy farms. In recent decades, south eastern Australia has experienced a decline in total annual rainfall (Australian Bureau of Meteorology 2008), with the largest decline occurring in autumn (Gallant et al. 2007). General Circulation Models (GCMs) provide the best means of estimating the potential changes to the climate on a global scale. However, projections of climate change are not evenly distributed over the globe. To assess the impact of changes in climate within Tasmania, the Climate Futures for Tasmania (CFT) project generated climate projections specific to Tasmania through a dynamical downscaling approach (Grose et al. 2010). This downscaling approach increased the spatial resolution from 2° to 3° grid cells (≈200 to 300km) in the GCMs down to a 0.1° grid (≈10km) for Tasmania, allowing the projected climate change impacts to be quantified on a local scale (Corney et al 2010).
The timing of the autumn break is most strongly influenced by precipitation, and its occurrence strongly influences feed availability for autumn calving herds or the accumulation of a feed wedge for late winter/ early spring calving herds. The timing and duration of springs may be short or long, depending on soil moisture availability and the onset of warmer temperatures. The length of the spring season influences both the quality and quantity of surplus pasture, which in turn influences the need to purchase feed. This study examined the changes in frequency of late and early autumn breaks and frequency of long and short spring seasons for two dairy regions of Tasmania out to 2090 using climate projection data from the CFT project.

Methods

Daily climate data developed from the CFT project (https://dl.tpac.org.au/) was accessed for Flowerdale (41.0°S, 145.6°E) and Ringarooma (41.3°S, 147.7°E). For both regions, six down-scaled A2 emissions scenario GCM files (CSIRO-Mk3.5, ECHAM5, GFDL 2.0, GFDL 2.1 and MIROC3.2 and UKHad) were used, in combination with the biophysical model DairyMod (Johnson et al. 2008), to simulate a monthly cut study to a residual of 1.4 t DM/ha for a rain-fed perennial ryegrass pasture sward using a generic clay loam soil. Monthly pasture growth rates (PGR; kg DM/ha.day) were simulated using climate data from a baseline period (years 1971 to 2000) and three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090). The frequency of late and early autumn breaks and frequency of long and short spring seasons were defined in terms of monthly PGRs following a similar method as described by Chapman et al. (2008):

- Early autumn break: PGR in both March and April > baseline period average for March and April
- Late autumn break: PGR in both April and May < baseline period average for April and May
- Short spring season: PGR in both October and November < baseline period average for October and November
- Long spring season: PGR in both November and December > baseline period average for November and December

Results

There was generally good agreement (less than 10kg DM/ha.day difference) between the six GCMs for simulating mean monthly PRGs for the baseline period (Figure 1). Across the six GCMs the mean daily temperature increase, relative to the baseline temperature, for Flowerdale and Ringarooma were 0.5, 1.2 and 2.2°C and 0.5, 1.3 and 2.3°C in the 2001-2030, 2031-2060 and 2061-2090 periods, respectively. Annual rainfall changes, relative to the baseline rainfall, for Flowerdale and Ringarooma were -2.3, -1.8 and -0.2% and -0.5, +1.6 and +4.8% in the years 2001 to 2030, 2031 to 2060 and 2061 to 2090 periods, respectively.
Figure 1. Mean monthly pasture growth rate (kg DM/ha.day) for Flowerdale (a) and Ringarooma (b) for the baseline (years 1971 to 2000) climatic period according to six general circulation models.

Autumn breaks

For Flowerdale and Ringarooma, the frequency of early autumn breaks (Figure 2), as a mean of the six GCMs, was lower than the frequency of late autumn breaks (Figure 3), as a mean of the six GCMs, during the baseline period of years. At Flowerdale, the frequency of early autumn breaks, as a mean of the six GCMs, was predicted to increase from 27% (i.e. 8.0 years out of 30) in the baseline period to 33% by years 2061 to 2090 (Figure 2a). At Ringarooma, the frequency of early autumn breaks, as a mean of the six GCMs, was predicted to increase from 26% (i.e. 7.7 years out of 30) in the baseline period to 34% by years 2061 to 2090 (Figure 2b).

Figure 2. Frequency (number of years out of 30) of early autumn breaks at Flowerdale (a) and Ringarooma (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).

At Flowerdale, the frequency of late autumn breaks, as a mean of the six GCMs, was predicted to decline from 31% (i.e. 9.3 years out of 30) in the baseline period to 16% by years 2061 to 2090 (Figure 3a). At Ringarooma, the frequency of late autumn breaks, as a mean of the six GCMs, was predicted to decline from 34% (i.e. 10.2 years out of 30) in the baseline period to 17%
by years 2061 to 2090 (Figure 3b).

Figure 3. Frequency (number of years out of 30) of late autumn breaks at Flowerdale (a) and Ringarooma (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).

Spring seasons

For Flowerdale and Ringarooma, the frequency of short springs (Figure 4), as a mean of the six GCMs, was lower than the frequency of long springs (Figure 5), as a mean of the six GCMs, during the baseline period of years. At Flowerdale, the frequency of short springs, as a mean of the six GCMs, was predicted to decline from 14% (i.e. 4.2 years out of 30) in the baseline period to < 1% by years 2061 to 2090 (Figure 4a). At Ringarooma, the frequency of short springs, as a mean of the six GCM’s, was predicted to decline from 16% (i.e. 4.8 years out of 30) in the baseline period to < 1% by years 2061 to 2090 (Figure 4b). There was general consensus between GCM’s that the frequency of short springs would decline dramatically in all three future climate periods when compared to their corresponding baseline period (with the exception of the MIRCO model for years 2001 to 2030 at Flowerdale; Figure 4a).

Figure 4. Frequency (number of years out of 30) of short spring seasons at Flowerdale (a) and Ringarooma (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).
At Flowerdale and Ringarooma, the frequency of long springs, as a mean of the six GCMs, was predicted to remain relatively stable across all climate periods at between 29% and 32% (i.e. between 8.7 and 9.7 years out of 30) for Flowerdale (Figure 5a) and between 26% and 31% (i.e. between 7.8 and 8.5 years out of 30) for Ringarooma (Figure 5b).

**Figure 5.** Frequency (number of years out of 30) of long spring seasons at Flowerdale (a) and Ringarooma (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).

**Conclusion**

This study has indicated that it is likely that the mean frequency of early autumn breaks, as defined within this study, for both regions of Flowerdale and Ringarooma would increase into the future. There is also a corresponding likelihood that the mean frequency of late autumn breaks will decline in the future for the two regions. Increases in PGR above the historical average PGR for the months of March and April could lead to farmers considering autumn only or split calving (i.e. autumn and spring) in these environments. This study also concluded that while the mean frequency of long springs, as defined in this study, was unlikely to change dramatically in the future, the mean frequency of short springs was predicted to decline substantially in the future. This predicted increase in early spring season growth was mostly likely a result of warmer temperatures, higher levels of atmospheric CO$_2$ and minimal changes in precipitation, leading to more consistent PGR for the spring period. An increased frequency of an early autumn break and a more consistent spring pasture growth may promote management changes, such as earlier calving times or increased stocking rates, to take advantage of any increase in the length of the pasture growing season.

**References**


This study was supported by funding from Dairy Australia, Tasmanian Institute of Agriculture and the Australian Government Department of Agriculture, Fisheries and Forestry under its Australia’s Farming Future Climate Change Research Program.
Appendix 8: Frequency of wet and dry soil conditions in Tasmanian beef and sheep regions under future climate scenarios


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Introduction

Climate is an important driver of pasture production and the intra-annual variability in climate results in different patterns of pasture production which needs to be managed to meet feed demands on extensive livestock farm systems (beef and sheep farms). In recent decades, south eastern Australia has experienced a decline in total annual rainfall (Australian Bureau of Meteorology 2008), with the most substantial reduction occurring in autumn (Gallant et al. 2007). General Circulation Models (GCMs) provide the best estimates for assessing potential changes to the climate on a global scale however projections of climate change are not evenly distributed over the globe. This necessitates that local or regional climate projections are required to quantify local or regional climate impacts (Corney et al. 2010). The Climate Futures for Tasmania (CFT) project generated climate projections specific to Tasmania through a dynamical downscaling approach (Grose et al. 2010). This downscaling approach increased the spatial resolution from 2° to 3° grid cells (~200 to 300km) in the GCMs down to a 0.1° grid (~10km) for Tasmania, thus capturing regional and sub-regional differences allowing the projected climate change impacts to be quantified on a local scale (Corney et al 2010).

Extended periods of both wet and dry soil conditions can strongly influence the managerial operations and productivity of a pasture based farming system. For example, extended periods of wet soil moisture conditions can result in significant pugging damage to pasture, erode the benefits of rotational grazing, reduce pasture growth, increase lameness and the incidence of footrot and foot abscess and other health challenges, add feed costs and incur remedial pasture management costs. Extended dry soil conditions can lower pasture production, live weight gain and wool quality, reduce pasture persistence, ground cover and increase erosion and weed ingress risk and require either reduced herd or flock size or increased reliance on purchased feed to meet animal dietary requirements. This study examined the changes in the frequency of wet and dry days per annum for two extensive agricultural regions of Tasmania out to the year 2090 using climate projection data from the CFT project.

Methods

Daily climate data developed from the CFT project (https://dl.tpac.org.au/) was accessed for Cressy (41.7°S, 147.1°E) and Ouse (42.5°S, 146.7°E). For both regions, six down-scaled A2 emissions scenario GCM files (CSIRO-Mk3.5, UKHad, ECHAM5, GFDL 2.0, GFDL 2.1 and MIROC3.2) were used, in combination with the Sustainable Grazing Systems (SGS) biophysical simulation tool (Johnson et al. 2003), to simulate a rain-fed perennial ryegrass pasture sward using a generic clay loam soil. The simulated soil moisture content to depth of 400mm was used as the criteria for determining number of wet (soil moisture > 160mm) and dry (soil moisture <120mm) days per annum. The number of wet days represents when the soil is above field capacity and...
the number of dry days represents the point where water in the soil profile is no longer readily available to the pasture sward, and evapotranspiration falls below its potential rate. The mean number of dry and wet days for each region, averaged across the six GCMs, was computed for the baseline period of years 1971 to 2000 and three future climate periods of years 2001 to 2030, 2031 to 2060 and 2061 to 2090.

**Results**

**Annual rainfall**

At Cressy, the mean annual rainfall, as an average of the six GCMs, was predicted to be 726 mm/annum during the baseline period and increase by 3.6, 4.3 and 7.7% during the periods of years 2001 to 2030, 2031 to 2060 and 2061 to 2090, respectively, when compared to the baseline period of years (Figure 1a). At Ouse, the mean annual rainfall, as an average of the six GCMs, was predicted to be 728 mm/annum during the baseline period and increase by 0.5, 2.6 and 4.5% during the periods of years 2001 to 2030, 2031 to 2060 and 2061 to 2090, respectively, when compared to the baseline period (Figure 1b). Most of the increase in annual rainfall occurred during summer and to a lesser extent in autumn, for both regions (data not shown).

![Figure 1. Mean annual rainfall for Cressy (a) and Ouse (b) for the climatic periods of years 1971 to 2000 (■), 2001 to 2030 (■), 2031 to 2060 (■) and 2061 to 2090 (■) according to six general circulation models (vertical bars indicate the standard error of the mean).](image)

**Wet days**

The mean number of wet days per annum at Cressy, averaged over the six GCMs, was predicted to decline by 3.0, 3.7 and 2.8 days for the period of years 2001 to 2030, 2031 to 2060 and 2061 to 2090, respectively, when compared to the baseline period (Table 1). At Ouse, the mean number of wet days per annum, averaged over the six GCMs, was predicted to decline by 4.4 and 1.5 days for the period of years 2001 to 2030 and 2031 to 2060, respectively, when compared to the baseline period, before increasing by 0.1 days for the period of years 2061 to 2090 (Table 1). Each GCM predicted varying changes in the number of wet days per annum for three future climate periods. During the period of years 2001 to 2030, four of the six GCMs predicted a reduction in the number of wet days per annum compared to the baseline period for both locations (Table 1). The only exceptions were a predicted increase in the number of wet days per annum with the ECHAM5 and UKHad models at Cressy and with the GFDL2.1 and UKHad models at Ouse (Table 1).
Table 1. Mean number of wet days (soil moisture > 160mm) per annum for Cressy and Ouse using six general circulation models for a baseline period (years 1971 to 2000) and change in the mean number of wet days per annum for three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090) compared to the baseline period.

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Dry days

At Cressy, the mean number of dry days per annum, averaged over the six GCMs, was predicted to increase by 0.4 and 3.9 days for the period of years 2001 to 2030 and 2031 to 2060, respectively, before declining by 0.2 days for the period of years 2061 to 2090 when compared to the baseline period (Table 2). At Ouse, the mean number of dry days per annum, averaged over the six GCMs, was predicted to increase by 1.2 days during the period of years 2001 to 2030 before declining by 3.4 and 4.5 days during the period of years 2031 to 2060 and 2061 to 2090, respectively, when compared to the baseline period (Table 2). This decline in the mean number of dry days per annum at Ouse was mainly as a consequence of the GFDL2.1 and UKHad models predicting that the number of dry days would decline by between 14 and 27 days during the latter two periods when compared to the baseline period (Table 2).
### Table 2. Mean annual number of dry days (soil moisture < 120mm) per annum for Cressy and Ouse using six general circulation models for a baseline period (years 1971 to 2000) and change in the number of dry days per annum for three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090) compared to the baseline period.

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### Discussion and conclusions

This study concluded that while there was substantial variation between GCMs, there is an indication that the mean number of wet days per annum at Cressy for all three future climate periods will decline. In contrast, the mean number of wet days was predicted to remain relatively similar at Ouse for the two latter periods of years (years 2031 to 2060 and 2061 to 2090) when compared to the baseline period. Managing extended wet periods could increase the need for improvements to on-farm drainage, the provision of feed pads, for sacrifice areas, for more consideration of topography and livestock class in the grazing/feed plan, flexible approaches to managing stock density aligned to triggers for action, and possibly consideration of pasture species more tolerant to water logging.

There was also substantial variation between GCMs in terms of the number of dry days per annum for both regions under the future climate scenarios. The mean number of dry days was predicted to increase at Cressy during the period of years 2031 to 2060. Interestingly the increase in rainfall during summer and autumn did not necessarily result in a reduction in the mean number of dry days per annum at Cressy, highlighting the importance of undertaking a biological assessment of future climate impacts through biophysical modelling and not relying
exclusively on meteorological data. In contrast, the mean number of dry days was predicted to decline at Ouse, predominantly as a consequence of two of the six GCMs predicting a substantial decline in the number of dry days per annum and thus diluting the influence of the four other GCMs that predicted an increase in the mean number of dry days per annum. Managing extended dry periods could include the adoption of better adapted and deeper rooted pasture species into the feedbase, making provision for confinement feeding or the implementation of irrigation, especially given the relatively low mean annual rainfall for both regions.

References


This study was supported by funding from Dairy Australia, Meat and Livestock Australia, Tasmanian Institute of Agriculture and the Australian Government Department of Agriculture, Fisheries and Forestry under its Australia’s Farming Future Climate Change Research Program.
Introduction

Climate is an important driver of pasture production and the intra-annual variability in climate results in different patterns of pasture production which needs to be managed to meet feed demands on beef and sheep farms. In recent decades, south eastern Australia has experienced a decline in total annual rainfall (Australian Bureau of Meteorology 2008), with the most substantial reduction occurring in autumn (Gallant et al. 2007). General Circulation Models (GCMs) provide the best estimates for assessing potential changes to the climate on a global scale however projections of climate change are not evenly distributed over the globe. This necessitates that local or regional climate projections are required to quantify local or regional climate impacts (Corney et al. 2010). The Climate Futures for Tasmania (CFT) project generated climate projections specific to Tasmania through a dynamical downscaling approach (Grose et al. 2010). This downscaling approach increased the spatial resolution from 2° to 3° grid cells (~200 to 300km) in the GCMs down to a 0.1° grid (~10km) for Tasmania, thus capturing regional and sub-regional differences allowing the projected climate change impacts to be quantified on a local scale (Corney et al. 2010).

The timing of the autumn break is most strongly influenced by precipitation, and its occurrence strongly influences feed availability for autumn calving/lambing or the accumulation of a feed wedge for late winter/ early spring calving/lambing. The ability to meet increased nutritional demands associated with an autumn joining is also strongly influenced by feed availability during the autumn period. The duration of springs may be short or long, depending on soil moisture availability and the onset of warmer temperatures. The length of the spring season influences both the quality and quantity of available feed, livestock production potential, and the demand for either conservation or purchase feeds. This study examined the changes in frequency of late and early autumn breaks and frequency of long and short spring seasons for two extensive agricultural regions of Tasmania out to the year 2090 using climate projection data from the CFT project.

Methods

Daily climate data developed from the CFT project (https://dl.tpac.org.au/) was accessed for Cressy (41.7°S, 147.1°E) and Ouse (42.5°S, 146.7°E). For both regions, six down-scaled A2 emissions scenario GCM files (CSIRO-Mk3.5, UKHad, ECHAM5, GFDL 2.0, GFDL 2.1 and MIROC3.2) were used, in combination with the Sustainable Grazing Systems (SGS) biophysical simulation tool (Johnson et al. 2003), to simulate a monthly cut study for a rain-fed perennial ryegrass pasture sward using a generic clay loam soil. Monthly pasture growth rates (PGR; kg dry matter/ha.day) were simulated using climate data from a baseline period (years 1971 to 2000) and three future climate periods (years 2001 to 2030, 2031 to 2060 and 2061 to 2090). The frequency of late and early autumn breaks and frequency of long and short spring seasons were
defined in terms of monthly PGRs following a similar method as described by Chapman et al. (2008):

- Early autumn break: PGR in both March and April > baseline period average for March and April
- Late autumn break: PGR in both April and May < baseline period average for April and May
- Short spring season: PRG in both October and November < baseline period average for October and November
- Long spring season: PRG in both November and December > baseline period average for November and December

**Results**

There was generally good agreement (less than 10kg DM/ha.day difference except in November at Cressy and in November and December at Ouse) between the six GCMs for simulating mean monthly PRGs for the baseline period (data not shown). The mean daily temperature, as an average of the six GCMs, was predicted to increase by 0.5, 1.3 and 2.3°C at Cressy and by 0.5, 1.2 and 2.2°C at Ouse in the period of years 2001 to 2030, 2031 to 2060 and 2061 to 2090, respectively, when compared to the baseline period of years. Annual rainfall changes, relative to the baseline rainfall, for Cressy and Ouse were +3.6, +4.3 and +7.7% and +0.5, +2.6 and +4.5% in the period of years 2001 to 2030, 2031 to 2060 and 2061 to 2090 periods, respectively.

**Autumn breaks**

The frequency of early autumn breaks, as a mean of the six GCMs, was predicted to increase from 18% (i.e. 5.5 years out of 30) in the baseline period of years to 28% by years 2061 to 2090 (Figure 1a) at Cressy. The frequency of early autumn breaks, as a mean of the six GCM, was predicted to increase from 19% (i.e. 5.7 years out of 30) in the baseline period of years to 29% by years 2061 to 2090 (Figure 1b) at Ouse.

**Figure 1.** Frequency (number of years out of 30) of early autumn breaks at Cressy (a) and Ouse (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).
The frequency of late autumn breaks, as a mean of the six GCMs, was predicted to decline from 39% (i.e. 11.7 years out of 30) in the baseline period of years to 26% by years 2061 to 2090 (Figure 2a) at Cressy. The frequency of late autumn breaks, as a mean of the six GCMs, was predicted to decline from 39% (i.e. 11.8 years out of 30) in the baseline period of years to 23% by years 2061 to 2090 (Figure 2b) at Ouse.

Figure 2. Frequency (number of years out of 30) of late autumn breaks at Cressy (a) and Ouse (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).

Spring seasons

The frequency of short springs, as a mean of the GCMs, was predicted to decline from 29% (i.e. 8.7 years out of 30) in the baseline period of years to 19% by years 2061 to 2090 (Figure 3a) at Cressy. The frequency of short springs, as a mean of the six GCMs, was predicted to decline from 22% (i.e. 6.5 years out of 30) during the baseline period of years to 13% by years 2061 to 2090 (Figure 3b) at Ouse.

Figure 3. Frequency (number of years out of 30) of short springs at Cressy (a) and Ouse (b) for six general circulation models for the periods of years 1971 to 2000 (■), 2001 to 2030 (□), 2031 to 2060 (■) and 2061 to 2090 (□).

The frequency of long springs, as a mean of the six GCMs, was predicted to decline from 22% (i.e. 6.7 years out of 30) during the baseline period of years to 20% during years 2061 to 2090 (Figure...
4a) at Cressy. The frequency of long springs, as a mean of the six GCMs, was predicted to decline from 27% (i.e. 8.0 years out of 30) during the baseline period of years to 18% during years 2061 to 2090 (Figure 4b) at Ouse.

**Figure 4.** Frequency (number of years out of 30) of long springs at Cressy (a) and Ouse (b) for six general circulation models for the periods of years 1971 to 2000 ( ), 2001 to 2030 ( ), 2031 to 2060 ( ) and 2061 to 2090 ( ).

**Discussion and conclusions**

This study has indicated that the likelihood of the mean frequency of early autumn breaks increased and the mean frequency of late autumn breaks declined, as defined within this study, into the future for both Cressy and Ouse. Increases in PGR above the historical average PGR for the autumn months and reduced autumn variability (early autumn’s increase, late autumn’s declined) could lead to increased winter feed supply, winter carrying capacity and management confidence. This may increase the capacity for autumn lambing/calving, winter finishing, or leverage increased winter stocking rates and consequent spring pasture harvests in spring calving/lambing enterprises.

This study also concluded that while the frequency of short springs, as defined in this study, was predicted to decline into the future, the frequency of long springs was also predicted to decline into the future. The decline in frequency of short springs was mostly likely a result of warmer temperatures, higher levels of atmospheric carbon dioxide concentrations and minimal changes in precipitation, leading to more consistent PGR for the spring period. However, the decline in the frequency of long spring periods could be as consequence of reduced soil moisture content in late spring/early summer restricting pasture growth. This decline in long springs in these two regions could be offset with deeper rooted pasture species with longer season growth potential, the introduction of irrigation to maximise productivity on beef and sheep enterprises, and the use of management like early weaning strategies or changes in sale target weights to adapt feed demand to changing feed supply. Increased consistency of spring may also assist planning by improving management confidence.

**References**


This study was supported by funding from Dairy Australia, Meat and Livestock Australia, Tasmanian Institute of Agriculture and the Australian Government Department of Agriculture, Fisheries and Forestry under its Australia’s Farming Future Climate Change Research Program.

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The Dairy Greenhouse gas Abatement Strategy (DGAS) software was developed to model the carbon dioxide, methane and nitrous oxide emissions associated with dairying in Australia, using standard national inventory methods, algorithms and emission factors (DCC, 2008). The user interface of the software includes two data entry pages; the farm and the herd. The farm data includes farm size, proportion of area rain-fed and irrigated, location, rainfall, tree plantings, manure management system, electricity, diesel, fertiliser and purchased feed inputs. The herd data includes herd milk production, five livestock classes including animal numbers, live weight and weight gain, and the dietary composition for each livestock class. The diet for the milking herd allows for seasonal variation, whereas the diets of other livestock classes are entered on an annual basis. The results are available as a comparative bar chart showing the 10 contributing sources of GHG emissions in addition to the potential storage of GHG emissions in tree plantings, expressed as t CO₂e/t milksolids. Total farm, broken down into four sub-totals (pre-farm embedded, carbon dioxide, methane and nitrous oxide) is also displayed.

Once the data has been entered for the farm, it can be copied to a hypothetical scenario. The software allows users to compare the hypothesised farm or ‘strategy’, against the existing farm allowing for a range of potential abatement strategies to be explored. Comparative analysis between the existing farm and the hypothesised farm are presented on the results page. Farm economic data can be entered for both the baseline and hypothesised farm. Should dairy GHG emissions be included as a liability or offset as part of a future emission trading scheme, two economics pages are included (existing and hypothetical farms) to assess the effects of an emissions trading scheme on farm income. The software requires very little data storage and as such has been developed using MS Excel. User forms provide a friendly interface while the data storage and modelling activities are stored on worksheets.

DGAS analysis of 60 Tasmanian dairy farms found that on average 56 and 21 percent of total farm GHG emissions came from methane and nitrous oxide, respectively. Pre-farm embedded emissions and fuel and electricity emissions both accounted for 11 percent of total farm emissions. This paper explores potential current GHG abatement options for Tasmanian dairy farm using the functionalities of DGAS.
Appendix 11: A whole farm systems analysis of the greenhouse gas emissions of 60 Tasmanian dairy farms

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The Australian dairy industry contribute approximately two percent of the nation’s greenhouse gas (GHG) emissions with 8.9 million tonnes of carbon dioxide equivalents per annum (t CO\(_2\)e; DCC 2008). This study examined the GHG emissions of 60 Tasmanian dairy farms using the Dairy Greenhouse gas Abatement Strategies calculator (DGAS; Christie et al. 2010), which incorporates the IPCC and national inventory methodologies, algorithms and emission factors.

Sources of GHG emissions including the pre-farm embedded emissions associated with key farm inputs, such as fertiliser and purchased forages and the on-farm emissions from carbon dioxide, methane and nitrous oxide were determined. The mean total farm GHG emissions was 2,785 t CO\(_2\)e, ranging between 704 and 5,339 t CO\(_2\)e/farm. Dividing total farm emissions by annual milk production, milking herd size and farm area, the mean GHG emission intensities was 14.5 t CO\(_2\)e/t milk solids, 6.9 t CO\(_2\)e/cow or 12.6 t CO\(_2\)e/ha.

Linear regression analysis showed that 0.93 of the variation in total farm emissions could be explained by milk production (equation 1) while milking herd size (equation 2) and farm area (equation 3) were less indicative.

\[
\begin{align*}
(1) & \quad \text{Total emissions} = \text{Milk solids production} \times 13.54 + 151.83; \quad R^2 = 0.93 \\
(2) & \quad \text{Total emissions} = \text{Milking herd size} \times 5.94 + 373.75; \quad R^2 = 0.75 \\
(3) & \quad \text{Total emissions} = \text{Total farm area} \times 7.68 + 993.95; \quad R^2 = 0.41
\end{align*}
\]

A stepwise multiple linear analysis showed that individual farm GHG emissions intensity could be explained using key farm indicators, expressed either on a per milk solids basis, per cow basis or per hectare basis:

\[
\begin{align*}
(1) & \quad \text{Milk solids intensity} (\text{t CO}_2\text{e} / \text{t milk solids}) = 29.156 + (-14.235 \times \text{feed conversion efficiency}) + (0.005 \times \text{kg nitrogen fertiliser/ha}); \quad R^2 = 0.60 \\
(2) & \quad \text{Cow intensity} (\text{t CO}_2\text{e} / \text{cow}) = -0.599 + (1.228 \times \text{total dry matter intake}) + (0.002 \times \text{kg nitrogen fertiliser/ha}); \quad R^2 = 0.87 \\
(3) & \quad \text{Farm area intensity} (\text{t CO}_2\text{e} / \text{ha}) = 1.891 + (0.011 \times \text{kg milk solids/ha}) + (0.008 \times \text{kg nitrogen fertiliser/ha}); \quad R^2 = 0.94
\end{align*}
\]

This study has shown that total GHG emissions of Tasmanian dairy farms can be accurately and most easily estimated by the farms total milk production. Feed conversion efficiency and nitrogen fertiliser inputs were able to explain 0.6 of the variation in the GHG emissions intensity of milk production for these pasture based dairy systems. This highlights these two factors as target areas for lowering the intensity of emissions associated with dairying in this environment.
Appendix 12: 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\textsubscript{2} equivalents (t CO\textsubscript{2}e) 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 (\textit{i.e.}, grains/concentrates, forages and fertilizers) and on-farm emissions from CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O 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\textsubscript{2}e/annum, with a mean of 2,811 t CO\textsubscript{2}e/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\textsubscript{2}e/kg fat and protein corrected milk (FPCM; ranged between 0.83 and 1.39 t CO\textsubscript{2}e/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\textsubscript{2}e/cow and 12.6 ± 4.37 t CO\textsubscript{2}e/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$_2$e), with Australia responsible for 553 Mt CO$_2$e, ~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$_2$O 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$_2$O 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$_2$O emissions into CO$_2$e 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:

\[
\text{FPCM (kg)} = \text{raw milk (kg; calculated by multiplying liters by 1.03 (Sevenster and de Jong, 2008))} \times (0.337 + (0.116 \times \text{fat content (g/100 g milk)}) + (0.06 \times \text{protein content (g/100 g milk)}) \quad (FAO, 2010).
\]

2.2. Pre-farm embedded emissions

Simapro life cycle assessment software (Simapro, 2006) was used to determine the CO\(_2\)e 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\(_2\)e) 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\(_2\)e 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\(_2\)e 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\textsuperscript{®} laboratory in Australia, as published in the Pasture Consumption and Feed Conversion Efficiency Calculator manual (Heard and Wales, 2009; Table 3). These estimates were 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 CH4 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 N2O emissions

Four sources of N2O emissions were estimated which were those associated with manure management, N based fertilizers, deposition of animal waste directly onto pastures during grazing and indirect N2O 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 N2O emissions associated with animal waste. Nitrogen based fertilizer N2O 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 N2O 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 CO2 emissions associated with the embedded pre-farm inputs, and the on-farm CO2, CH4 and N2O 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$_2$e/kg FPCM), emissions/milking cow (t CO$_2$e/cow) and emissions/unit of land (t CO$_2$e/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$_2$e/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$_2$e/annum) = Fat protein corrected milk production (t FPCM) $\times$ 0.96 + 42.90; $r^2 = 0.93$ ($P < 0.001$)
2. Total GHG emissions (t CO$_2$e/annum) = Milking herd size (number of cows) $\times$ 5.94 + 373.75; $r^2 = 0.75$ ($P < 0.001$)
3. Total GHG emissions (t CO$_2$e/annum) = Total farm area (ha) $\times$ 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$_2$e/kg FPCM, estimated GHG emissions intensity/cow was 6.9 ± 1.46 t CO$_2$e/cow, and estimated GHG emissions intensity/hectare was 12.6 ± 4.37 t CO$_2$e/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$_2$O 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$_2$e/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:

\[(\text{kg CO}_2\text{e/kg FPCM}) = 2.03 + (-0.91 \times \text{FCE (kg FPCM/kg DM intake)}) + (2.82E-04 \times \text{N based fertilizer application rate (kg N/ha}})\].

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\(_2\)e/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/hecate 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\(_2\)e/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\(_2\)e/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\(_2\)O emission from soils. The rate, source and timing of N fertilizers have all been shown to influence N\(_2\)O emissions (O’Hara et al., 2003). One example of reduced N\(_2\)O 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\(_2\)O 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$_2$e/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$_2$e/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$_2$e/kg milk, while Basset-Mens et al. (2005) found that the typical New Zealand dairy farm emitted 0.72 kg CO$_2$e/kg milk. Results from 23 conventional and organic farms in Sweden ranged between 0.90 and 1.04 kg CO$_2$e/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$_2$e/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$_2$e/kg milk at the farm gate. However, there were substantial regional variations, ranging from a low of 1.0 to 1.5 kg CO$_2$e/kg milk for western industrialized regions (e.g., USA, Eastern and Western Europe) to a high of ~7.5 kg CO$_2$e/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$_2$e/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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$e. 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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B.SBP.0071 - Whole Farm Systems Analysis of Climate Change Impacts on the Southern Grazing Industries

Future Climate Change Research Program. The authors thank Dairy Australia for providing data for the 60 dairy farms and the contribution to farm data collation by the Dairy Business Centre 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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Australian Standing Committee on Agriculture, 1990. Feeding standards for Australian livestock, Ruminants. Standing Committee on Agriculture, Ruminant sub-committee, CSIRO, Melbourne, Victoria, Australia.


Climate Analysis Indicators Tool, 2009. CAIT version 7.0., World Resources Institute, 2010; Washington, DC, USA. http://cait.wri.org/


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\(_2\)e) and the mean (minimum and maximum in parenthesis) values for each of these key farm inputs for the 60 Tasmanian dairy farms.

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

\(^a\)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).

<table>
<thead>
<tr>
<th>Key farm input</th>
<th>Emission factor (kg CO$_2$e/kg product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain/concentrates</td>
<td>0.30</td>
</tr>
<tr>
<td>Pasture hay and silage</td>
<td>0.25</td>
</tr>
<tr>
<td>Cereal/Maize silage</td>
<td>0.25</td>
</tr>
<tr>
<td>Lucerne hay</td>
<td>0.20</td>
</tr>
<tr>
<td>Urea</td>
<td>0.89</td>
</tr>
<tr>
<td>Single superphosphate</td>
<td>0.23</td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>0.13</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Feed source</th>
<th>Dry matter digestibility (g/kg dry matter)</th>
<th>Crude protein (g/kg dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home grown consumed pasture</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>Home grown conserved forage</td>
<td>650</td>
<td>180</td>
</tr>
<tr>
<td>Purchased forage</td>
<td>650</td>
<td>180</td>
</tr>
<tr>
<td>Grain</td>
<td>800</td>
<td>120-190$^a$</td>
</tr>
<tr>
<td>Other feed source</td>
<td>600-750$^b$</td>
<td>180-240$^b$</td>
</tr>
</tbody>
</table>

$^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$_2$O emissions and their corresponding emission factor.

<table>
<thead>
<tr>
<th>Source</th>
<th>Proportion available for loss to the environment</th>
<th>Emission factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct N$_2$O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N based fertilizer (irrigated pastures and crops)</td>
<td>1.0</td>
<td>0.4%</td>
</tr>
<tr>
<td>N based fertilizer (non-irrigated pastures and crops)</td>
<td>1.0</td>
<td>0.3%</td>
</tr>
<tr>
<td>Urine</td>
<td>1.0</td>
<td>0.4%</td>
</tr>
<tr>
<td>Faeces</td>
<td>1.0</td>
<td>0.5%</td>
</tr>
<tr>
<td>Stored manures</td>
<td>1.0</td>
<td>1.8%</td>
</tr>
<tr>
<td>Indirect N$_2$O - leached/runoff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N based fertilizers</td>
<td>0.3</td>
<td>1.25%</td>
</tr>
<tr>
<td>Animal waste</td>
<td>0.3</td>
<td>1.25%</td>
</tr>
<tr>
<td>Indirect N$_2$O - atmospheric deposition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-based fertilizers</td>
<td>0.1</td>
<td>1.0%</td>
</tr>
<tr>
<td>Animal waste</td>
<td>0.07 to 0.4$^a$</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

$^a$ 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.

<table>
<thead>
<tr>
<th>Greenhouse gas emission source</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enteric CH$_4$</td>
<td>0.551</td>
<td>0.455 – 0.669</td>
</tr>
<tr>
<td>CO$_2$ from electricity and diesel</td>
<td>0.114</td>
<td>0.031 – 0.220</td>
</tr>
<tr>
<td>Indirect N$_2$O from N-based fertilizers and animal waste</td>
<td>0.109</td>
<td>0.088 – 0.143</td>
</tr>
<tr>
<td>Direct N$_2$O from animal waste$^a$</td>
<td>0.074</td>
<td>0.060 – 0.099</td>
</tr>
<tr>
<td>CO$_2$ from purchased grain/concentrates</td>
<td>0.061</td>
<td>0 – 0.098</td>
</tr>
<tr>
<td>CO$_2$ from purchased fertilizers (N and non-N based)</td>
<td>0.036</td>
<td>0.002 – 0.076</td>
</tr>
<tr>
<td>Direct N$_2$O from N-based fertilizers</td>
<td>0.025</td>
<td>0.001 – 0.056</td>
</tr>
<tr>
<td>CO$_2$e from purchased forage</td>
<td>0.018</td>
<td>0 – 0.068</td>
</tr>
<tr>
<td>CH$_4$ from manure management</td>
<td>0.013</td>
<td>0.011 – 0.016</td>
</tr>
</tbody>
</table>

$^a$ includes N$_2$O 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 CO₂e/kg FPCM), cow intensity (t CO₂e/cow) and area intensity (t CO₂e/ha), where \( b \) is the unstandardized coefficient, \( SE \ b \) is the standard error of \( b \), \( \beta \) is the standardized coefficient and \( R^2 \) is the coefficient of determination.

<table>
<thead>
<tr>
<th>Milk intensity (kg CO₂e/kg FPCM)</th>
<th>( b )</th>
<th>( SE \ b )</th>
<th>( \beta )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>2.01</td>
<td>0.12</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Feed conversion efficiency (kg milk/kg DMI)</td>
<td>-0.85</td>
<td>0.10</td>
<td>-0.74***</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>2.03</td>
<td>0.11</td>
<td></td>
<td>0.60</td>
</tr>
<tr>
<td>Feed conversion efficiency (kg milk/kg DMI)</td>
<td>-0.91</td>
<td>0.10</td>
<td>-0.80***</td>
<td></td>
</tr>
<tr>
<td>Nitrogen fertilizer (kg N/ha)</td>
<td>2.82E-04</td>
<td>1.17E-04</td>
<td>0.21*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cow intensity (t CO₂e/cow)</th>
<th>( b )</th>
<th>( SE \ b )</th>
<th>( \beta )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.60</td>
<td>0.41</td>
<td></td>
<td>0.86</td>
</tr>
<tr>
<td>Total feed intake (t DMI/cow/lactation)</td>
<td>1.28</td>
<td>0.07</td>
<td>0.93***</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.70</td>
<td>0.40</td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>Total feed intake (t DMI/cow/lactation)</td>
<td>1.25</td>
<td>0.07</td>
<td>0.90***</td>
<td></td>
</tr>
<tr>
<td>Nitrogen fertilizer (kg N/ha)</td>
<td>1.89E-03</td>
<td>7.28E-04</td>
<td>0.13*</td>
<td></td>
</tr>
<tr>
<td><strong>Step 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.9</td>
<td>0.39</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>Total feed intake (t DMI/cow/lactation)</td>
<td>1.36</td>
<td>0.08</td>
<td>0.98***</td>
<td></td>
</tr>
<tr>
<td>Nitrogen fertilizer (kg N/ha)</td>
<td>3.03E-03</td>
<td>8.18E-04</td>
<td>-0.20***</td>
<td></td>
</tr>
<tr>
<td>Area production (t FPCM/ha)</td>
<td>-0.05</td>
<td>0.02</td>
<td>-0.17*</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Area intensity (t CO₂e/ha)</th>
<th>( b )</th>
<th>( SE \ b )</th>
<th>( \beta )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>2.06</td>
<td>0.45</td>
<td></td>
<td>0.92</td>
</tr>
<tr>
<td>Area production (t FPCM/ha)</td>
<td>0.85</td>
<td>0.03</td>
<td>0.96***</td>
<td></td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Constant</td>
<td>8.41</td>
<td>1.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area production (t FPCM/ha)</td>
<td>0.94</td>
<td>0.04</td>
<td>1.05***</td>
<td></td>
</tr>
<tr>
<td>Feed conversion efficiency (kg milk/kg DMI)</td>
<td>-6.50</td>
<td>1.58</td>
<td>-0.17***</td>
<td></td>
</tr>
<tr>
<td><strong>Step 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Constant</td>
<td>7.62</td>
<td>1.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area production (t FPCM/ha)</td>
<td>0.86</td>
<td>0.04</td>
<td>0.96***</td>
<td></td>
</tr>
<tr>
<td>Feed conversion efficiency (kg milk/kg DMI)</td>
<td>-5.94</td>
<td>1.39</td>
<td>-0.15***</td>
<td></td>
</tr>
<tr>
<td>Nitrogen fertilizer (kg N/ha)</td>
<td>6.76E-03</td>
<td>1.59E-03</td>
<td>0.15***</td>
<td></td>
</tr>
</tbody>
</table>

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$_2$e/annum), as estimated with the DGAS calculator, and milk production (a), milking herd size (b) and farm area (c).
Appendix 13: Whole farm systems analysis of the greenhouse gas emissions of Australian dairy farms

Published in the CCRSPI Conference Proceedings; February 2011, Melbourne, VIC, Australia

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²Department of Primary Industries, 1301 Hazeldean Road, Ellinbank, Vic. 3820

The Australian dairy industry contributes approximately 1.6% of the nation’s greenhouse gas (GHG) emissions, emitting an estimated 8.9 million tonnes of carbon dioxide equivalents (t CO₂e) per annum (DCC, 2008). This study examined GHG emissions of 41 dairy farms from throughout eight dairying regions of Australia, using the Dairy Greenhouse gas Abatement Strategies calculator, which incorporates International Panel on Climate Change and Australian inventory methodologies, algorithms and emission factors. The sources of GHG emissions were the CO₂ emissions associated with the pre-farm embedded emissions of key farm inputs and on-farm emissions from CO₂, methane and nitrous oxide. The mean total farm GHG emission was 2,214 t CO₂e/annum. The estimated milk GHG emission intensity was 1.07 ± 0.21 kg CO₂e/litre of milk (mean ± standard deviation), with a range of between 0.79 and 2.01 kg CO₂e/litre of milk. The estimated mean area GHG emission intensity was 7.6 ± 3.7 t CO₂e/ha, with a range of between 1.4 and 17.7 t CO₂e/ha. Farms were grouped according to the farm system (FS) classification as defined by Dairy Australia. This resulted in 19 FS1, 13 FS2 farms and 9 FS3 farms being assessed. Farm system 1 farms are characterised by being predominantly pasture based with less than 30% purchased supplementary feed, FS2 farms are characterised by being pasture based with high levels (>30%) of purchased supplementary feed and FS3 farms are characterised by being a hybrid between a pasture based system with supplementary feeds (FS1 or FS2) and a total mixed ration feeding system (FS4). The mean emission intensity of milk production was found to be significantly (P<0.05) higher for FS1 farms than FS2 and FS3 farms which were not significantly (P>0.05) different to each other. There was no significant (P>0.05) differences in mean milk GHG emissions intensity between the regions, with the exception of Tasmania, which was significantly (P<0.05) higher, at 1.42 kg CO₂e/litre of milk, compared to between 0.98 and 1.07 kg CO₂e/litre of milk. One reason for Tasmania being significantly higher was partially due to one farm having an estimated milk GHG emission intensity that was approximately 50% greater than the next highest farm. While these results indicate that adopting a more intensive farming system resulted in reducing milk GHG emissions intensity, this could potentially diminish our international competitive advantage of producing milk at a lost cost in addition to reducing the resilience of the farming system in a changing climate.

References

Appendix 14: Australian dairy farm greenhouse gas emissions

Published in The Australian Dairyfarmer Magazine, November 2011
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Livestock account for around 11 per cent of Australia’s greenhouse gas emissions and researchers are working hard to develop practical on-farm options to reduce emissions without compromising farm productivity. Karen Christie, Project Officer from the Tasmanian Institute of Agricultural Research, was tasked with estimating the greenhouse gas (GHG) emissions of the 44 dairy farms to value-add to the Accounting for Nutrients (A4N) on Australian Dairy Farms project.

The A4N project involved collecting detailed data on nutrient imports, exports and within-farm nutrient flows from 44 dairy farms, on a quarterly basis. The study took place between February 2008 and February 2009 and the farms were located in the eight dairying regions of Australia (Figure 1). These farms represented the diversity of the industry in terms of herd size, farm size, level of milk production per cow, grain and forage feeding, fertiliser usage and reliance on irrigation.

While the A4N project was never intended to be used as a source of farm data for estimating on farm GHG emissions, it was clear that the dataset was an invaluable source of farm data that could be used to examine this. Of the 44 farms, 41 farms had sufficient data to estimate each farms’ GHG emissions, using the Dairy Greenhouse gas Abatement Strategies (DGAS) calculator (version 1.3). DGAS estimates four sources of GHG emissions; carbon dioxide from the consumption of electricity and fuel, methane from enteric fermentation and management of animal waste, nitrous oxide from management of animal waste and nitrogen fertilisers and a pre-farm embedded emission incorporating the carbon dioxide emitted with the production of grains/concentrates, hay, silage and fertilisers that are brought onto the farm.

The average total farm GHG emissions across the 41 farms was estimated to be 2,255 tonnes of carbon dioxide equivalents (t CO₂e), but varied between 411 and 9,416 t CO₂e. To compare farms within and across dairying regions, total farm GHG emissions were divided by annual milk production (milk solids), milking herd size and total farm area (including runoff/outblock areas in addition to milking platform), to calculate a milk GHG emissions intensity (t CO₂e/t MS), cow GHG emissions intensity (t CO₂e/cow) and area GHG emissions intensity (t CO₂e/ha). Karen found that there was a strong linear relationship between total farm GHG emissions and either milk production (Figure 2a) or milking herd size (Figure 2b), but not between total farm GHG emissions and farm size (Figure 2c).

Overall, the average milk GHG emissions intensity was 14.7 kg CO₂e/kg MS across all regions (Table 1). The average milk GHG emission for Tasmania was significantly (P<0.05) higher than all other regions, with the exception of Queensland, at 18.1 kg CO₂e/kg MS. The four Tasmanian dairy farms were predominantly pasture based with zero or very low levels of grain/concentrate feeding per cow and low milk production per cow at an average of 340 kg MS/cow. Previous research has shown that milk production per cow has a strong influence on the GHG emission intensity of milk production and these abovementioned points contributed to the higher mean GHG emissions intensity of milk production for Tasmania compared to all other regions.

The estimated average GHG emissions per cow was 6.3 t CO₂e/cow, with little variation between regions (Table 1), indicating that regional mean GHG emissions per cow were relatively consistent, irrespective of farm location. However, there was still quite some variation between farms within and across regions. The average GHG emissions per hectare was 7.7 t CO₂e/ha (Table 1), with noticeable variation between regions. Tasmania and to a lesser extent, south eastern Victoria, on
average, had a higher GHG emissions per hectare than the other regions as a result of these two regions generally possessing a higher stocking rate (cows/ha). Given the consistent GHG emissions per cow, this increased stocking rate resulted in greater GHG emissions per unit of land. The reverse was the case for regions with lower stocking rates (e.g. New South Wales, Queensland and Western Australia).

A stepwise linear regression analysis of key farm variables identified milk production per cow as a key farm variable driver influencing the GHG emissions intensity of milk production. Increasing in milk production per cow resulted in reductions in the GHG emission intensity of milk production (kg CO₂e/kg MS) and GHG emissions per hectare (t CO₂e/ha). Increasing milk production per hectare and increasing the application rate of nitrogen fertilisers (kg N/ha) were key farm variables that increased the GHG emissions per hectare. Identifying and adopting approaches that improve milk production per cow and/or improve nitrogen fertiliser efficiency are key areas to consider for GHG emissions mitigation, although it is very important that these strategies do not result in lowering farm profitability.

It is also important to note that the estimates of GHG emissions are derived by following the International Panel on Climate Change and Australian GHG inventory methodologies. It is currently not practically possible to directly measure the GHG emissions on all farms due to the significant amount of cost and technology required. Although the methodology used to estimate GHG emissions incorporates the most recent of scientific knowledge, there is still a significant amount of research being undertaken to provide a greater level of accuracy to GHG accounting on-farm.

This project was funded by TIAR, Dairy Australia and the Australian Government Department of Agriculture, Fisheries and Forestry through its Australia’s Farming Future Climate Change Research Program.

Contact: For more information on the A4N project, contact Dr Cameron Gourley on (03) 5624 2222 or Cameron.Gourley@dpi.vic.gov.au. For more information on this study, contact Karen Christie on (03) 6430 4921 or Karen.Christie@utas.edu.au or to view the DGAS calculator, visit the Dairying for Tomorrow website http://www.dairyingfortomorrow.com.au/index.php?id=47.

Table 1. Regional means and ranges of milk greenhouse gas emissions intensity (t CO₂e/t MS), cow greenhouse gas emissions intensity (t CO₂e/cow) and farm area greenhouse gas emissions intensity (t CO₂e/ha).

<table>
<thead>
<tr>
<th>Region</th>
<th>Milk GHG emissions intensity (t CO₂e/t MS)</th>
<th>Cow GHG emissions intensity (t CO₂e/cow)</th>
<th>Area GHG emissions intensity (t CO₂e/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>NSW</td>
<td>14.9b</td>
<td>12.0 – 18.7</td>
<td>6.8a</td>
</tr>
<tr>
<td>QLD</td>
<td>15.7ab</td>
<td>13.6 – 19.2</td>
<td>6.2a</td>
</tr>
<tr>
<td>SA</td>
<td>13.8b</td>
<td>12.1 – 15.0</td>
<td>6.8a</td>
</tr>
<tr>
<td>TAS</td>
<td>18.1a</td>
<td>14.4 – 22.7</td>
<td>6.0a</td>
</tr>
<tr>
<td>Nth VIC</td>
<td>13.2b</td>
<td>12.6 – 13.6</td>
<td>6.4a</td>
</tr>
<tr>
<td>SE VIC</td>
<td>14.0a</td>
<td>10.6 – 16.4</td>
<td>6.3a</td>
</tr>
<tr>
<td>SW VIC</td>
<td>13.0b</td>
<td>11.0 – 14.6</td>
<td>5.8a</td>
</tr>
<tr>
<td>WA</td>
<td>14.5b</td>
<td>13.1 – 15.4</td>
<td>6.1a</td>
</tr>
<tr>
<td>Overall</td>
<td>14.7</td>
<td>10.6 – 22.7</td>
<td>6.3</td>
</tr>
</tbody>
</table>
Superscript letters which differ indicate a significant (P<0.05) difference in greenhouse gas emissions intensity.

**Figure 1.** Location of the 44 farms involved in the Accounting for Nutrients project.

**Figure 2.** Linear relationship between total farm greenhouse gas emissions (t CO$_2$e/annum) and milk production (a; t MS/annum), milking herd size (b) and farm area (c; ha).
Appendix 15: Whole farm systems analysis of Australian dairy farms greenhouse gas emissions

Submitted to be published in the Animal Production Science journal in 2012

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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\textsubscript{2}e) 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\textsubscript{2}e/ 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 (CH₄) emissions from cows or nitrous oxide (N₂O) 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:

\[
DMD\% = \frac{ME + 1.037}{0.1604} \quad (Minson\ and\ McDonald\ 1987)
\]

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\textsubscript{4} and N\textsubscript{2}O 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:

\[
FPCM\ (kg) = raw\ milk\ (kg;\ litres \times 1.03\ \{Sevenster\ and\ de\ Jong\ 2008\}) \times (0.337 + (0.116 \times fat\ content\ (g/\ 100g\ milk)) + (0.06 \times protein\ content\ (g/\ 100g\ milk)) \quad (FAO\ 2010)
\]

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:

\[
Diesel\ (l) = 25.5 \times milk\ production\ (t\ MS/farm) + 5,500
\]

**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\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O emissions into CO\textsubscript{2} equivalent (CO\textsubscript{2}e) emissions, respectively (DCCEE 2009). The DGAS calculator incorporates the Australian NGGI methodology (DCCEE 2009) to estimate on-farm emissions (CH\textsubscript{4}, N\textsubscript{2}O and CO\textsubscript{2} from energy). In addition, the DGAS calculator also incorporates calculations of CH\textsubscript{4}, N\textsubscript{2}O and CO\textsubscript{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$_2$e 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$_2$e/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$_2$e/kg DM for lucerne hay, 0.25 kg CO$_2$e/kg DM for pasture and cereal hay and silage, and 0.30 kg CO$_2$e/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$_2$e) 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$_2$e/kWh, with an exception for Western Australia farms, where natural gas was selected with an emission factor of 0.5 kg CO$_2$e/kWh (DCCEE 2009). The extraction/refinement and consumption of diesel fuel by farm vehicles and machinery was equivalent to 3.4 kg CO$_2$e/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 etc) 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:

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

(4)

Where    $W_{ijk}$ = live weight (kg)
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LWG<sub>ijk</sub> = 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<sub>ijk</sub>; kg DM/head.day) is calculated as:

\[ MI_{ijk} = MP_{ijk} \times NE / (k \times q \times 18.4) \] (5)

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

\( NE = 3.054 \text{ MJ (net energy/kg milk)} \)

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

\( q = \text{metabolisability of the diet (0.00795} \times \text{ DMD}_{ijk} \times 100 - 0.0014); \text{ dry matter digestibility of diet expressed as a fraction of DM} \)

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<sub>ijk</sub>) is calculated as:

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

Where \( L \) is set to zero

The percentage of gross energy intake (GEI<sub>ijk</sub>%) that is yielded as enteric CH<sub>4</sub> (Y<sub>ijk</sub>) is calculated as:

\[ Y_{ijk} = 1.3 + 0.112 \times \text{DMD}_{ijk} \times 100 + L_{ijk} \times (2.37 - 0.050 \times \text{DMD}_{ijk} \times 100) \] (7)

Where \( \text{DMD}_{ijk} = \text{dry matter digestibility of diet expressed as a fraction of DM} \)

The total daily production of enteric CH<sub>4</sub> (M<sub>ijk</sub> enteric CH<sub>4</sub>; kg CH<sub>4</sub>/head.day) is calculated as:

\[ M_{ijk} \text{ enteric CH}_4 (\text{kg CH}_4/\text{head.day}) = (Y_{ijk} / 100) \times (\text{GEI}_{ijk} / F) \] (8)

Where \( \text{GEI}_{ijk} = I_{ijk} \times 18.4 \)

\( F = 55.22 \text{ (MJ/kg CH}_4; \text{ Brouwer 1965)} \)

From this, total enteric CH<sub>4</sub> production (Gg CH<sub>4</sub>/annum) is calculated as:

\[ \text{Total enteric CH}_4 \text{ production (Gg CH}_4/\text{annum}) = \sum (M_{ijk} \times N_{ijk} \times 365) \times 10^{-6} \] (9)

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

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<sub>4</sub>/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:

\[ VS_{ijk} = I_{ijk} \times (1 - \text{DMD}_{ijk} \times 100) \times (1 - A) \] (10)

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

\( \text{DMD}_{ijk} = \text{dry matter digestibility of diet expressed as a fraction of DM} \)

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

From this, daily animal waste CH<sub>4</sub> production (M<sub>ijk</sub> waste CH<sub>4</sub>; kg CH<sub>4</sub>/head.day) is calculated as:

\[ M_{ijk} \text{ waste CH}_4 (\text{kg CH}_4/\text{head.day}) = VS_{ijk} \times B_o \times \text{MCF} \times \rho \] (11)

Where \( B_o = \text{emission potential (0.24 m}^3/\text{ kg VS}) \)
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)

\( \rho = \text{density of methane (0.662 kg/m}^3\) 

From this, total animal waste \( \text{CH}_4 \) production (Gg \( \text{CH}_4/\text{annum} \)) is calculated as:

\[
\text{Total animal waste } \text{CH}_4 (\text{Gg } \text{CH}_4/\text{annum}) = \sum (M_{ijk} \times N_{ijk} \times 365) \times 10^{-6} \tag{12}
\]

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

**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 (\( \text{CPI}_{ijk}; \text{kg/head/day} \)) is calculated as:

\[
\text{CPI}_{ijk} (\text{kg/head/day}) = I_{ijk} \times \text{CP}_{ijk} \times 100 \tag{13}
\]

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

\( \text{CP}_{ijk} = \text{crude protein of the diet expressed as a fraction of DM} \)

The amount of N excreted in faeces (\( \text{F}_{ijk}; \text{kg/head/day} \)) is calculated as:

\[
\text{F}_{ijk} (\text{kg/head/day}) = (0.3 \times (\text{CPI}_{ijk} \times (1-[(\text{DMD}_{ijk} \times 100 + 10) / 100])) + 0.105 \times (\text{ME}_{ijk} \times I_{ijk} \times 0.008) + (0.0152 \times I_{ijk}) / 6.25 \tag{14}
\]

Where \( \text{DMD}_{ijk} = \text{dry matter digestibility of diet expressed as a fraction of DM} \)

\( \text{ME}_{ijk} = \text{Metabolisable energy (MJ/kg DM; calculated as 0.1604 \times \text{DMD}_{ijk} – 1.037; Minson and McDonald 1987)} \)

\( 1 / 6.25 = \text{factor for converting CP into N} \)

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

\[
\text{NR}_{ijk} (\text{kg/head/day}) = \{(0.032 \times \text{MP}_{ijk}) + (0.212 – 0.008 \times (L_{ijk} – 2) – [(0.140 – 0.008 \times (L_{ijk} – 2)) / (1 + \exp(-6 \times (Z_{ijk} – 0.4))))] \times (\text{LWG}_{ijk} \times 0.92) \} / 6.25 \tag{15}
\]

Where \( \text{MP}_{ijk} = \text{milk production (kg/head/day)} \)

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

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

\( \text{LWG}_{ijk} = \text{live weight gain (kg/day)} \)

Therefore N excreted in urine (\( \text{U}_{ijk}; \text{kg/head/day} \)) is calculated by subtracting \( \text{NR}_{ijk}, \text{F}_{ijk} \) and dermal protein loss from total N intake such as:

\[
\text{U}_{ijk} (\text{kg/head/day}) = (\text{CPI}_{ijk} / 6.25) – \text{NR}_{ijk} – \text{F}_{ijk} – [(1.1 \times 10^{-4} \times W_{ijk}^{0.75}) / 6.25 \tag{16}
\]

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

From this, total faeces (\( \text{AF}_{ijk}; \text{Gg N/annum} \)) and urinary (\( \text{AU}_{ijk}; \text{Gg N/annum} \)) N excreted is calculated as:

\[
\text{AF}_{ijk} (\text{Gg N/annum}) = \sum F_{ijk} \times N_{ijk} \times 365 \times 10^{-6} \tag{17}
\]

\[
\text{AU}_{ijk} (\text{Gg N/annum}) = \sum U_{ijk} \times N_{ijk} \times 365 \times 10^{-6} \tag{18}
\]
Where \( N_{ijk} \) = number of dairy cattle per state (i), stock class (j) and season (k)

The direct and indirect \( \text{N}_2\text{O} \) 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\(_2\)e/kg FPCM), cow intensity (t CO\(_2\)e/cow) and farm area intensity (t CO\(_2\)e/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\(_2\)e/annum ranging between 411 and 9,416 t CO\(_2\)e/annum (Table 3). There was substantial variation in the regional mean total farm GHG emissions, between a low of 1,184 t CO\(_2\)e/annum in Queensland and a high of 4,450 t CO\(_2\)e/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\(_2\)e/kg FPCM. The mean estimated GHG emissions intensity of milk production for Tasmania was 1.30 kg CO\(_2\)e/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\(_2\)e/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\(_2\)e/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\(_2\)e/kg FPCM while the GHG emissions intensity per cow also varied between 4.78 and 8.59 t CO\(_2\)e/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).

\[
\text{Total farm GHG emissions (t CO}_2\text{e/annum)} = 0.89 \times \text{annual milk production (t FPCM)} + 258.34; \quad R^2 = 0.95 
\]  
(19)

\[
\text{Total farm GHG emissions (t CO}_2\text{e/annum)} = 6.46 \times \text{milking herd size} - 41.81; \quad R^2 = 0.97 
\]  
(20)

\[
\text{Total farm GHG emissions (t CO}_2\text{e/annum)} = 3.97 \times \text{total farm area (ha)} + 911.73; \quad R^2 = 0.30 
\]  
(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\(_2\)O 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\(_2\)e/kg FPCM) and accounted for 0.70 of the variation (Table 5). The SMLR analysis showed that milk production per cow (kg CO\(_2\)e/kg FPCM) alone could explain 0.64 of the variation in emissions intensity per cow (t CO\(_2\)e/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\(_2\)e/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$_2$e/kg FPCM, compared to the FS2 and FS3 groups, at 0.98 and 0.97 kg CO$_2$e/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$_2$e/cow.annum, compared to the FS1 and FS3 groups, at 5.79 and 6.08 t CO$_2$e/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$_2$e/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$_2$e/kg FPCM compared to between 0.86 and 1.09 kg CO$_2$e/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$_2$e/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$_2$e/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$_2$e/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$_2$e/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$_2$e/kg milk, while Basset-Mens et al. (2005) found that the typical New Zealand dairy farm emitted 0.72 kg CO$_2$e/kg milk. Results from 23 conventional and organic farms in Sweden ranged between 0.90 and 1.04 kg CO$_2$e/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$_2$e/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$_2$e/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 that different methodologies, emissions factors and assumptions can have on the estimations. For example, the direct N$_2$O 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$_2$O emission factors for animal waste are also lower in Australia compared to other countries, with the result that direct N$_2$O emissions will be lower than indirect N$_2$O 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$_2$e/kg FPCM compared to a mean of 1.04 kg CO$_2$e/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 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 compared to FS2 and FS3 groups. 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 CH4 (Moe and Tyrrell 1979; Johnson and Johnson 1995; Boadi et al. 2004) and reduces enteric CH4 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 CO2e 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 CH4 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 CH4, 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 CH4 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 snapshot 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 CH4 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 CH4/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 CH4/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 CH4 emission of 27.3 g CH4/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, CH4 emissions were not significantly (P<0.05) different at 18.2 and 18.0 g CH4/kg DDMI. The Ulyatt et al. (2002a) study showed that diets with the same DMD% resulted in varied CH4 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.
Acknowledgements

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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.

<table>
<thead>
<tr>
<th>Farm area- total (ha)</th>
<th>Farm area- milking platform (ha)</th>
<th>Farm area- irrigated (ha)</th>
<th>Farm area- non-irrigated (ha)</th>
<th>Electricity (000’s kWh/year)</th>
<th>Diesel (000’s L/year)</th>
<th>N fertilizer (000’s kg N/year)</th>
<th>P fertilizer (000’s kg P/year)</th>
<th>K fertilizer (000’s kg K/year)</th>
<th>S fertilizer (000’s kg S/year)</th>
<th>Purchased concentrates (t DM/year)</th>
<th>Purchased forages (t DM/year)</th>
<th>Purchased other feeds (t DM/year)</th>
<th>Percentage of grain in the milking herd diet</th>
<th>Dieteral dry matter digestibility (%)</th>
<th>Feed conversion efficiency (litres of milk/kg DMI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>338.6 (67.3 – 1,045.6)</td>
<td>191.7 (52 – 460)</td>
<td>63.2 (0 – 329)</td>
<td>128.6 (3 – 460)</td>
<td>145.8 (27.2 – 1,023.1)</td>
<td>9.6 (6.2 – 25.4)</td>
<td>23.4 (0.0 – 154.3)</td>
<td>4.4 (0.0 – 25.1)</td>
<td>8.5 (0.0 – 64.4)</td>
<td>4.1 (0.0 – 26.0)</td>
<td>436.1 (19.9 – 2,336.6)</td>
<td>233.4 (0.0 – 1,788.7)</td>
<td>132.7 (0.0 – 2,375.9)</td>
<td>22.3 (0 – 57.4)</td>
<td>74.5 (68.9 – 78.9)</td>
<td>1.04 (0.55 – 1.56)</td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th>Source</th>
<th>Equation and emission factors to estimate N₂O losses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct</strong></td>
<td></td>
</tr>
<tr>
<td>Faeces excreted onto pastures</td>
<td>0.005 x faeces N x % faeces deposited onto pastures during grazing</td>
</tr>
<tr>
<td>Urine excreted onto pastures</td>
<td>0.004 x urinary N x % urine deposited onto pastures during grazing</td>
</tr>
<tr>
<td>Stored waste</td>
<td>0.001 x sum of faeces &amp; urinary N x % faeces and urinary N stored in lagoons and as liquid/slurry^A</td>
</tr>
<tr>
<td>Spread stored waste</td>
<td>0.01 x (faeces &amp; urinary N stored – N₂O lost during the storage phase – N₂O lost through volatilisation)</td>
</tr>
<tr>
<td>N fertiliser applications</td>
<td>(0.004 x N fertiliser applied to pastures) and (0.003 x N fertiliser applied to crops)</td>
</tr>
<tr>
<td><strong>Indirect</strong></td>
<td></td>
</tr>
<tr>
<td>Volatilisation (faeces and urine)</td>
<td>0.01 x ((% faeces &amp; urinary N deposited onto pastures x 0.2) + (% faeces &amp; urinary N stored in lagoon x 0.35) + (% faeces &amp; urinary N stored as liquid/slurry x 0.4) + (% faeces &amp; urinary N spread daily x 0.07))</td>
</tr>
<tr>
<td>Volatilisation (N fertiliser)</td>
<td>0.1 x 0.01 x sum N in fertiliser applied to pastures &amp; crops</td>
</tr>
<tr>
<td>Leaching/runoff (faeces and urine)</td>
<td>0.3 x 0.0125 x (faeces N + urinary N + spread and stored waste N)</td>
</tr>
<tr>
<td>Leaching/runoff (fertiliser)</td>
<td>0.3 x 0.0125 x sum N in fertiliser applied to pastures &amp; crops</td>
</tr>
</tbody>
</table>

^Faeces and urine stored and spread daily is also classified as stored waste, however this source of waste does not emit N₂O during the storage phase, only the spreading phase, and therefore is not a source of stored N₂O emissions.
Table 3. Regional means and ranges of total farm greenhouse gas emissions (t CO$_2$e/annum) and greenhouse gas emissions intensities (kg CO$_2$e/kg fat and protein corrected milk (FPCM); t CO$_2$e/cow; t CO$_2$e/ha).

<table>
<thead>
<tr>
<th>Number of farms</th>
<th>Total farm GHG emissions</th>
<th>Greenhouse gas emissions intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t CO$_2$e/annum</td>
<td>kg CO$_2$e/kg FPCM</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>NSW</td>
<td>9</td>
<td>1,723$^{bc}$</td>
</tr>
<tr>
<td>QLD</td>
<td>4</td>
<td>1,184$^c$</td>
</tr>
<tr>
<td>SA</td>
<td>3</td>
<td>4,450$^d$</td>
</tr>
<tr>
<td>TAS</td>
<td>4</td>
<td>3,645$^{ab}$</td>
</tr>
<tr>
<td>Nth VIC</td>
<td>3</td>
<td>2,521$^{abc}$</td>
</tr>
<tr>
<td>SE VIC</td>
<td>10</td>
<td>1,993$^{bc}$</td>
</tr>
<tr>
<td>SW VIC</td>
<td>3</td>
<td>1,639$^{bc}$</td>
</tr>
<tr>
<td>WA</td>
<td>5</td>
<td>2,373$^{abc}$</td>
</tr>
<tr>
<td>Mean</td>
<td>41</td>
<td>2,255</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Source of greenhouse gas emission</th>
<th>NSW</th>
<th>QLD</th>
<th>SA</th>
<th>TAS</th>
<th>Nth VIC</th>
<th>SE VIC</th>
<th>SW VIC</th>
<th>WA</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enteric CH(_4) (%)</td>
<td>54.4</td>
<td>56.6</td>
<td>49.8</td>
<td>55.3</td>
<td>55.2</td>
<td>56.4</td>
<td>56.2</td>
<td>57.8</td>
<td>55.5</td>
</tr>
<tr>
<td>CO(_2) from fuel &amp; electricity (%)</td>
<td>11.5</td>
<td>10.8</td>
<td>12.7</td>
<td>10.9</td>
<td>8.6</td>
<td>8.8</td>
<td>8.1</td>
<td>5.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Indirect N(_2)O from animal waste(^a) (%)</td>
<td>8.2</td>
<td>7.5</td>
<td>7.5</td>
<td>9.3</td>
<td>7.6</td>
<td>8.9</td>
<td>7.6</td>
<td>9.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Direct N(_2)O from animal waste(^a) (%)</td>
<td>6.4</td>
<td>6.0</td>
<td>5.9</td>
<td>7.2</td>
<td>5.9</td>
<td>6.9</td>
<td>5.9</td>
<td>7.4</td>
<td>6.6</td>
</tr>
<tr>
<td>CO(_2) from purchased grains/concentrates (%)</td>
<td>6.8</td>
<td>7.2</td>
<td>6.9</td>
<td>2.3</td>
<td>5.6</td>
<td>5.3</td>
<td>8.7</td>
<td>6.1</td>
<td>6.0</td>
</tr>
<tr>
<td>CH(_4) from animal waste (%)</td>
<td>5.1</td>
<td>3.8</td>
<td>7.1</td>
<td>4.7</td>
<td>4.8</td>
<td>5.1</td>
<td>5.3</td>
<td>2.3</td>
<td>4.7</td>
</tr>
<tr>
<td>CO(_2) from purchased fertilisers (%)</td>
<td>1.9</td>
<td>3.0</td>
<td>2.4</td>
<td>4.0</td>
<td>1.0</td>
<td>3.0</td>
<td>3.2</td>
<td>5.0</td>
<td>2.9</td>
</tr>
<tr>
<td>CO(_2) from purchased forage (%)</td>
<td>3.0</td>
<td>0.1</td>
<td>5.0</td>
<td>1.2</td>
<td>10.1</td>
<td>1.6</td>
<td>0.9</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Indirect N(_2)O from N fertilisers (%)</td>
<td>1.4</td>
<td>2.8</td>
<td>1.5</td>
<td>2.7</td>
<td>0.7</td>
<td>2.2</td>
<td>2.3</td>
<td>3.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Direct N(_2)O from N fertilisers (%)</td>
<td>1.2</td>
<td>2.3</td>
<td>1.3</td>
<td>2.3</td>
<td>0.6</td>
<td>1.9</td>
<td>1.9</td>
<td>2.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\(^a\)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$_2$/kg fat and protein corrected milk; FPCM), cow intensity (t CO$_2$/cow.annum) and area intensity (t CO$_2$/ha.annum), where $b$ is the unstandardized coefficient, $SE\ b$ is the standard error of $b$, $\beta$ is the standardized coefficient and $R^2$ is the coefficient of determination.

<table>
<thead>
<tr>
<th></th>
<th>$b$</th>
<th>$SE\ b$</th>
<th>$\beta$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Milk intensity (kg CO$_2$/kg FPCM)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>1.685</td>
<td>0.069</td>
<td>-1.0E-04</td>
<td>-1.1E-05</td>
</tr>
<tr>
<td>Milk production (kg FPCM/cow.lactation)</td>
<td>-1.0E-04</td>
<td>1.1E-05</td>
<td>-0.835***</td>
<td>0.698</td>
</tr>
<tr>
<td><strong>Cow intensity (t CO$_2$/cow.annum)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>3.572</td>
<td>0.342</td>
<td>0.799***</td>
<td>0.639</td>
</tr>
<tr>
<td>Milk production (kg FPCM/cow.lactation)</td>
<td>4.4E-04</td>
<td>5.3E-05</td>
<td>0.799***</td>
<td>0.639</td>
</tr>
<tr>
<td>Step 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>3.633</td>
<td>0.326</td>
<td>0.677***</td>
<td>0.682</td>
</tr>
<tr>
<td>Milk production (kg FPCM/cow.lactation)</td>
<td>3.8E-04</td>
<td>5.9E-05</td>
<td>0.677***</td>
<td>0.682</td>
</tr>
<tr>
<td>Grain feeding (% grain in milker diet)</td>
<td>0.016</td>
<td>7.2E-03</td>
<td>0.240*</td>
<td></td>
</tr>
<tr>
<td><strong>Area intensity (t CO$_2$/ha.annum)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.974</td>
<td>0.461</td>
<td>0.935***</td>
<td>0.875</td>
</tr>
<tr>
<td>Milk production (t FPCM/ha.annum)</td>
<td>0.887</td>
<td>0.054</td>
<td>0.935***</td>
<td>0.875</td>
</tr>
<tr>
<td>Step 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>5.300</td>
<td>0.631</td>
<td>1.038***</td>
<td>0.951</td>
</tr>
<tr>
<td>Milk production (t FPCM/ha.annum)</td>
<td>0.985</td>
<td>0.036</td>
<td>1.038***</td>
<td>0.951</td>
</tr>
<tr>
<td>Milk production (kg FPCM/cow.lactation)</td>
<td>-8.1E-04</td>
<td>1.1E-04</td>
<td>-0.295***</td>
<td>0.951</td>
</tr>
<tr>
<td>Step 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>4.581</td>
<td>0.593</td>
<td>0.969***</td>
<td>0.963</td>
</tr>
<tr>
<td>Milk production (t FPCM/ha.annum)</td>
<td>0.919</td>
<td>0.037</td>
<td>0.969***</td>
<td>0.963</td>
</tr>
<tr>
<td>Milk production (kg FPCM/cow.lactation)</td>
<td>-7.0E0.4</td>
<td>9.7E-05</td>
<td>-0.256***</td>
<td>0.963</td>
</tr>
<tr>
<td>Nitrogen fertiliser (kg N/ha.annum)</td>
<td>7.3E-03</td>
<td>2.1E-03</td>
<td>0.128**</td>
<td></td>
</tr>
</tbody>
</table>

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$_2$/kg fat and protein corrected milk (FPCM); t CO$_2$/cow.annum; t CO$_2$/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).

<table>
<thead>
<tr>
<th>Greenhouse gas emissions intensity</th>
<th>kg CO$_2$/kg FPCM</th>
<th>t CO$_2$/cow.annum</th>
<th>t CO$_2$/ha.annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1</td>
<td>1.23</td>
<td>5.79</td>
<td>8.21</td>
</tr>
<tr>
<td>FS2</td>
<td>0.98</td>
<td>6.78</td>
<td>7.67</td>
</tr>
<tr>
<td>FS3</td>
<td>0.97</td>
<td>6.08</td>
<td>7.37</td>
</tr>
</tbody>
</table>

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$_2$e/kg fat and protein corrected milk; A), per cow (t CO$_2$e/cow; B) and per hectare (t CO$_2$e/ha; C) for individual farms.

**Fig 2.** Cumulative distribution function of the greenhouse gas emissions intensity of milk production (kg CO$_2$e/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).
Appendix 16: Improvements/alterations to the Dairy Greenhouse gas Abatement Strategies (DGAS) calculator

There have been many improvements and changes made to the DGAS calculator since the release of version 1.2 in 2009. These changes/improvements have been undertaken during the duration of this project and are listed below (in no particular order):

1. Inclusion of the current version and date of release in the top right corner of the introduction page.
2. Changes to manure CH\(_4\) emissions due to changes to the manure methane conversion factor (MCF) for milking and non-milking dairy cattle. These changes will affect all farms and locations and therefore the overall results for all farm systems. Users can either define the actual farm management practices for the farm being assessed (preferred method) or use the previous MMS1 - Pasture-based system factors (less preferred method). We introduced this option of User estimated as it more accurately reflects how manure is handled on individual farms, as opposed to the previous default state-based averages. The User can now define the amount of time spent in the dairy and on feedpad and/or loafing areas where manure is deposited and then handled. This data is used to estimate the MCF for the milking herd and for all other stock classes in addition to estimating the amount of waste handled by up to five different manure management systems (i.e daily spread, lagoon, dry lot, solids storage and voided onto pastures during grazing). We suggest users refer to the section titled manure management in this manual (page 18) when familiarising themselves with this updated version as they need to access two new data entry pages for the milking herd and other stock classes and implement the copying of the baseline data to the strategy farm via a different mechanism than for copying all other data from the baseline farm to the strategy farm.
3. Changes to indirect N\(_2\)O emissions for fertilisers and animal wastes. After discussions with Dr Richard Eckard (methodology expert), it was clear that the risk of leaching/runoff of N fertilisers applied to dryland pastures/crops and animal waste was too low for some regions, especially NSW, QLD, SA and WA. Increases will also occur for VIC and TAS but to a lesser extent as these states already had high emission factors for this source of indirect N\(_2\)O emissions. Therefore for all farms and all locations, the indirect N\(_2\)O emission will increase due to the changes in DGAS version 1.3. Therefore we suggest when reporting any results, that it is made clear that the version of DGAS used to estimate GHG emissions is version 1.3.
4. Change in the equation to calculate enteric CH\(_4\) for non-milking herd stock classes, resulting in a slight reduction in enteric CH\(_4\) for non-milking stock.
5. Incorrect emission factor for phosphorus-based fertilisers fixed. This will increase the pre-farm fertiliser GHG emissions for farms with phosphorus fertiliser applications.
6. Fixed the radio button option for fertiliser application rates so that the user can use kg/ha for the baseline farm and tonnes/annum for the strategy farm. Previously you needed to use one or the other for baseline and strategy farm.
7. In the Fats and Oils strategy help message- reduced the percentage of reduction in CH\(_4\) from 5.6 to 3.5% for every 1% increase in dietary fat fed in the diet. Fats and oils can now only be fed during summer and autumn as the fat content of pastures are generally high in winter and spring, thus restricting the potential of this as an option during winter and spring.
8. Altered when condensed tannins is a viable abatement strategy to now only be winter and/or spring as opposed to year-round as in previous versions of DGAS. This has due to this strategy only being suitable when diets contain excess crude protein. Implementing the condensed tannin strategy in winter and/or spring will reduce CH\(_4\) emissions by 10% in the activated seasons. Activating this strategy will also reduce the CP content of the diet to 18%, thus replicating the process by which tannins bind excess protein in the diet from being excreted as urine N. If however, the diet is already < 18%, there will be no change to the diet and
therefore N₂O emissions as in reality, feeding a diet with < 18% CP in addition to feeding a source of condensed tannin could result in a CP deficit.

9. Added a new nitrification inhibitor strategy for spraying the inhibitor onto pastures directly after grazing, with a default 40% seasonal reduction in urine, dung and manure N for direct and indirect leached N₂O emissions. Differences in the % reduction in N₂O emissions between the direct and indirect animal waste are due to different emission factors applied to these two sources.

10. Users define the percentage of annual fertiliser that is coated with a nitrification inhibitor and effective in reducing N₂O emissions.

11. Separated indirect N₂O emissions from N fertilisers and indirect N₂O emissions from animal waste. Also added this to the Ad-hoc calculator so can assess the impact of a reduction on these two sources independently.

12. Included the sheets and cells linked to the abatement strategies at the base of the backdrop sheet for any future reference.

13. Greater information in this manual and in the help messages in DGAS regarding abatement strategies and the things to be considered when adopting the strategies. For example, when feeding dietary fats, has the user considered any changes to diet quality and/or milk production and made manual changes to DGAS to reflect these impacts?

14. As each form is opened by progressing through DGAS, the forms remain maximised to the size of the user’s monitor.

15. Additional help messages for farm area and electricity and fuel consumption, with unleaded petrol to be included with diesel consumption.

16. Coding to check that the daily diet intake is within an expected range of the estimated intake required to achieve the annual milk production and/or the live weight and live weight gain for the replacements. Users have the option to either accept that their data entry is correct or can re-check and change data entry if an error has been made.

17. Coding to check that diet intakes are filled out for all 4 seasons for the milking herd. Also if stock numbers for replacements and/or bulls are entered, that the diet intakes are also filled out, otherwise incorrect estimations can occur if no annual digestibility and crude protein figures are determined. A message will appear when progressing to the results page indicating which areas need filling in.

18. Altered the layout of the results page by moving the bar chart to the bottom of the page, altering the chart to be a column graph, colour coded the column and pie charts so that all sub-sources are the same colour (i.e. all 4 N₂O emissions are blue, CH₄ are yellow), the baseline farm results is a solid column and the strategy results is a faded/hashed column, re-worded some of the source headings to be more reflective of the source.

19. Removed the Save Results button from the results page – removed due to complications with saving formulas and formatting between workbooks. We recommend that the User can either print the results and/or save a new copy of DGAS using the ‘SAVE DGAS AS’ option.

20. Altered the ETS liability to now read CH₄ & N₂O only figure to the table of results for the Baseline and Strategy farm. This is due to the changes to the government policy in regards to the Australian emissions trading scheme since the last DGAS release.

21. Added a button to hide/unhide the Ad-hoc calculator when not in use.

22. Altered the economics page to reflect the more recent policy changes regarding agriculture, emissions trading and carbon credits. Farmers may now have the opportunity to gain carbon credits for management practices that meet the rigorous requirements under the Carbon Farming Initiative (CFI). It is not clear if the abatement strategies currently available in DGAS will meet the requirements of the CFI in terms of additionality, permanence, avoidance of leakage, measurable and verifiable, scientifically sound and meets international consistency. The economics calculations also do not take into consideration the additional costs in terms of time required to meet the requirements needed on-farm to meet methodology requirements.
Therefore the economics page should still be used with a high degree of caution when reporting to farmers the economic benefits of adopting abatement strategies, especially in light of carbon policies.

23. General tidying up of headings, data entry, greater explanation for some of the help messages etc.

24. Data entry sheet included as an appendix in manual to use when collecting data from farmers.
Appendix 17: Development of the Carbon Offsets Scenario Tool (COST) calculator

Throughout this project the priorities for the dairy industry in terms of mitigating their GHG emissions has changed. In 2010, the Australian Federal Government proposed a cap-and-trade emissions trading scheme called the Carbon Pollution Reduction Scheme (CPRS). Due to a lack of bipartisan support, the CPRS was not legislated. However, a new emissions trading scheme, the Clean Energy Future Plan, was legislated in 2011 and to be implemented in 2012. One component of the Clean Energy Future Plan was a shift in the focus from agriculture being a sectoral source of GHG emissions, and thus requiring ‘taxing’ of a proportion of their GHG emissions (as proposed with the CPRS), to agriculture being a sector of the economy that could implement practices that achieve mitigation and gain financial incentive to do so. To facilitate this, the Carbon Farming Initiative (CFI) was the proposed mechanism within the Clean Energy Bill for assisting agricultural farmers and land managers to obtain carbon offset credits by sequestering carbon on-farm or by reducing/avoiding on-farm GHG emissions. These carbon credits could then be tradable, allowing for other high carbon polluting industries (e.g. electricity companies) to offset their GHG emissions.

In 2011 the TIA project team were approached by this projects’ Dairy Australia steering committee member to assist Dairy Australia in developing a list of standard practices for the Department of Agriculture, Fisheries and Forestry (DAFF) in formulating farm practices that could be included as methodologies that qualify for the ‘additionality’ requirements in the CFI. These farm practices were broadly grouped into the 3 broad themes of nutrients and effluent, pasture management and herd and dairy shed practices. For each theme, current farm practices were described and a list of potential mitigation strategies identified as they relate to each of the five Dairy Australia defined farming systems (FS). For example, FS1 farms currently are predominantly pasture-based with a low amount of grain supplement per cow (i.e. < 1 t DM/cow.lactation). Therefore a potential mitigation strategy for these farms could be to supplement the pasture feedbase with a source of supplements high in dietary fats/oils to lower methane production. This strategy is less likely to be relevant for FS5 farms where a large proportion of their diet is through supplements and thus might not meet the ‘additionality’ requirement in the CFI.

In addition to assisting Dairy Australia to formulate this list of farm practices and potential mitigation strategies, the TIA team were also asked by this projects’ Dairy Australia steering committee member to develop a tool to explore the viability of a range of mitigation strategies that could be potentially included as CFI offsets. The MS Office Excel spreadsheet Carbon Offset Scenarios Tool (COST) calculator was developed and expanded the three abovementioned themes and potential mitigation options provided to DAFF into four theme areas. These were herd and breeding management, diet management, feedbase management and waste management (Figure 1). Within each theme area, mitigation strategies were identified and at the time of finalising the final report, seven individual mitigation strategies had been identified and incorporated into the COST calculator (Figure 1). However, several more have been identified (e.g. improved reproductive performance, manure digesters to reduce the amount of stored animal waste in lagoons; listed in italics in Figure 1) and these will be incorporated into the COST calculator into the future. In addition, as science progresses and/or the CFI encourages the development of new technologies to reduce and/or remove on-farm GHG emissions, these too will be incorporated into the COST calculator.
Whole Farm Systems Analysis of Climate Change Impacts on the Southern Grazing Industries

**Figure 1.** Schematic diagram of the four broad theme areas and individual mitigation strategies currently incorporated into the COST calculators for reducing on-farm dairy greenhouse gas emissions (*italics strategies are to be incorporated into the calculator at a later date*).

Within the COST calculator, each mitigation strategy has four main data entry/calculation sections (highlighted in green, pink, purple and blue; Figure 2). The first section (highlighted in green) relates to the baseline farm system which allows the COST calculator to estimate the baseline farm GHG emissions associated with the milking herd, based on currently agreed NGGI methodology. These questions varied between mitigation strategies to estimate the baseline on-farm GHG emissions. For example, to estimate the baseline emissions for supplementing with dietary fats/oils, the questions related to milking herd size, average live weight of the milking herd (kg/cow), current average milk production per cow (litres/cow.day), and diet digestibility and crude protein concentration (%). In contrast, the only key question to estimate the baseline GHG emissions for the mitigation strategy of coapplying nitrogen fertilisers with a nitrification inhibitor was the amount of nitrogen fertiliser applied to pastures (t nitrogen/annum).

**Figure 2.** Schematic diagram illustrating the abatement strategy of replacing a supplement with a low fat content with another supplement with a higher fat content, the four main data entry/calculation sections and the specific questions needed to estimate the GHG emissions reduction associated with the mitigation strategy and potential farm profit as associated with the Carbon Farming Initiative.
The second section (highlighted in pink; Figure 2) in each COST mitigation strategy are key questions as they relate to either the estimation of reduction in GHG emissions or the likely change in expenses and income associated with implementing the mitigation strategy in combination with the CFI. For some mitigation strategies there are many aspects that need to be considered while for others, there are only a few questions required to estimate the reduction in GHG emissions and the changes to income and expenses associated with the mitigation strategy. For example, the mitigation strategy of applying a nitrification inhibitor to urine patches only has five specific questions. These questions relate to the proportion of urine deposited onto pastures, the number of days per year that the nitrification inhibitor is effective, the efficacy of the nitrification inhibitor (i.e. % reduction in urinary N with the strategy), the cost of implementing the strategy (i.e. $/cow) and the on-farm income received with the CFI ($/t CO₂).

In contrast, the example of a mitigation strategy of replacing one supplement lower in dietary fats/oils with another supplement higher in dietary fats/oils has many specific questions. Given that the diet quality and quantity will change with this strategy, users need to estimate the fat concentration of the baseline diet (%), the quantity (kg DM/cow.day) and quality (digestibility and fat %) of supplement to be replaced, the cost of the supplement to be replaced ($/t DM), the quantity (kg DM/cow.day) and quality (digestibility and fat %) of the new higher fat supplement to be fed, the cost of the new higher fat supplement to be fed ($/t DM) and the number of days per annum that the new higher fat supplement will be fed. Within the COST calculator, an estimation of the change in diet energy is estimated with this energy assumed to be converted into additional milk production (i.e. an extra litre of milk/ 5.5 MJ of Metabolisable energy). Therefore within this section, users are also required to estimate the average annual price received for milk ($/litre) and the price received for milk ($/litre) when the mitigation strategy is implemented as milk prices could be different and thus influence income from any additional milk when the mitigation strategy is implemented. The last question is an estimation of the on-farm income received with the CFI ($/t CO₂).

The third section in the COST calculator (highlighted in purple; Figure 2) gives users an indication of changes to non-GHG related aspects of the mitigation strategy. For example, in the mitigation strategy of replacing a low dietary fat source with a supplement with a higher concentration of dietary fats/oils, it is critical that users understand that the dietary fat concentration should not exceed 6 to 7% as milk depression can occur with diets above this level. Therefore with this mitigation strategy, users can view how the manipulation of the baseline diet with additional dietary fat alters the overall diet fat concentration. If users implement a supplement which is either too high in dietary fat concentration or too much supplement is replaced, a warning message informs users to reconsider the diet. An estimation of the additional milk produced per cow (litres/cow.day) and per farm (litres/farm) is also indicated.

The last section in the COST calculator (highlighted in blue; Figure 2) is a summary table indicating the reduction (t CO₂e/annum). For most mitigation strategies currently in the COST calculator, there is a reduction in GHG emissions (reported as a positive number) but in the case of the improved diet quality through supplementation mitigation strategy, enteric methane could increase due to increased intakes (reported as a negative number as it’s a negative reduction in GHG emissions. Other results in the summary table are the potential CFI income ($/farm), the cost to implement the mitigation strategy ($/farm), the change in income associated with the mitigation strategy assuming no change to milk production ($/farm), the estimated additional income from milk production associated with the mitigation strategy ($/farm), the estimated change in income associated with the mitigation strategy taking into consideration the income from the CFI and from milk production ($/farm), an estimation of what proportion of total income from milk production and the CFI is attributed to the CFI (%) and an estimation of the change in milk GHG emissions intensity (kg CO₂e/litre of milk) associated with implementing the mitigation strategy. In addition to the summary section, a graph to the right of the mitigation strategy illustrates income from the CFI ($/farm), the
cost to implement the mitigation strategy ($/farm), any additional income from additional milk production ($/farm) and the total farm income benefit of implementing the mitigation strategy ($/farm) (Figure 2).

An example of the COST calculator can be seen in Figure 3 where the impact of replacing a supplement with low dietary fat concentration (i.e. 2.5%) with a supplement with a higher dietary fat concentration (i.e. 18.0%) would have on enteric methane production. For this farm example, GHG emissions were reduced by 22.7 t CO₂e/annum, giving a potential CFI return of $340 to the farm, based on a carbon price of $15/t CO₂e. To implement this offset method, an additional outlay of $4,793 would be required to purchase the higher fat concentration supplement. This high fat supplement was predicted to increase milk production by approximately 28,000 litres for the 90 days it was fed, thus increasing milk income by $11,740. The increase in milk production in this example was driven by the relatively higher digestibility (75% DMD) of the high fat supplement compared to the baseline supplement (65% DMD) that was being replaced. Taking into account the income from the CFI and from the additional milk minus the cost of implementing the mitigation offset, this offset strategy was predicted to have a net increase in income of $7,288/annum. This COST calculator will most likely be incorporated in DGAS in 2012 so that a full farm assessment (i.e. impact on pre-farm, methane and nitrous oxide emissions) of a CFI offset methodology can be explored. A full farm systems analysis is critical as changes to diet quality (as explored in the above mentioned example) could also alter the crude protein concentration of the diet, thus altering the nitrous oxide emissions.

![Figure 3](image.png)