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Systems analysis to quantify the role of farm management in GHG emissions and sinks for pastoral sector

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Contents

A. Executive Summary

Building knowledge, understanding, tools and capability to support NZ pastoral farmers understand the systems level productivity, environmental and economic impacts of adopting GHG mitigation strategies has been the key objective of this project. The opportunities and implications of management changes on the farming system, total and intensity of GHG emissions have been explored across dairy and mixed livestock sectors. Component models have been compared, validated and further developed, while the principles underpinning life cycle assessment tools have been strengthened and systems compared. Finally together with farmer groups, the project has explored the 'practical feasibility' of current low emissions intensity farming systems and investigated aspects of the farmer management style and capability in the success of these businesses.

Objective 1 considered both dairy and sheep and beef systems. Modelling results of dairy systems indicate that GHG mitigation does not necessarily have to implicate a reduction in milk production and profitability. It is suggested that production and profitability can be maintained, or even increased, by designing more efficient systems based on a 5-point plan that includes reduced N fertiliser use (together with using nitrification inhibitors), reduced stocking rate but with higher genetic merit cows and getting the best out of each cow, reduced replacement rate that cuts costs and environmental footprint from replacement stock, growing or importing high-energy low-protein grain feed that boosts the high genetic merit cows in the second half of lactation and also reduces urinary-N excreted, and removing a part of the urinary-N from the paddocks by standing cows on a loafing pad during critical times like late-summer and autumn. The key to success is to implement all five strategies because of the synergies between them. However, if all five cannot be implemented for some reason, then key leverage points are N fertiliser use, stocking rate and cow genetic merit. Questions remaining are the effectiveness of this plan across dairy systems with different levels of imported feed, the potential practical difficulties e.g. controlling pasture quality with low stocking rate, and the costs of implementing the plan.

Four farm systems, representing both intensive and extensive North and South Island sheep and beef farms, based on Beef + LambNZ Economic Service farm survey data, were used for the analysis. Every 10% increase in breeding-ewe weaning % can reduce total farm GHG emissions by 1% and reduce its emissions intensity by 3%, while at the same time increasing the farm gross margin by 6%. These effects were generally consistent across all farm types, but the strength of the response also depends on the farm's ratio of sheep:cattle:deer. This mitigation strategy showed the clearest benefits, and can readily be adopted as weaning % is a measure of reproduction efficiency that farmers are already familiar with and generally strive to improve. Increasing the proportion of trading/dairy-heifer cattle in the system as opposed to breeding cows also reduced total farm emissions and emissions intensity. Changing from an entirely breeding system (where all non-replacement cattle were sold at weaning) to an entirely trading system (where weaned calves were purchased and finished for slaughter) could reduce total emissions by 1-12% and emissions intensity by 11-31%, while changes that just increase the proportion of trading/dairy-heifer cattle in the system rather than eliminating breeding cows have a proportionally smaller effect. The actual result varied considerably between farms and again was strongly influenced by the particular farm's ratio of sheep:cattle:deer. Moving to more trading cattle is also generally profitable, but does entail

greater financial risk than breeding. This is a strategy that is also worth consideration by farmers.

Decreasing the breeding-ewe replacement rate had little effect on GHG emissions, although it did improve farm profitability. This strategy may be adopted for financial reasons, but had no merit from a GHG perspective in this analysis.

Overall, the results demonstrated that it is possible for farmers to reduce both total emissions and emissions intensity on a wide range of sheep and beef farm types through changes in farm management, while improving profitability. Emissions intensity can be reduced more readily than total emissions. The magnitude of the reductions is small for an individual farm, but when adopted on a large number of farms could make a significant contribution to New Zealand's total emissions liability given the high proportion of GHG emissions that originate from agriculture.

Objective 2 was closely linked to New Zealand Agricultural Greenhouse gas Research Centre (NZAGRC) projects, the screening of denitrification and gaseous N emission models in the literature resulted in a selection of potential models of which the sub-models will be integrated into a farm systems model such as the Agricultural Production System Simulator (APSIM). It was demonstrated how the strengths of a dairy systems model, the Whole Farm Model (WFM) can be combined with the strengths of a detailed soil model (water-nitrogen-carbon) in APSIM to predict nitrogen leaching on paddock and farm scale while considering individual urine patches. The incorporation of gaseous N sub-models into APSIM (like the NEMIS model) will provide more capabilities to simulate GHG emissions from dairy systems. An alternative approach of using WFM in combination with segregated emission factors for N_2O was also demonstrated. However, this approach should be seen as an intermediate step between inventory calculations (e.g. Overseer) and full mechanistic predictions (e.g. WFM+APSIM). The latest version of the Molly cow model (version 8.5) in the DairyNZ Whole Farm Model was found to have the capability to predict CH_4 production of pasture fed dairy cows with acceptable accuracy with the majority of prediction error apportioned to unexplained random bias in the observed data from respiration chambers. Improvements to Molly's digestive parameters contributed to this, and there is a further opportunity to increase the accuracy by incorporating three different pools of rumen microbes.

In Objective 3, Life Cycle Assessment (LCA) models for dairy and sheep and beef farm systems were updated and developed to account for all off-farm factors and recent changes in methodology and emission factors. The models were used in collaboration with international researchers from Sweden for dairying and France for sheep farm systems. That evaluation revealed a large effect of methodology on carbon footprint value and that where the same models were used the New Zealand farm systems had a lower carbon footprint than their European counterparts. The dairy LCA model was then applied across contrasting New Zealand dairy farm systems with different levels of intensification due to increased farm inputs and particularly the level of brought-in feed. This was based on a survey of Waikato dairy farm systems and showed little difference between the farm systems in carbon footprint i.e. total greenhouse gas emissions per kg milk. Effects of various management and mitigation options were also examined across these farm systems and showed a reduction of up to 10% in carbon footprint, with different levels of reduction for different options depending on the farm system. This illustrates that optimal strategies for carbon footprint reduction will vary across different farm systems.

In Objective 4, farmer groups identified farmers running systems already achieving low emissions intensity, commonly with systems which the wider community considered complex and not easy to replicate. The surveyed farmers were all strong strategic planners who had set long term goals that fitted their own farming philosophy. These farmers intuitively made decisions on farm, an approach that was strongly based on their own prior experiences and active learning on farm, as well as engagement in information networks. The survey participants had well defined ideas of what the land and animals were capable of producing for them with the resources available and were confident of working within these boundaries to achieve productivity goals. All of the farmers were achieving high productivity without forcing their systems. It was difficult within this small number of case studies to identify specific actions or decision rules that the case study farmers used that differentiated them significantly from their farming peers. However, it appears that they were efficient at farming all components of their systems, rather than only some elements.

The project has developed both depth and breadth in understanding and information on the role of components and elements of the farming system in GHG emissions across the key pastoral sectors. The life cycle assessment tools have been updated and developed to meet current and future industry needs. Component model validation, calibration and development progress must be considered along with the progress in the NZAGRC funded projects; further development is required. The development of capability and linkages in using existing tools in a platform to explore impacts of farm management on GHG has been a key success of this project leading to cross sector and cross agency contribution to all aspects of the research. The links to farmer groups and modelling of current farming systems has enabled an industry perspective to be maintained across the project and contributed to depth of analysis.

B. Objective 1.1 Farm Systems and GHG

We will understand the impacts of changing farm management practices and farm inputs on GHG emissions/soil carbon, farm profitability and production in dairy, sheep and beef and deer sectors. We will know the components of the farming systems which have the most leverage on GHG emissions and soil carbon changes.

1.1. DAIRY FARMING SYSTEMS

1.1.1 International literature review

A literature review of the use of versatile farm simulation models for estimating GHG/soil carbon was undertaken. The conclusion was that New Zealand is in a good position regarding system level prediction of enteric CH_4 for the dairy industry because the DairyNZ WFM includes a dynamic and mechanistic dairy cow model (Molly) that predicts CH_4 giving proper consideration to herd structure (age, breed, live weight, genetic merit) affecting individual intakes, and giving consideration to changes in diet quality affected by seasonal pasture quality changes and imported supplements. The WFM is linked to the APSIM framework that predicts N cycling in the soil and therefore N leached and gaseous losses. There is good progress in incorporating a module in APSIM that distinguishes between N_2 and N_2O losses. This will be an important step towards a full mechanistic estimation of GHG emissions from dairy farms. Big gaps in our models are emissions from effluent capture and storage facilities and soil carbon storage and release. See Appendix 1 for the full report.

1.1.2 Describing representative farms from different sectors

A typical Waikato dairy farm was described in the DairyNZ WFM in an attempt to address the question regarding the potential reduction in GHG emissions on a dairy farm if currently available and practical mitigation strategies were implemented. The strategies included in this modelling exercise were selected after a thorough review of potential leverage points within these systems and the role of farm management in these, including interviews with experts, by Groundworks Consultancy (Annie Perkins) in a project for PGGRC. The five selected strategies were also debated and approved by the DairyNZ science team: 1) reducing the mineral N fertiliser use and replacing some with nitrification inhibitor and gibberellins, 2) reducing stocking rate and increasing cow genetic merit, 3) improving reproductive performance, reducing empty rate and replacement rate, 4) growing on-farm or import energy-dense, low crude protein grain feed to reduce N intake, get more days in milk and increase body condition of high genetic merit cows, 5) using stand-off strategies to remove urinary-N from paddocks during certain critical times of the year. The modelling showed that GHG emissions on a typical Waikato dairy farm can be reduced by 30% if these five strategies can be implemented and if the milk production is maintained at the level before mitigation (i.e. same as the baseline). The mitigated farm can be expected to be more profitable compared to the baseline because of greater efficiencies. In another modelling exercise the aim was to find potential GHG reduction but with an increase in milk production of 12%. Results showed a potential reduction in GHG emissions of 24% and an increase in profitability of 33%. See Appendices 2 and 3 for the paper references and abstracts.

1.1.3 Farming systems analysis

In a study as part of the fulfilment of the requirements for MPhil (University of Waikato) Alfredo Adler (Research Technician, Modelling Team, DairyNZ) is modelling New Zealand dairy farm systems to design greenhouse gas mitigation strategies. The study is looking at dairy farm systems from both an environmental and economic point of view with the two approaches having similar bearing on the objectives. When the project is completed (thesis submission planned for March 2013) a full range of representative dairy farming systems across different NZ regions will have been analysed using systems modelling, including each of the currently available and most practical mitigation options identified for the dairy sector. Greenhouse gas outputs, together with production and profitability, will be recorded, and results will be used to identify the most efficient mitigations strategies for NZ dairy farms. The study has four objectives: 1) To describe representative farms (baseline) for different farming systems and regions across NZ, 2) To identify practical and currently available GHG mitigation options for these representative farms, 3) To analyse the different farming systems using computer modelling (Farmax/linear programming (LP)/Overseer) to predict production, profitability and GHG emissions from the baseline farms when a restriction in GHG emissions is implemented (potential profit loss) and when mitigation strategies are implemented (GHG mitigation potential), and 4) Analysis of results to identify the most cost-effective mitigation strategies.

In order to describe the actual current situation (baseline), typical farm systems were modelled across six regions of NZ for production, profitability and GHG emissions using the Farmax Dairy Pro model and Overseer. Traditionally NZ dairy systems have been categorized into 5 classes according to level and timing of imported supplementary feeding. However, due to time constraints in this study, systems 1 and 2 are merged to represent a low-input system, and systems 4 and 5 are merged to represent a high-input system. These three farming systems were modelled for the Northland, Waikato/Bay of Plenty, Taranaki, Lower North Island, Canterbury and Southland regions. DairyBase (www.dairybase.co.nz) is a database used for benchmarking purposes by storing physical and financial data for individual New Zealand dairy farms. DairyBase was used to define representative values for these 14 different farm situations (baseline farms; some regions only have two typical systems and not all three). Farmax Dairy Pro was used to model the farm systems for profitability. The environmental implications of different production decisions simulated in Farmax Dairy Pro were estimated using the Overseer model. Once the baseline farms were described using these models, the impacts of different mitigation strategies on GHG emissions and profitability was simulated using a non-linear programming (NLP) optimisation model. See Appendix 4 for an abstract of a manuscript submitted to Journal of Dairy Science describing the development of this NLP model.

A variety of mitigation options is explored: 1)Reduce replacement rate to reduce the proportion of non-productive animals in the herd, 2) Introduce crops and/or pasture species able to capture N and/or reduce emission by modifying rumen environment and/or increase intake potential by providing energy dense feed at certain times of the year, 3) Improved effluent management and introduction of standing off strategy for part of the year, 4) Reduced N fertilizer and increasing its efficiency by incorporating DCD and gibberellins, 5) Production per cow by manipulating genetic merit, stocking rate, feeding per cow and days in milk.

The following sequence is applied to each of the 14 baseline farm situations. Once each baseline farm (BL) is defined and modelled with Farmax, an optimized version for profitability is generated using the NLP model (BLOpt). This version (BLOpt) is used as the new baseline to provide the reference point for comparison. The next step is to optimize the BL farm for profitability when a GHG emission restriction (10% cap) is applied (BLCap) to determine the cost of imposing the cap on farms in terms of potential profit loss. After that, the mitigation strategies are applied to the BL farm while maintaining the cap and then optimized for profitability (BLCap+Strategies). Finally, an optimized situation is generated by withdrawing the cap but maintaining the strategies available to maximize profit (BLOpt+strategies). The two unrestricted versions (BLOpt and BLOpt+strategies) are compared in terms of GHG emission per ha and per unit of product (intensity) to see what the results are of using the efficiency gain provided by the mitigation strategies to increase profit. The two restricted versions (BLCap and BLCap+strategies) are compared to show the effect of mitigation strategies on profitability when an emissions cap is introduced.

At the time of writing this report the modelling work for Waikato and Canterbury regions have been completed. The Waikato work has been documented as a conference paper (NZSAP 2012, see Appendix 5 for an abstract of this paper), but will also be submitted as a peer-reviewed paper. Two further peer-reviewed papers are planned, one on the Canterbury results and one combining the results for the Northland, Taranaki, Lower North Island and Southland regions.

1.1.4 Identification of leverage points for soil carbon/GHG

The work under objective 1.1.3 indicated that for the Waikato region N fertiliser, stocking rate, cow genetic merit and replacement rate are important leverage points for GHG mitigation. A reduction in N fertiliser from 120 to 50 kg/ha (58%) achieved a 10% reduction in emissions while a reduction in stocking rate from 3.1 to 2.8 (10%) also achieved a 10% reduction in GHG. A 10% cap on GHG emissions resulted in a decrease of 8% in profitability if no mitigation strategies were implemented, but an increase in genetic merit and milk yield per cow from 330 to 345 kg MS/year resulted in a 5% increase in profitability. See Appendix 5 for the abstract of a paper accepted for publication in the Proceedings of the New Zealand Society of Animal Production Conference 2012. It is anticipated that three peer-reviewed papers and an MPhil thesis (University of Waikato) will be submitted by March 2013 as a result of this work.

1.1 SHEEP, BEEF AND DEER FARMING SYSTEMS

Agriculture is a major contributor to New Zealand's greenhouse gas (GHG) emissions, primarily through the production of methane (CH_4) from ruminant livestock, but also through the production of nitrous oxide (N_2O) from agricultural soils. Farmers presently have limited 'tools' that they can directly apply to reduce these emissions. There are farm system changes that can improve farm production efficiency and also potentially reduce GHG emission levels, but currently it is unknown which ones will have the greatest leverage across a wide range of 'typical' New Zealand sheep and beef farm systems. This report looks at three key management changes which hold considerable promise for reducing GHG emissions on sheep and beef farms, and determines their likely impact on farm profitability and GHG emissions levels for a wide range of 'typical' New Zealand sheep and beef farms.

It is difficult at present to reduce total agricultural GHG emissions. The primary N_2O mitigation technology currently available is the nitrification inhibitor dicyandiamide (DCD), which can help to reduce N_2O emissions from agricultural soils. A wide range of mitigation approaches are also being researched to reduce CH_4 emissions from individual farm animals (Waghorn, 2011). However, as yet none are commercially available for practical on farm use. As the largest single component, we must address CH_4 emissions to markedly reduce New Zealand's total agriculture GHG emissions.

As CH_4 is produced when ingested feed is fermented in the rumen of farmed livestock (e.g. sheep, cattle, and deer), total CH_4 emissions are roughly proportional to the quantity of feed consumed on individual farms. This makes it difficult to reduce total CH_4 emissions without reducing the amount of feed consumed, and therefore the total number of animals that can be carried on a farm. Using such an approach to reduce GHG emissions would potentially reduce both the productivity and profitability of many current farm systems, with negative financial consequences for both individual farmers and the wider economy.

It is however possible to reduce the intensity of CH_4 emissions, in other words the quantity of CH_4 emitted per kilogram of product produced (e.g. meat or wool). For example, a steer that is growing rapidly consumes feed and produces CH_4 as it digests this feed. Some of the feed it consumes in order to survive (this is called its maintenance feed intake), while the remainder is used to grow - in other words, to produce meat or fibre that can be sold. On the other hand, a breeding bull consumes a large amount of feed just in order to survive (i.e. for maintenance), but it is already at its mature weight and does not grow through the year. It therefore produces no product that can be sold.

A farm that was entirely stocked with growing steers would produce a lot more meat for every unit of CH_4 that was produced than a farm that was stocked entirely with breeding bulls. The steer farm would have a lower GHG emissions intensity (i.e. emissions per unit of product produced) than the breeding bull farm. They would however both have similar total annual GHG emissions if they grew, and their livestock consumed, a similar total amount of feed.

While neither of these farms may be entirely realistic, they illustrate that different classes of livestock have different emissions intensities, even if they have similar total annual CH_4 emissions. This means we can reduce the emissions intensity from a real farm by adjusting the proportion of different livestock classes on that farm. We must do this in a realistic fashion - we cannot eliminate all breeding animals and just have growing ones for instance. However we can make small, realistic adjustments to farm management strategies that result in real improvements in the GHG emissions intensity of a farm.

Several components of a farm system are known to influence its overall GHG emissions intensity (Cruickshank et al. 2009; Dynes et al. 2011; Ludemann et al. 2011; Waghorn 2011). However, the extent to which these components can alter it is not well understood, especially at the whole farm system level and across a wide range of typical New Zealand farming systems. This report looks in detail at three practical aspects of farm management that could decrease a farm's GHG emission intensity and quantifies the actual changes in total emissions, emissions intensity, and profitability that can be achieved when using them across a wide range of New Zealand sheep and beef farming systems.

METHODOLOGY

There are a wide range of different sheep, beef and deer farming systems in New Zealand. This study first investigated the potential to use existing classification systems for different farming systems to determine which data and systems to model. The Beef + LambNZ farm classes were selected as suitable to identify farm systems that were representative of a large number of New Zealand farms and data was available for average, low and high production systems.

Four farm classes were selected:

Class 2: South Island Hill Country (representing 850 farms nationwide)
Class 3: North Island Hard Hill Country (representing 1155 farms)
Class 5: North Island Intensive Finishing (representing 1590 farms)
Class 6: South Island Breeding/Finishing (representing 2825 farms)

These four farm classes represent an estimated 6,420 farms out of a total of 12,700 farms in the country, and feature an extensive breeding system and an intensive finishing system from both the South Island and North Island (B+LNZ, 2012).

For each of these classes, two farms were modelled, to give a broad range in systems performance - an average farm (Av) (based on B+LNZ farm survey data), and a farm performing in the bottom 10% in terms of its gross margin per hectare (source B+LNZ Economic Service) were modelled, giving a total of eight baseline farms. The lower performing farms may partly represent farms on which there is a high potential that management improvements could improve profitability. However, they may also represent farms that have poorer natural resources than an average farm, resulting in its profitability being limited by the environment rather than poor management. It is impossible to separate these two factors using the available farm survey data.

The biophysical characteristics of the representative farms were modelled in Farmax Pro (White et al. 2010) and Overseer® (Wheeler et al. 2003), to estimate their production outputs, profitability, and GHG emissions. These 'baseline' farms were then each altered to investigate how several types and levels of farm management efficiency measures may alter the whole farm system and affect the productivity, profitability and GHG emissions of the farms. These changes may also impact on a farm's soil carbon (C) status. However, this pathway was not investigated further owing to the lack of a suitable available model for New Zealand environmental conditions.

The three management factors adjusted for each of the farms were chosen based on an earlier study by Duchemin (2011):

- **Breeding-ewe weaning percentage:** This is a factor that many farmers continually strive to increase for profitability reasons. It may be altered primarily through improved genetics and feeding levels. There is a large difference in weaning percentages between the bottom 10% and class average farms in this dataset, indicating the potential for improvement on at least some properties. A higher weaning percentage increases the amount of lambs (and therefore meat product) produced per breeding ewe.

- **Breeding-ewe replacement rates:** This represents the number of replacement ewe hoggets entering the breeding-ewe flock. A high breeding-ewe replacement rate indicates that the ewes are not lasting for many years in the flock before being culled. A range of ewe replacement rates exist on farms, as ewe longevity is affected by a number of factors (for instance feed type over winter). It is often possible to increase ewe longevity and reduce the number of replacements required. Hoggets that must be kept for replacements cannot be sold as lambs, reducing the quantity of lambs sold per breeding ewe. The total amount of meat sold may however be offset to some extent by selling cull ewes.

- **The proportion of breeding versus trading and dairy-heifer grazing cattle:** Breeding cattle were defined as cows, beef-heifer replacements, and breeding bulls; whereas, trading cattle and dairy-heifers were defined as all other cattle on the farm, irrespective if they were bred on-farm or purchased. The proportion of trading cattle can be reduced by selling more of the breeding herd's progeny as store stock at weaning, or alternatively can be increased by purchasing additional calves from other farms, making it feasible to consider altering the ratio of breeding:trading&dairy-heifer grazing cattle on a particular property. For farms carrying dairy-heifer grazers, their baseline ratio of trading:dairy-heifer grazers was also kept the same for all alternative scenarios. Breeding cows, replacement beef-heifers, and breeding bulls must be maintained all year, producing CH_4 emissions, while it is only the progeny from the breeding cow enterprise that directly contribute to farm outputs. In contrast, trading cattle are growing and producing saleable meat the entire time they are on the property. This means there are lower maintenance CH_4 emissions from trading cattle than breeding cattle.

Each of the eight baseline farms was modelled with changes separately made to each of the above factors. The specific changes are described in detail below:

- Breeding-ewe weaning percentage was increased by 10, 20 and 30% for each farm (so a farm with 95% weaning was also modelled at 105, 115 and 125%).

- Breeding-ewe replacement rate was reduced by 3, 6 or 9% (so a farm with a 27% replacement rate was also modelled at 24, 21 and 18%).

- The proportion of the total cattle stock units (CSU) that were carried over winter were adjusted so that 0%, 50%, or 100% were trading&dairy-heifer cattle. Any other cattle carried over winter were breeding cattle.

After each change was made, the number of livestock of that species on the farm was adjusted to consume approximately the same amount of feed as the baseline farm. For example, when the breeding-ewe weaning percentage was increased, the total number of sheep was reduced to compensate for the increased feed demand from the additional lambs.

The baseline farms and their 9 alternative scenarios were modelled in Overseer® to determine the CH_4 and N_2O emissions under each management system. The total annual GHG emissions produced per hectare (kg CO_2-e/ha), intensity of emissions measured as kg CO_2-e/kg net product grown, and the farm gross margin per ha ($/ha) were compared across the range of efficiency measures tested, to determine how much influence each measure had on these attributes. For the purpose of calculating GHG emissions intensity, "product" was the sum of the total quantity of carcass weight grown on the farm (whether or not it was sold in that year), and the total quantity of wool produced.

RESULTS AND DISCUSSION

Baseline farm data

The biophysical characteristics of the baseline farms used in this study are presented in Tables 1-3. Table 1 covers management and general information, including the current values for weaning percentage (%) and ewe replacement rate. Table 2 presents the actual numbers of livestock in each class on each property. Table 3 presents data on the quantity of product sold, finances, and GHG emissions.

The effective area of the baseline farms ranged from 269 to 3312 hectares (ha), depending on the farm class (Table 1). The Class 2 lower 10% (10%) performance farm is almost twice the size of the Class 2 average farm, suggesting that biophysical limitations may have a large bearing on which South Island hill country farms have been rated as having a low profitability per ha (if large land areas are required to make an economic unit, the land is likely to be poorer and have lower potential yields on these properties). This emphasises the fact that the lower 10% farms do not necessarily represent poorly managed units, but both management and physical resources are likely to be factors.

The total GHG emissions per ha also vary greatly between farms, ranging from 787 - 3658 kg/ha (Table 3). The total emissions generally reflect the stocking rate of the farm (in stock units per ha) and the total pasture production per hectare (Table 1), demonstrating the close link between the largest single contributing GHG gas (CH_4) and the total amount of feed consumed per ha.

Table 1: Baseline farm characteristics for each average (Av) and lower 10% (L10%) modelled by B+LNZ farm class

Farm class	Class 2Av	Class 2L10%	Class 3Av	Class 3L10%	Class 6Av	Class 6L10%	Class 5Av	Class 5L10%
Effective area (ha)	1599	3312	791	645	450	622	273	269
Feed supply (kg DM/ha)[1]:								
Pasture	2418	1161	5220	3556	5422	3712	6280	5034
Forage crops & supplements	226	72	47	58	742	441	396	363
Stock units wintered[2]	7300 (4.6)	7182 (2.2)	7405 (9.4)	4477 (6.9)	4927 (10.9)	4514 (7.3)	3096 (11.3)	2597 (9.7)
Sheep:Cattle:Deer	74:26:0	78:22:0	69:31:0	65:35:0	80:17:3	79:21:0	54:46:0	71:29:0
Feed eaten (kg DM/ha)[3]	2457	1115	5031	3423	6011	4014	6485	5202
Sheep:								
% feed supply eaten	69	74	65	60	76	73	50	64
% hoggets successfully mated	-	-	-	-	30	-	50	-
Lamb weaning %	118	95	117	90	130	127	125	100
Lamb weaning live weight (kg)	25.4	23.3	24.1	22.8	29.4	29.2	29.3	26.4
% of lambs sold prime	54	32	48	30	83	70	82	70
Lamb carcass weight (kg)	17.0	17.2	16.7	16.5	17.0	16.6	17.2	16.6
Wool sold (kg/SSU)	4.5	5.0	4.2	4.1	3.9	3.7	4.4	4.4
Ewe replacements (% of flock)	27	24	29	32	24	26	25	19
Cattle:								
% feed supply eaten	31	26	35	40	21	27	50	36
Calf weaning %	84	76	84	76	84	75	86	79
Calf weaning live weight (kg)	238	210	210	200	238	215	237	237
% weaners sold store	10	17	-	5	-	-	-	-
% wintered trading/grazers	31	22	26	24	32	45	77	66
Cow replacements (% of herd)	17	10	21	18	13	11	17	20
Deer:								
% feed supply eaten	-	-	-	-	3	-	-	-
Calf weaning %	-	-	-	-	80	-	-	-
Calf weaning liveweight (kg)	-	-	-	-	64	-	-	-
% of weaners sold store	-	-	-	-	0	-	-	-
Velvet sold (kg/DSU)	-	-	-	-	0.03	-	-	-
Hind replacements (% of herd)	-	-	-	-	16	-	-	-

[1]At 10.8 MJ ME/kg DM. [2]Stock units per ha given in parentheses. [3] Estimated from Farmax feed budget assuming 10.8 MJ ME/kg DM eaten.

Table 2: Baseline livestock numbers wintered for each modelled B+LNZ farm class (average (Av) lower 10% (L10%).

Farm class	Class 2Av		Class 2L10%		Class 3Av		Class 3L10%		Class 6Av		Class 6L10%		Class 5Av		Class 5L10%	
	Head	**SU[1]**	**Head**	**SU**	**Head**	**SU**	**Head**	**SU**	**Head**	**SU**	**Head**	**SU**	**Head**	**SU**	**Head**	**SU**
Sheep:		5390		5577		5130		2899		3955		3574		1674		1850
MA ewes	3600	4140	3950	3950	3200	3680	1850	1758	2500	3250	2300	2875	1000	1200	1225	1286
Replacement ewe hoggets	1000	1000	951	951	1000	1000	657	657	630	630	600	600	261	261	240	240
Finishing hoggets	200	200	241	241	400	400	450	450	35	35	63	63	198	198	304	304
Wethers	-	-	550	385	-	-	-	-	0	-	0	-	-	-	-	-
Breeding rams	50	50	50	50	50	50	34	34	40	40	36	36	15	15	20	20
Cattle:		1911		1605		2275		1579		809		940		1422		747
MA cows	175	1050	150	900	165	990	130	780	60	360	61	366	35	210	30	180
2Yr-old heifers	0	-	31	140	76	342	46	207	18	81	11	50	10	45	6	27
1Yr-old heifers	59	207	48	168	86	301	51	179	26	91	23	81	16	56	12	42
2Yr-old steers/bulls	35	175	33	165	54	270	40	200	13	65	29	145	111	608	54	270
1Yr-old steers/bulls	106	424	47	188	82	328	45	180	25	100	23	92	123	492	27	108
Breeding bulls	10	55	8	44	8	44	6	33	3	17	3	17	2	11	1	6
1Yr-old dairy-heifer grazers	-	-	-	-	-	-	-	-	50	95	100	190	-	-	60	114
Deer:	-	-	-	-	-	-	-	-	-	164	-	-	-	-	-	-
MA hinds	-	-	-	-	-	-	-	-	-	105	-	-	-	-	-	-
1Yr-old hinds	-	-	-	-	-	-	-	-	-	24	-	-	-	-	-	-
1Yr-old stags	-	-	-	-	-	-	-	-	-	28	-	-	-	-	-	-
Breeding stags	-	-	-	-	-	-	-	-	-	7	-	-	-	-	-	-

[1]SU, equivalent stock units (Lincoln University Farm Technical Manual 2003).

Table 3: Baseline farm production indices for each modelled B+LNZ farm class . (average (Av) lower 10% (L10%).

Farm class	Class 2Av	Class 2L10%	Class 3Av	Class 3L10%	Class 6Av	Class 6L10%	Class 5Av	Class 5L10%
Product sold (kg/ha/yr):								
Meat	66.9	24.4	124.7	73.8	162.2	101.1	321.6	172.0
Fibre	16.5	8.8	28.6	19.1	41.2	25.7	31.5	33.7
Net product grown (kg/ha/yr):								
Meat	63.0	23.3	122.7	73.0	174.64	115.0	239.1	146.8
Fibre	16.5	8.8	28.6	19.1	41.3	25.7	30.7	31.7
Total	79.5	32.1	151.3	92.0	215.9	140.7	269.7	178.5
Feed conversion efficiency:								
kg DM eaten/kg CW sold	36.7	45.7	40.4	46.4	37.1	39.7	20.2	30.3
kg DM eaten/kg net product grown	30.9	34.7	33.3	37.2	27.8	28.5	24.0	29.1
Financial ($):								
Revenue/ha	256	111	511	307	764	470	929	600
Variable costs/ha	119	56	172	130	297	192	358	219
Gross margin/ha	137	55	339	177	467	278	571	381
Gross margin/SU wintered	30	26	36	25	43	38	50	40
Feed costs (% Expenditure)	36	32	9	11	44	43	46	30
Animal costs (% Expenditure)	27	29	37	35	22	24	21	30
GHG emissions (kg CO_2-e):								
Total GHG/ha	1618	787	3658	2528	3628	2499	3541	3136
Total GHG/SU wintered	354	363	391	364	331	344	312	325
GHG/kg CW sold	24.2	32.3	29.3	34.3	22.4	24.7	11.0	18.2
GHG/kg net product grown	20.4	24.5	24.2	27.5	16.8	17.8	13.1	17.6
GHG/kg DM eaten	0.66	0.71	0.73	0.74	0.60	0.62	0.55	0.60

Breeding-ewe weaning percentage

Figures 1-6 present the impact of changing the farm's breeding-ewe weaning percentage (%) on farm GHG emissions and profitability.

Figure 1 presents the effect of increasing the breeding-ewe weaning % on total GHG emissions per ha. Each baseline farm is plotted along with their three alternative weaning % scenarios. In general, total GHG emissions decreased by between 9 and 37 kg CO_2-e/ha/yr for every 10% increase in breeding-weaning %. Compared to the total GHG emissions per ha of the baseline farms, this rate of change, although moving in the right direction, is relatively small, and over the range of breeding-ewe weaning percentages tested, resulted in at most a 3% reduction in total emissions.

The very wide range of total GHG emissions per ha for each of the baseline farms, and the resulting scale used on the vertical axis of Figure 1, make it difficult to see many of the marginal trends. As an alternative, Figure 2 presents the same relationship but with the response (GHG emissions per ha) and predictor (weaning %) variables converted to % baseline farm values. When pooled across all of the farms, total farm GHG emissions per ha decreased by 1% of baseline levels for every 10% increase in breeding-ewe weaning % (Figure 2). The rate of reduction in GHG emissions was lowest for the North Island Class 5Av and Class 3L10% farms, and greatest for the South Island classes 2 and 6 (Figure 2).

Increasing the breeding-ewe weaning % had a greater effect on reducing the GHG emission intensity than on the total emissions of the farms, decreasing the former by 5 to10% over the range of weaning percentages tested (Figure 3). When pooled across the farms, the GHG emissions intensity decreased by 3% of baseline levels for every 10% increase in breeding ewe weaning % (Figure 4). This finding is in agreement with the trend found previously by Duchemin (2011) when comparing a large number of commercial farms with differing weaning percentages.

For all of the modelled farms, increasing the breeding-ewe weaning % decreased the total number of stock units (SU) that were carried on the farm over winter, but at the same time increased the total net product grown on the farm (as lamb carcass net growth), thus increasing the feed conversion efficiency of the sheep enterprise (kg dry matter eaten/kg net product grown) – in other words, more net product is grown as lambs and less non-productive sheep (e.g. ewes and replacement hoggets) are carried through the year.

There was a smaller reduction in GHG emission intensity with increasing breeding-ewe weaning % for Class5Av, followed by Class 5L10% and Class 3L10% model farms (Figure 4). The remainder of the farm classes performed similarly to each other. This was likely influenced by the ratio of sheep:cattle:deer on each farm. In comparison to the other farm classes, Class 5Av sheep make up a smaller proportion of the total SU carried on the farm and as such they consume a much smaller percentage of the total feed supply (Table 1). Thus, because the sheep enterprise only converts a small proportion of the farm's total feed resources into product, increasing its efficiency has a smaller impact on the farm's total production efficiency and GHG emissions.

Increasing the breeding-ewe weaning % caused the farm gross margin per ha (GM/ha) to increase by between 7% and 23% over the ranges tested (Figure 5). When pooled across all of the farms, the total farm GM/ha increased by 6% of baseline levels for every 10% increase in breeding-ewe weaning % (Figure 6). The primary reason for this was an increase in the total sales of sheep, at little or no extra cost, with a higher weaning %.

The increase in GM/ha with increasing breeding ewe weaning % was particularly marked for Class 2Av and 2L10% models, followed in order by: Class 6Av and L10% models; Class 3Av, L10% and Class 5%L10% models; with Class5Av having the lowest response (Figures 5 and 6). Again, the strength of the response is likely strongly influenced by the sheep:cattle:deer ratio of the particular farm and also its associated primary outputs (e.g. meat, wool, velvet). For Class 2, 3, 6 and 5%L10% farms the sheep enterprise was the largest enterprise on the farm, with slaughter and store sales from this enterprise generating the most revenue.

Overall, increasing the breeding-ewe weaning % of a farm reduced its GHG emissions intensity while improving its profitability. However, using this reproduction efficiency measure, very large increases in weaning % will be required to markedly reduce a farm's total GHG emissions per ha.

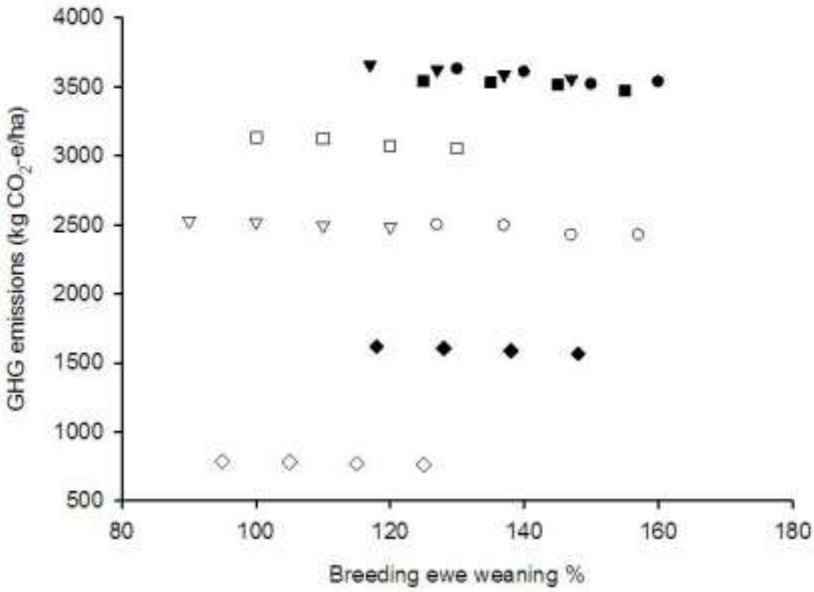

Figure 1: Annual farm GHG emissions over a range of breeding-ewe weaning rates (WR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

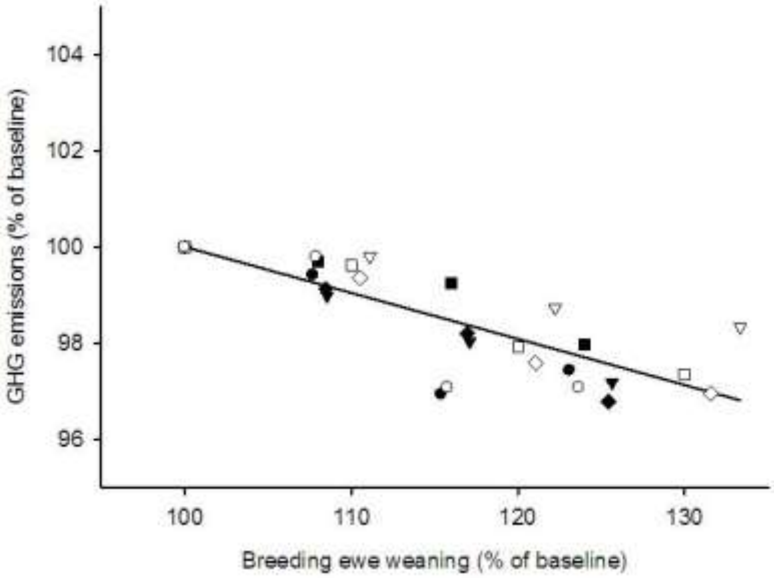

Figure 2: Annual farm GHG emissions over a range of breeding ewe weaning rates (WR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 109.6 (1.2) – 0.1 (0.01)*WR, $r^2 = 0.73$, RMSE= 0.6253, $P<0.001$; Standard errors of regression parameters given in parentheses.

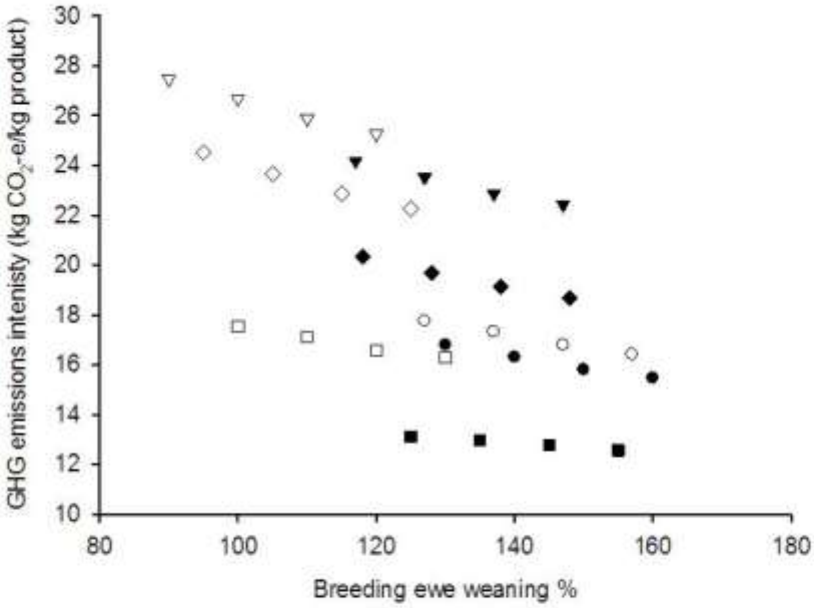

Figure 3: Farm GHG emissions intensity per kg of product over a range of breeding ewe weaning rates (WR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

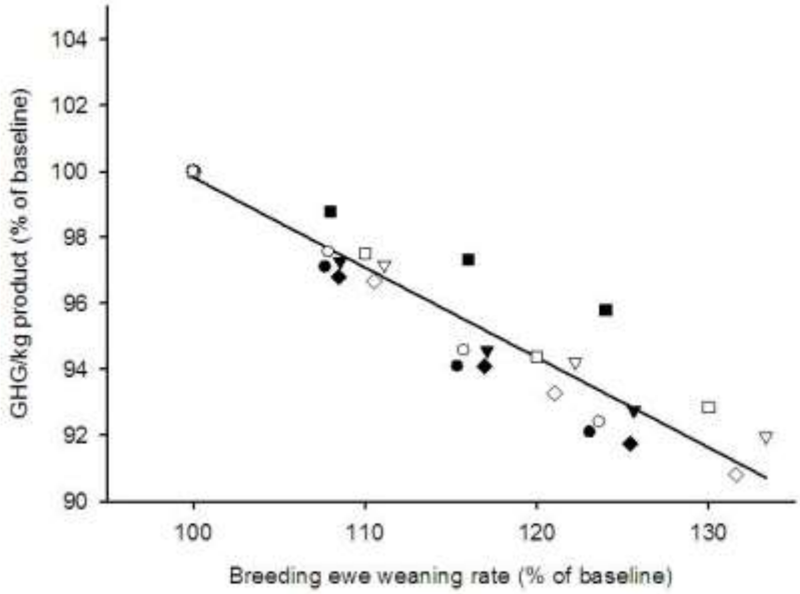

Figure 4: Farm GHG emissions intensity per kg of product over a range of breeding ewe weaning rates (WR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 127.1 (1.8) – 0.3 (0.02)*WR, $r^2 = 0.91$, RMSE=0.9293, P<0.0001; Standard errors of regression parameters given in parentheses.

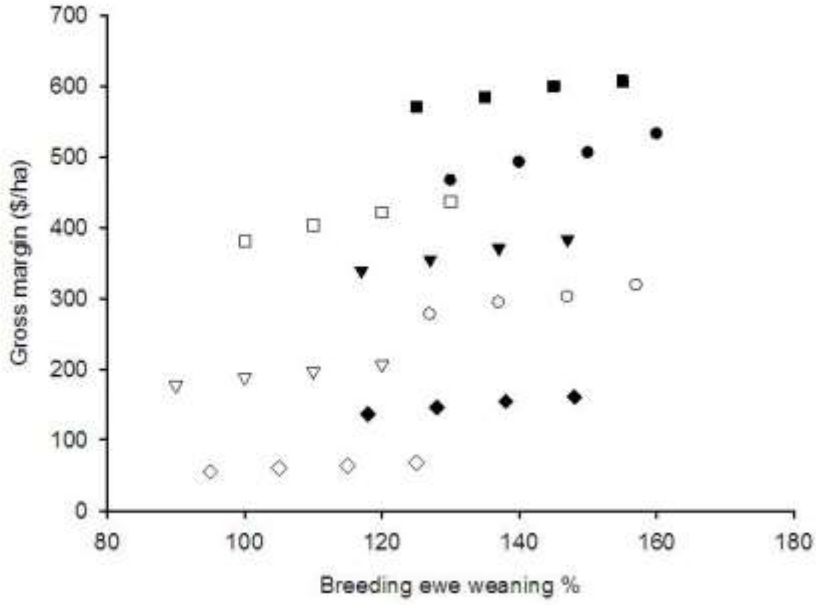

Figure 5: Farm gross margin over a range of breeding ewe weaning rates (WR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

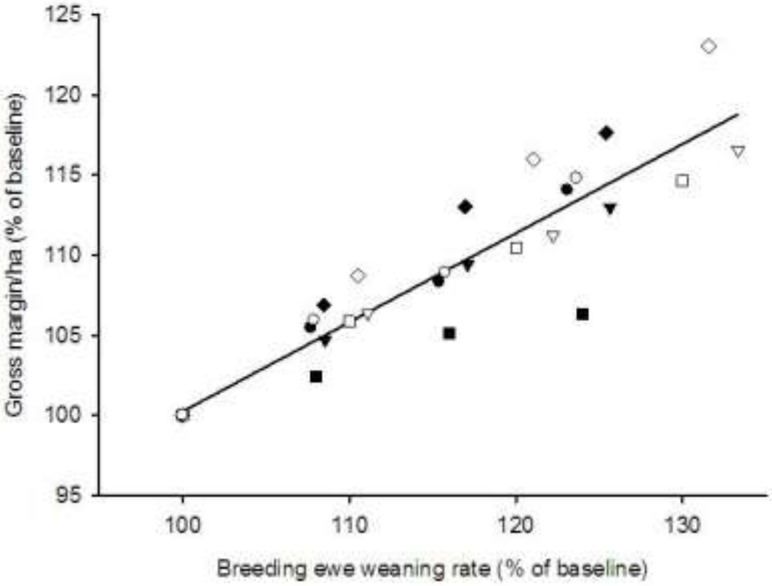

Figure 6: Farm GM/ha over a range of breeding ewe weaning rates (WR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 44.6 (4.7) + 0.6 (0.04)*WR, $r^2 = 0.86$, RMSE=2.3957, $P<0.0001$; Standard errors of regression parameters given in parentheses.

Breeding-ewe replacement rate

For each of the modelled B+LNZ farm classes, decreasing the breeding-ewe replacement rate had very little impact (0-1%) on total farm GHG emissions per ha (Figure 7). Figure 8 presents this same relationship, but with the response (GHG emissions per ha) and predictor (replacement rate) variables converted to % of baseline farm values. When pooled across all of the farms, total farm GHG emissions per ha actually increased marginally by 0.1% of baseline levels for every 10% decrease in the relative breeding ewe replacement rate (Figure 8).

Overall, these results show that decreasing the breeding-ewe replacement rate has little effect on a farm's total GHG emissions per ha if the stocking rates are then adjusted so that a similar amount of animal feed is consumed in all scenarios. As for weaning percentage, for each of the B+LNZ farm classes the total amount of estimated dry matter (DM) that was consumed remained constant, irrespective of breeding ewe replacement rate. DM consumed has been shown to be highly correlated with GHG emissions per ha (Duchemin, 2011), resulting in minimal change in total GHG emissions. In these models, the reduction in GHG per ha emissions attained by carrying fewer ewe-hogget replacements is countered by replacing these animals with more breeding ewes.

For each B+LNZ farm class, decreasing the breeding-ewe replacement rate also had very little effect on the farm's GHG emissions intensity (GHG emissions/kg net product grown) over the ranges tested (Figure 9). When pooled across all of the farms modelled, total farm GHG emissions/kg product grown increased by 0.1% of baseline levels for every 10% decrease in breeding-ewe replacement rate (Figure 10A).

The slight increase in emissions per kg product grown was likely an artefact of the GHG emissions intensity measure used. The 'total product grown' on a farm includes all net gains in animal live weight and fibre (wool and velvet) grown annually on a farm. This enables the live weight gain of dairy grazer cattle to be included as farm output. However, this measure also includes the live weight gain of young replacement breeding stock (e.g. replacement ewe hoggets and heifers). Thus, even though decreasing the ewe replacement rate increases the number of lambs available for sale it does not markedly change the total amount of net product grown on the farm. This illustrates that the intensity measure used can become an important influence when any trends are borderline. To illustrate this, Figure 10B graphs GHG emissions intensity using a slightly different measure: kg CO_2e per kg carcass weight sold, ignoring unsold weight gain and wool production. By this alternative measure, the GHG emission intensity decreases by almost 0.1% of baseline levels for every 10% decrease in breeding-ewe replacement rate - this showing the opposite trend. Nevertheless, for all practical purposes, breeding-ewe replacement rate has no discernible effect on emissions intensity according to this analysis.

Decreasing the breeding-ewe replacement rate increased the farm GM/ha by 3-10% over the ranges tested (Figure 11). When pooled across all of the farms modelled, the total farm GM/ha increased by 2% of the baseline levels for every 10% decrease in the breeding ewe replacement rate (Figure 12). The % increase in GM from baseline values with decreasing breeding-ewe replacement rate was particularly marked for

Class 2Av, 2L10%, 3L10%, and 6L10% models, followed in order by Class 6Av and 3Av models, with Class 5L10% and 5Av having the smallest response (Figure 12).

The increase in profitability can be attributed to a greater number of the total progeny from the sheep flock being either slaughtered prime or sold store, increasing the total revenue of each farm at no additional cost. Again, the strength of the response was likely strongly influenced by the ratios of sheep:cattle:deer on the particular farm class, its associated primary outputs (e.g. meat, fibre, etc.), and the selling policies (e.g. target carcass weights).

For some farm classes (e.g. Class 2Av and 3L10%), reducing the number of ewe replacements kept enabled a greater percentage of the lambs to be slaughtered prime (data not shown), while for others it changed the distribution of sales over the season but did not change the proportion sold either prime or store. For the Class 2, 3, 6 and 5%L10% farms the sheep enterprise was by far the largest enterprise on the farm, with slaughter and store sales from this enterprise generating the largest percentage of the total farm revenue.

Overall, for the B+LNZ farm class models tested, reducing the breeding-ewe replacement rate improved farm profitability, but had little effect on either total GHG emissions or the intensity of emissions.

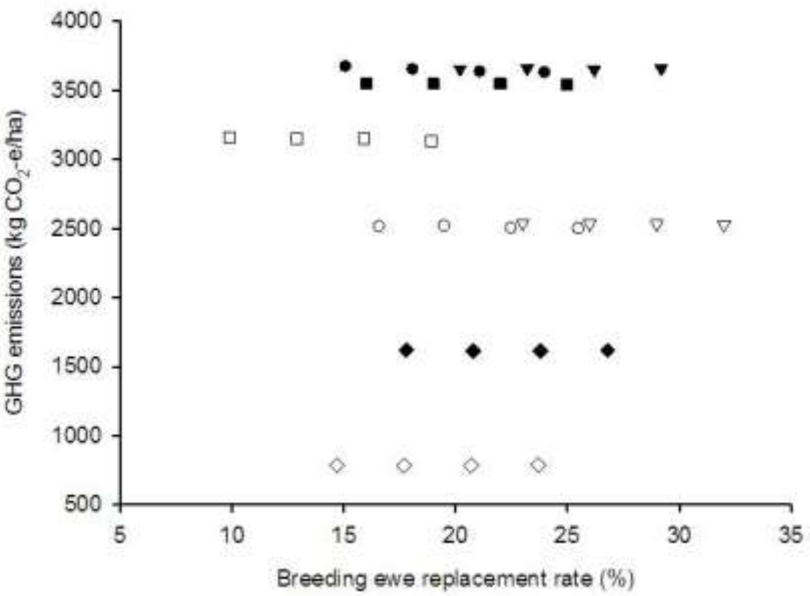

Figure 7: Annual farm GHG emissions over a range of breeding ewe replacement rates (RR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

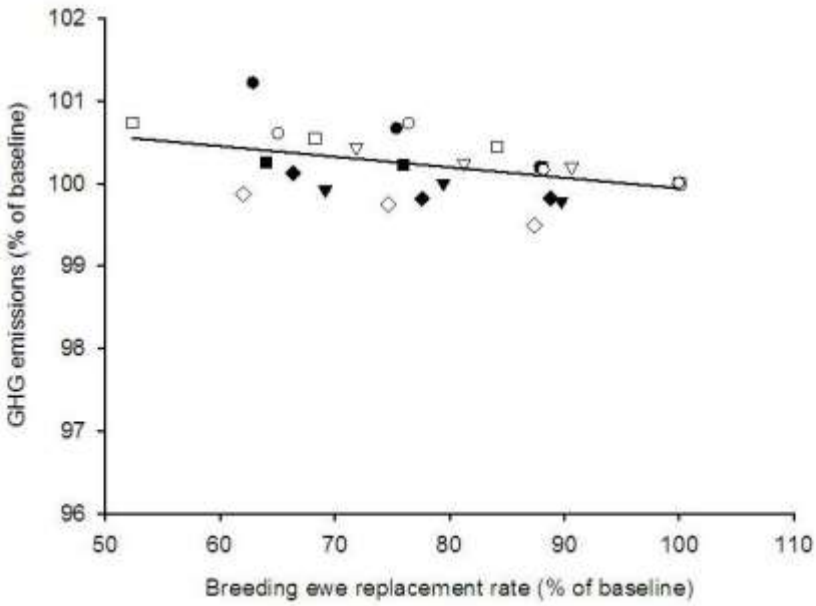

Figure 8: Farm GHG emissions over a range of breeding ewe replacement rates (RR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 101.2 (0.3) – 0.01 (0.004)*RR, r^2 = 0.25, RMSE=0.3113, P=0.0033; Standard errors of regression parameters given in parentheses.

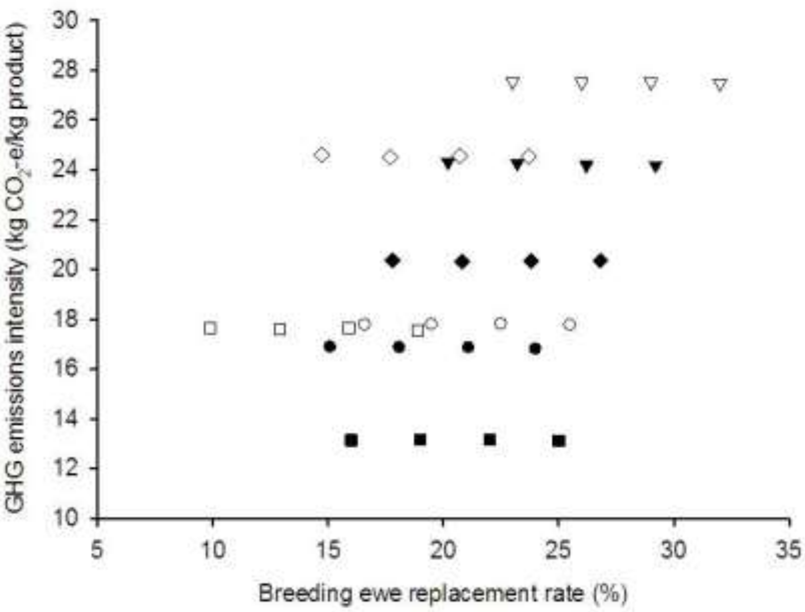

Figure 9: Farm GHG emissions intensity per kg of product over a range of breeding ewe replacement rates (RR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

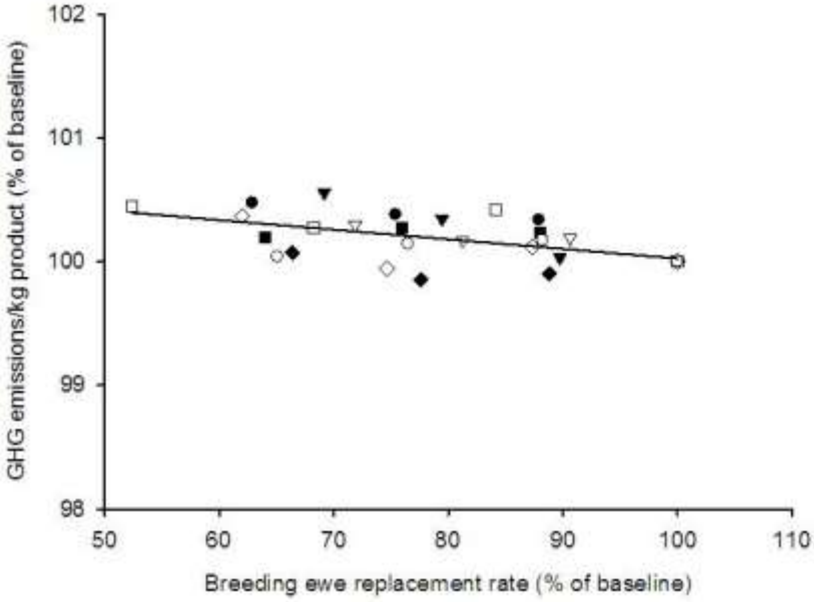

Figure 10A: Farm GHG emissions/kg product over a range of breeding ewe replacement rates (RR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 100.8 (0.2) – 0.008 (0.002)*RR, r^2 = 0.34, RMSE=0.1532, P=0.0004; Standard errors of regression parameters given in parentheses.

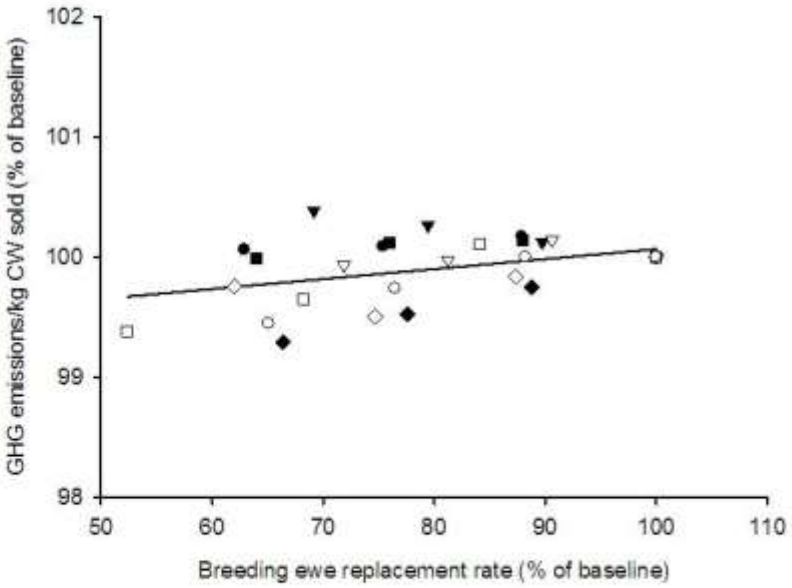

Figure 10B: Farm GHG emissions/kg CW sold over a range of breeding ewe replacement rates (RR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 99.2 (0.3) + 0.008 (0.003)*RR, r^2 = 0.20, RMSE=0.2392, P=0.0112; Standard errors of regression parameters given in parentheses.

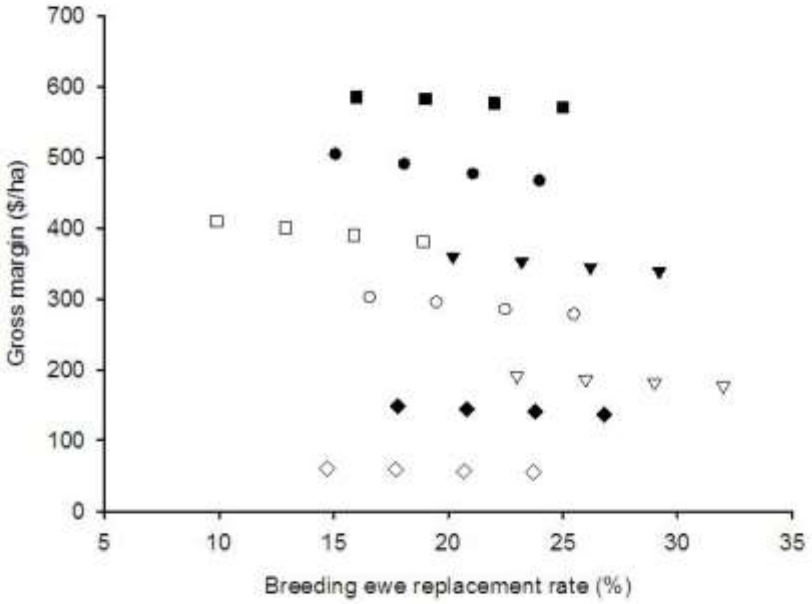

Figure 11: Farm gross margin over a range of breeding replacement rates (RR) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

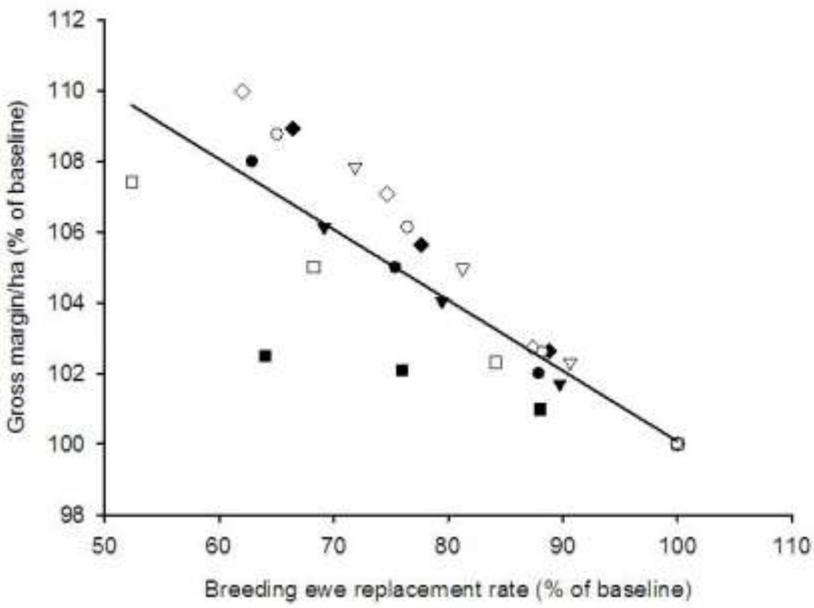

Figure 12: Farm Gross Margin/ha over a range of breeding ewe replacement rates (RR), as percentages of each baseline farm for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 120.1 (1.6) – 0.2 (0.02)*RR, r^2 = 0.78, RMSE=1.4934, P<0.0001; Standard errors of regression parameters given in parentheses.

The proportions of Breeding vs. trading and dairy-heifer grazing cattle

The total GHG emissions per ha for each farm class cattle scenario are shown in Figure 13. The horizontal 'x-axis' represents the percentage of trading & dairy-heifer grazing cattle that are carried over winter: 100% means all of the cattle stock units wintered are trading &dairy-heifer grazers; whereas, 0% means all of the cattle stock units wintered are breeding cows, replacement beef-heifers, and breeding bulls. All the baseline farms were breeding/finishing units, ranging from 22 - 77% of the cattle wintered being trading & dairy-heifer grazer cattle. The three scenarios tested are 0, 50 and 100% trading & dairy-heifer grazer cattle. Figure 13 shows a general reduction in total GHG emissions per ha as the proportion of trading & dairy-heifer grazer cattle is increased.

However, similarly to the relationships for breeding-ewe weaning %, the very wide range of total GHG emissions per ha for each of the baseline farms, and the resulting scale used on the vertical axis of Figure 13, make it difficult to clearly see these trends. As an alternative, Figure 14 shows the total emissions per ha as a percentage of the baseline farms. When pooled across all of the farms, total GHG emissions per ha decreased by 2% for every 10% increase in trading & dairy-heifer cattle carried over winter (Figure 14). However, there was considerable variation between farms, with greater rates of reduction occurring on the less intensive Class 2 and 3 farms, and smaller rates of reduction occurring on the more intensive Class 5 and 6 farms. Some of the relationship also did not appear to be linear, although this interpretation is somewhat limited by the small number of data points generated for each farm class. For Class 2L10% and 3Av farms in particular, the decrease in total farm GHG emissions per ha became more prominent as the cattle policy approached wintering 100% trading & dairy-heifer grazer cattle (Figure 14).

Changing the cattle enterprise from entirely breeding cattle to entirely trading & dairy-heifer grazers markedly reduced the intensity of GHG emissions on all of the farms by 11% to 31% (Figure 15 and 16). The reduction was particularly marked for the Class 5Av farm (Figure 16). Cattle are a much larger component of the total outputs on this farm in comparison to the other farm classes modelled (Table 1 and 3). Breeding cows have a high maintenance cost in terms of DM consumed and associated GHG emissions for little or no direct gain in net product produced on the farm. By swapping them for trading & dairy-heifer grazer cattle this DM can instead be fed to animals whose intake is partitioned to a much greater extent into actual product (e.g. meat & live weight gain).

Increasing the percentage of cattle wintered that are trading & dairy-heifer grazer cattle increased the GM/ha of most of the farm classes modelled (Figure 17). In general, changing the cattle enterprise from entirely breeding cattle to entirely trading & dairy-heifer grazers increased the farm's GM/ha by 12% to 36% (Figure 18). The two most notable exceptions were for Class 3Av and 2Av. For the former the GM/ha increased by only 2% when substituting all breeding cattle wintered for trading & dairy-heifer grazer cattle. Whereas, for the latter the GM/ha actually decreased by 6% (Figure 18). Again, not all of the relationships appeared to be linear, especially for Class 2Av, 3L10%, 5Av, 5L10%, 6L10% (Figure 18). Duchemin (2011) also found that farms with mainly breeding cows had a much higher GHG emission intensity than systems with mainly trading/finishing cattle

(18.7 ± 1.6 kg CO2-e/kg output vs. 15.0 ± 0.6 kg CO2-e/kg output), supporting the present study.

For all of the Farmax models it was assumed that the trading & dairy-heifer grazer cattle were able to maintain a similar live weight gain profile to when there were also breeding cattle on the farms. One of the major benefits of using breeding cattle especially in hill country is they are able to significantly improve the pasture quality of paddocks by removing rank herbage of low feed value. Without this class of stock present, it is likely the pasture quality on many hill pastures would deteriorate, reducing the potential growth rates of any trading & dairy-heifer grazer cattle and also the sheep. Thus, it is likely that the estimated increase in GM/ha by swapping breeding cattle for trading & dairy-heifer grazers will be to some extent overestimated.

It is also difficult to fairly compare the emissions from breeding versus trading cattle, since in a trading/finishing system the young stock must be sourced from a breeding cow, so the cow emissions will be occurring whether they are on this farm or not. The low emissions are due to a transfer of emissions off the farm rather than necessarily having an efficient system. However the dairy industry is already producing a large number of calves, which can be utilised on a beef farm without requiring a beef cow to be maintained elsewhere to produce the calf. This means it is possible to increase the proportion of trading stock on a beef farm to some extent without just causing additional emissions elsewhere, by using the dairy industry as the breeding herd.

To produce consistent scenarios that could be compared across all farm types, a very simplistic strategy had to be adopted for trading cattle - buying in weaner steers and finishing them. This may not represent the most optimum trading cattle policy for each farm class in regards to reducing GHG emissions and maximising profitability (for instance, buying older cattle at other times of the year may be more optimal on some properties). Therefore, greater efficiency gains may be possible than have been modelled here by tailoring the trading policy to suit the feed supply available on an individual farm.

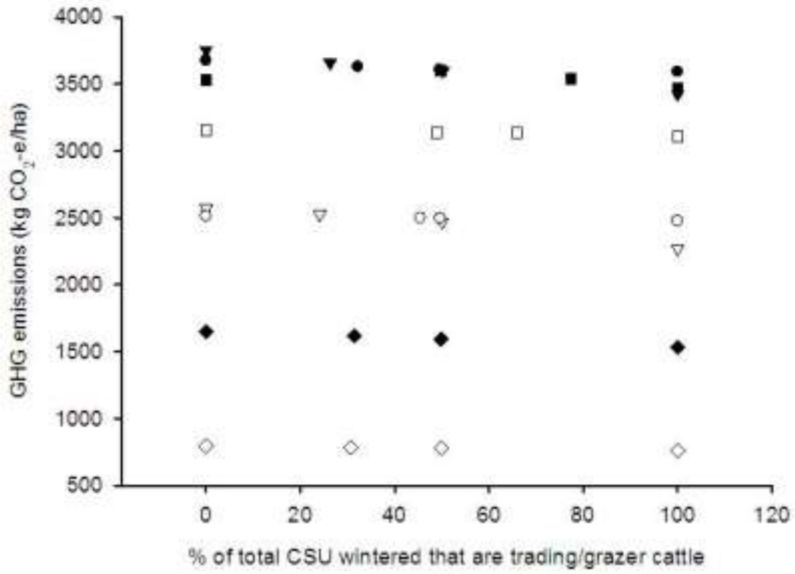

Figure 13: Annual farm GHG emissions over a range of trading & dairy-heifer grazers wintered (Cattle Stock Units (CSU)) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

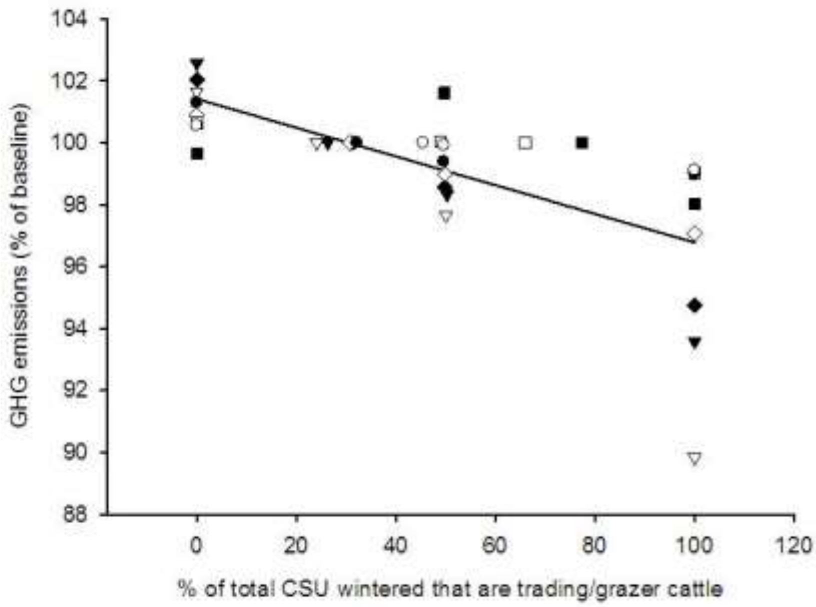

Figure 14: Farm GHG emissions/ha relative to the baseline farm over a range of CSU wintered as trading and dairy-heifer grazers (CSU) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 101.4 (0.5) – 0.05 (0.009)*CSU, r^2 = 0.47, RMSE=1.8696, P<0.0001; Standard errors of regression parameters given in parentheses.

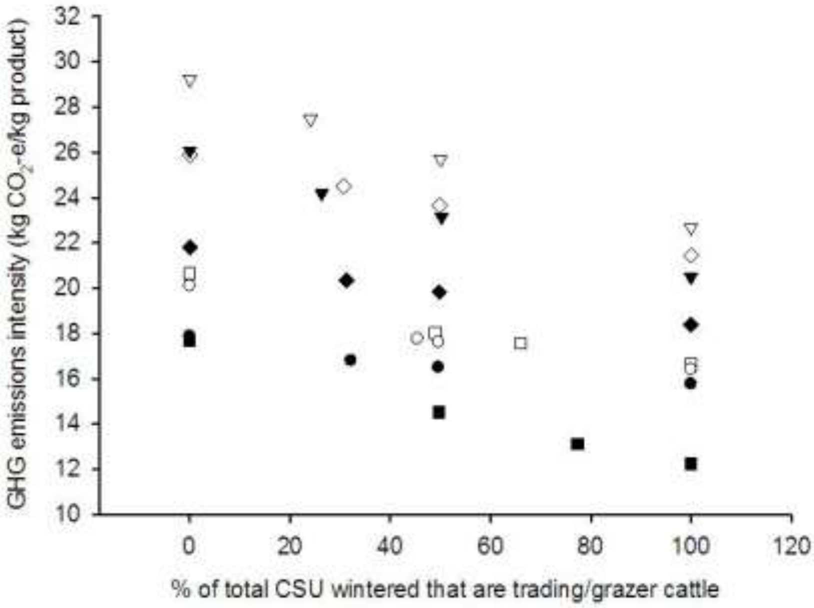

Figure 15: Farm GHG emissions intensity per kg of product over a range of CSU wintered as trading and dairy-heifer grazers (CSU) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

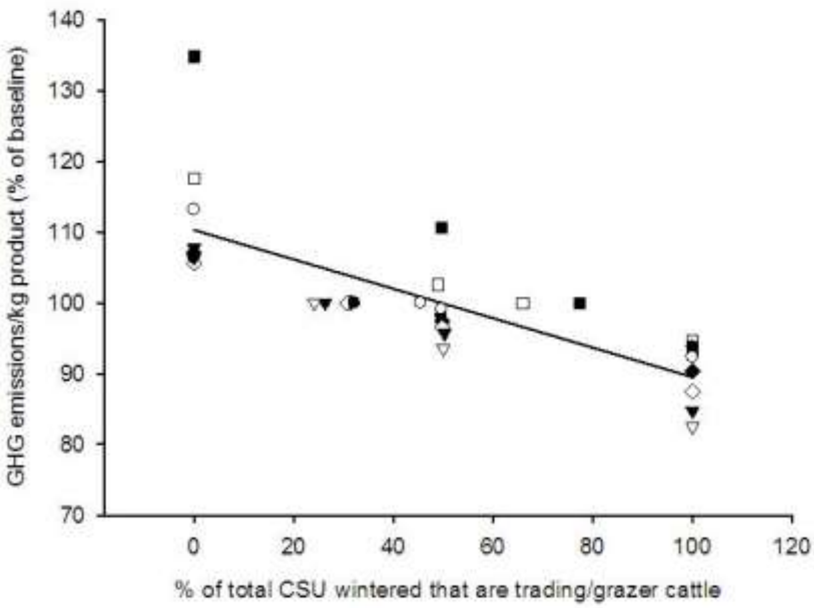

Figure 16: Farm GHG emissions/kg product, relative to the baseline, over a range of CSU wintered as trading & dairy-heifer grazers (CSU)for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 110.3 (1.8) – 0.21 (0.03)*CSU, r^2 = 0.60, RMSE=6.3682, P<0.0001; Standard errors of regression parameters given in parentheses.

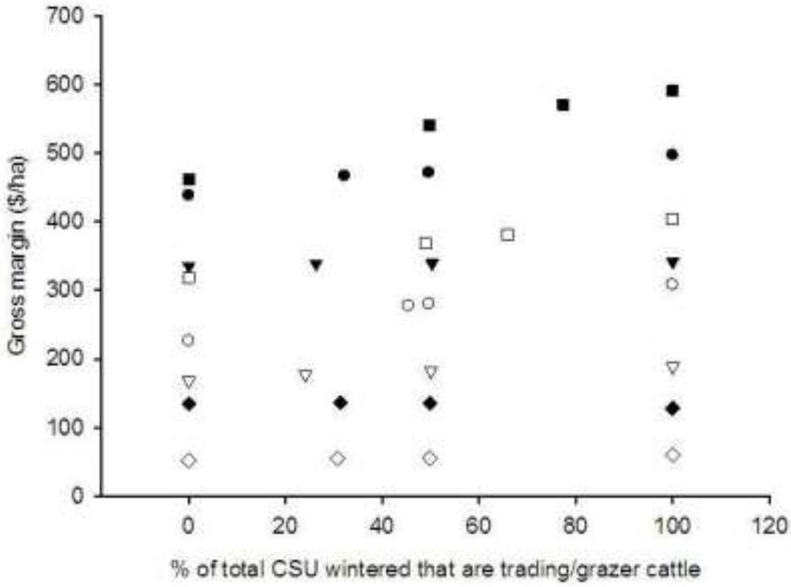

Figure 17: Farm gross margin over a range of CSU wintered as trading & dairy-heifer grazers (CSU) for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes.

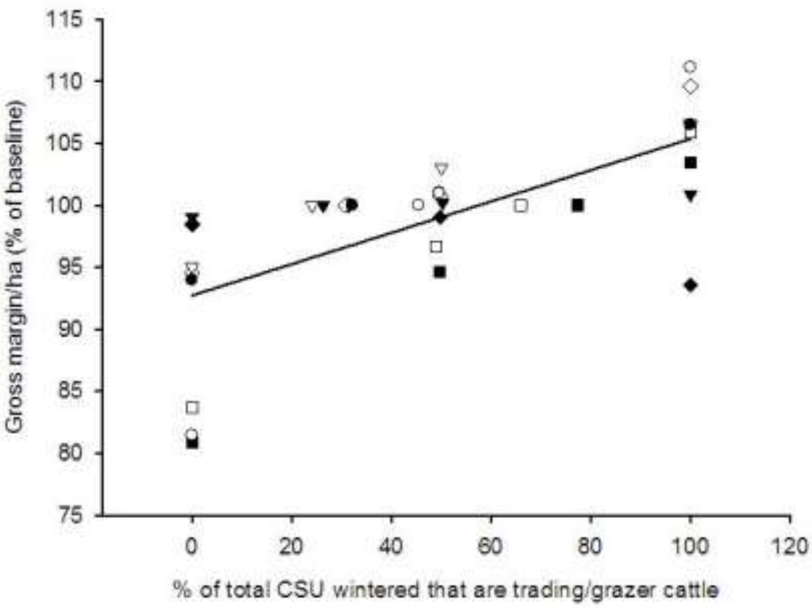

Figure 18: Farm Gross Margin/ha, relative to the baseline, over a range of CSU wintered as trading & dairy-heifer grazers for: ◆ Class 2Av, ◇ Class 2L10%, ▼ Class 3Av, ▽ Class 3L10%, ■ Class 5Av, □ Class 5L10%, ● Class 6Av, and ○ Class 6L10% B+LNZ model farm classes. Regression: 92.7 (1.5) + 0.13 (0.02)*CSU, $r^2 = 0.47$, RMSE=5.0949, $P<0.0001$; Standard errors of regression parameters given in parentheses.

CONCLUSIONS

Increasing the breeding-ewe weaning %, decreasing the breeding-ewe replacement rate, and increasing the proportion of total cattle run on a farm which are trading/dairy grazers are three farm management changes that showed potential for reducing on-farm GHG emissions. This report investigated in detail what level of impact these three farm management changes will likely have on a farm's total emissions, emissions intensity, and profitability for a wide range of representative New Zealand sheep and beef farming systems.

Of the farm management changes investigated, increasing the breeding-ewe weaning % was found to be the most promising method for reducing GHG emissions on-farm. Every 10% increase in weaning % can reduce total emissions by 1% and reduce emissions intensity by 3%, while improving the farm gross margin by an estimated 6%. These general trends were highly consistent across all farm types, but were greater on farms where the sheep enterprise dominates the farm system. It is therefore a mitigation strategy that can be readily promoted among and adopted by farmers, however this would be a substantial target for many farmers to achieve

Decreasing the breeding-ewe replacement rate was found to have minimal effect on either total emissions or emissions intensity, although it was also profitable. Farmers may choose to adopt this strategy for financial reasons, but it appears unlikely to affect their farm's GHG emissions.

Increasing the proportion of trading & dairy-heifer grazer cattle in the farm system was found to also reduce emissions, with every 10% increment in the proportion of the total farm feed consumed by trading & diary-heifer cattle (as opposed to breeding cows) reducing total emissions by 0.5% and emissions intensity by 2.1%, while increasing the farm's gross margin by 1.3%. The practicality of this option will vary between farms, and the economic advantage and risk will vary from year to year. However, it is a strategy that is used by many farmers already for economic reasons and is therefore practical to promote for reducing GHG emissions.

Overall, these results demonstrate it is possible to reduce whole-farm GHG emissions using practical and well-understood changes to farm management. The reductions in emissions that are achievable using these techniques are also highly consistent across farm types, and the figures presented in these conclusions can be used as "rules-of-thumb" for anybody considering the likely outcome of a change in these factors.

As with all agricultural GHG mitigation strategies, the actual reductions that are achievable are quite small compared to reductions that may be attained through efficiency gains in other industries. If they were adopted by a large number of farmers however, they could make an important contribution to reducing New Zealand's emissions as a whole.

REFERENCES

Beef + Lamb New Zealand. 'Farm Classes'. *Beef + Lamb New Zealand*, 2012. http://www.beeflambnz.com/information/on-farm-data-and-industry-production/farm-classes/.

Duchemin, M. *Greenhouse Gas Emissions in Dairy and Sheep & Beef Systems: a Cross-sector Analysis*. Sustainable Farming Fund project C08/008 report. Ministry for Primary Industries, 2011. http://maxa.maf.govt.nz/sff/about-projects/search/C08-008/cross-sector-analysis-ghg-emissions.pdf.

Dynes, R.A., Smeaton, D.C., Rhodes, A.P., Fraser, T.J., Brown, M.A., 2011. Modelling farm management scenarios that illustrate opportunities farmers have to reduce greenhouse gas emissions while maintaining profitability. Proceedings of the New Zealand Society of Animal Production 71, 167-171.

Ludemann, C.I., Byrne, T.J., Sise, J.A., Amer, P.R. 2011. Proceedings of the New Zealand Society of Animal Production 71, 162-167.

Ministry for the Environment. 'A Flowchart of New Zealand's Greenhouse Gas Emissions'. *Ministry for the Environment*, 2008. http://www.mfe.govt.nz/publications/climate/gas-emissions-flowchart/gas-flowchart.html.

Ministry for the Environment. *New Zealand's Greenhouse Gas Inventory 1990–2010*. Ministry for the Environment, 2012. http://www.mfe.govt.nz/publications/climate/greenhouse-gas-inventory-2012/index.html.

Van Reenen, E.H., Pickering, A.H., 2011. The role of legislation in improving farm sustainability and how the New Zealand Government intends to incentivise the agricultural industry. Proceedings of the New Zealand Society of Animal Production 71, 152-156.

Waghorn, G.C., 2011. Can livestock production be increased without increasing greenhouse gas emissions? Proceedings of the New Zealand Society of Animal Production 71, 156-162.

Wheeler, D.M., Ledgard, S.F., DeKlein, C.A.M., Monaghan, R.M., Carey, P.L., McDowell, R.W., Johns, K.L. 2003. OVERSEER® nutrient budgets – moving towards on-farm resource accounting. Proceedings of the New Zealand Grassland Association 65, 191-194.

White, T.A., Snow, V.O., King, W. 2010. Intensification of New Zealand beef farming systems. Agricultural Systems 103, 21-34.

C. Objective 1.2 Component models for key systems processes

The component models which are required to understand the farm systems GHG/soil carbon and productivity responses to changed management have been identified. The critical models for predicting GHG/soil carbon have been improved or demonstrated adequate. Methodology to link component and system models has been established.

The project proposal (in 2009) aimed to take existing component models and evaluate these using recent NZ data and where possible modify these models to better represent GHG emissions. The subsequent farm systems co- investment by NZAGRC in component model research and development enabled the wider research objectives to go beyond existing models. The focus of the SLMACC investment has been on the nitrous oxide model development and evaluation with some investment in use of Molly cow model for methane prediction.

1.2.1 International review of literature and databases

A literature review of publicly available N_2O models has been completed. The objective of the review was to identify and/or develop an improved model for predicting N_2O production for NZ's pastoral systems which is (i) publicly available, (ii) is mechanistically sensible, (iii) can be tested with datasets from NZ spanning a range of soils and climates, (iv) adequately describes NZ farming systems including urine patches, and (v) can be used to evaluate mitigation options such as nitrification inhibitors and their effect on the whole farm system.

Twenty three deterministic models, of varying complexity governing the carbon and nitrogen cycling in the soil plant atmosphere continuum, were selected. From the initial screening 10 models were selected for a more detailed screening and for identifying the best candidate(s) for further development and testing. The following denitrification and N_2O models were chosen as potential candidates for predicting N_2O production for NZ's pastoral systems: APSIM, DayCent, DNDC, NEMIS- for denitrification only, VISIT and WNMM. An internal report on "N_2O model review and selection of appropriate models" has been written (Appendix 22).

A review was conducted in an attempt to identify models for consideration for predicting enteric CH_4. Statistical models are useful for quick appraisals of CH_4 emissions, particularly when information on dietary ingredients, production conditions and feed intake is lacking. However, they do not explain the variation in emissions for different feeding regimes with sufficient accuracy. Dynamic and mechanistic models like Molly, Ansje and Karoline (see Appendix 6 for details) are more suitable as starting points for predicting CH_4 emissions because of the mechanistic description of rumen digestive processes. Although the methane predictions from these models are generally better than statistical models, the actual methane sub-model in all of them is still empirical and based on stoichiometry models for volatile fatty acids (VFA) production depending on substrate type. A flexible and accurate prediction of VFA production as a result of substrate fermentation in the rumen is one of the key elements of improving mechanistic rumen methane models. In this regard a move to a thermodynamic approach to model VFA production in the rumen is a promising development. See Appendix 6 for the full review.

Also see review by Iris Vogeler, Val Snow, Donna Giltrap and Frank Li, November 2010. Identification of a Model for predicting N_2O production from farming systems in New Zealand (Appendix 22).

1.2.2 Component model validation

A study was conducted to compare the outcomes of three versions of DairyNZ's metabolic cow model, Molly, with two different VFA stoichiometry constructs, to describe ruminal VFA pattern and methane production (g/day). The work is summarized as an abstract submitted to ADSA 2012, Phoenix, USA (see Appendix 7) and will also be submitted to Journal of Dairy Science (see appendix 8 for abstract of draft manuscript).
The sensitivity of Molly's CH_4 predictions to changes in feeding strategy was explored in a study that reviewed the literature regarding the impact of specific feeding strategies on reducing urinary nitrogen (UN). The study used Molly in the WFM to scale each strategy up to a farm level. It then explored the capacity of each strategy to reduce UN and collateral enteric-methane (CH_4) emissions from those on a baseline all-pasture dairy farm in the Waikato, New Zealand (3.45 cow/ha; 1300 kg milk solids/ha/year). See Appendix 9 for a full reference and abstract.

1.2.3 Improved component models

The best suited three N submodules from DayCent, Nemis and WNMM were linked to the SoilN module of APSIM. Predictions of nitrification, denitrification, and N_2O emissions based on these different N submodules have been compared to measured datasets done in the Waikato region. The agreement between the various models and measured data was very variable, dependent on the timing of N application, and thus the prevailing environmental conditions. So far none of the models could be identified as being suitable model for estimating N_2O production and mitigation strategies in NZ farm systems. A poster on this model comparison has been presented at the 2nd annual NZAGRC conference. (see Appendix 18).

A model comparison between two conceptually different models, APSIM and DNDC, has been done to identify how the two models respond to various environmental factors. A paper on this has been submitted for a special issue in Science of the Total Environment (see Appendix 13), and a paper has been presented at the International Nitrogen Workshop in Ireland (see Appendix 17)

Furthermore, APSIM and DNDC have been compared to four different N_2O datasets from the Waikato and Southland region,s and a paper on this is in preparation: "Comparison and validation of the APSIM and DNDC models with measurements from urine patches".

The digestive parameters in the Molly cow model within the DairyNZ Whole Farm Model were derived some years ago using the data available at that stage, mostly from experimental results using conserved forages and concentrates. There was a need to re-visit these parameters and update them, if necessary, with the latest information because these parameters have such an important bearing on the digestion of feed, CH_4 production, absorption and post-absorptive fluxes of nutrients in the cow model. In work conducted by Mark Hanigan and students from Virginia Polytech and State University (Virginia, USA) in collaboration with Pablo Gregorini (DairyNZ) the pH prediction equation in Molly was re-parameterized simultaneously with a number of ruminal and post-ruminal digestion parameters resulting in new parameter estimates for ruminal fiber digestion, and moderate reductions in prediction errors for pH; NDF, ADF, and microbial N outflow from the rumen; and post-ruminal digestion of NDF, ADF, and protein. The effect of these improvements on Molly's CH_4 predictions were evaluated as part of the work conducted under milestone 1.2.2 (see above). See Appendix 10 for the abstract of the manuscript in preparation.

1.2.4 Linked component and farm systems models

The DairyNZ Whole Farm Model was linked to the APSIM framework via a urine patch framework (UPF). The purpose of the UPF is to take account of individual urine patches, area of a paddock covered by single and multiple urine patches, and timing of patch deposition. The UPF runs 1000's of APSIM simulations to get the N leaching below each urine patch then scales the results up to paddock and farm level. This is an example of linking system models with different strengths and weaknesses. The strengths of WFM with Molly (Methane and urinary-N per urination event) and the farm management rules giving the model user knowledge of when the cows visit each paddock i.e. timing relative to climatic conditions. The weakness of WFM is the lack of a sophisticated soil model that deals with N/C cycling. The strengths of APSIM are the SoilWat and SoilC/N models driven by climate and the run speed. The weakness is the lack of a cow model and dairy farm management rules. The APSIM model can be improved by linking a N_2O model to the soil water and N/C models (see review by Vogeler et al Appendix 22.). However, this is a task for the future. The WFM-UPF-APSIM linkage was documented and published (see appendix 11 for the reference and abstract). The capabilities of the WFM linked to a system of segregated emission factors for N_2O was demonstrated by Vogeler et al (see Appendix 12 for a reference and abstract).

1.2.5 Inventory calculations

The use of improved emission factors based on statistical analysis of our N_2O database, linked with outputs from Dairy NZ's WFM shows potential for improved inventory calculations at the farm scale, including the effect of wise farm management. The approach has potential as a bottom up approach for Inventory calculations. The work has been published in Soil Research (Appendix 12), and a paper has been accepted for poster presentation at the Australasian Dairy Science Symposium in Melbourne, November 2012 (Appendix 14).

One of the results of the work reported in Appendix 3 is the finding that mechanistic CH_4 models as part of farm-scale models are important because the current inventory methodology (e.g. Overseer) cannot properly evaluate CH_4 emissions for the range of potential mitigation strategies. There is also a need for developing capabilities in farm-scale models to accurately simulate urine patches and nitrous oxide (N_2O) emissions generated from these.

D. Objective 1.3: Life Cycle Assessment to assess management and mitigation effects on the GHG footprint

Research within this Objective involved three main components: updating carbon footprint methodology, comparisons with overseas farm systems, and dairy farm systems analysis including effects of mitigation options.

1.3.1 Carbon footprint methodology: Updating models

Previous research resulted in application of Life Cycle Assessment (LCA) to develop carbon footprint models for regional and average New Zealand (NZ) dairy farm systems (Ledgard et al., 2008) based on use of dairy farm survey data from DairyNZ (DairyBase). Similarly, carbon footprint models for sheep and beef farm systems were developed for the various Beef+LambNZ farm class types using farm survey data (Ledgard et al., 2010). An important driver of the updates for the dairy model was the International Dairy Federation report (IDF 2010), which outlined a number of important approaches of relevance to international dairy production systems.

A number of methodological and technical aspects have been updated, which include:

- The excreta nitrogen is now partitioned into urine and dung nitrogen using the equations from Ledgard et al. (2003).
- The N_2O emissions calculated from urine and dung deposited on pasture now used the most recent National Inventory direct emission factors where urine had 1% of N emitted as N_2O-N and dung had 0.25% of N emitted as N_2O-N. Previously excreted N had direct emission factor of 0.01 kg N_2O-N/kg excreta N
- Recommendations and data from the report of Thomas et al. (2008) were used for the calculations of N inputs from crop residues and followed the modified IPCC (2006) methodology for NZ conditions. The method adopted included the above-ground and below-ground crop residues.
- Options for accounting for farm dairy effluent emission factors to include both pond and land-based treatment systems were developed and included.
- The most recent LCAs of NZ fertilisers were used in the model (Ledgard et al., 2011). Each fertiliser in the model had GHG emissions included from the extraction of its raw materials, manufacturing, transportation, and application.
- For DCD modelling, emissions from its manufacturing, transport and application were developed and used.
- A maize silage production inventory was obtained from contractor data and was updated to include the latest IPCC emission factors.
- The inventory for the production of palm kernel expeller (PKE) was updated from Schmidt (2007) to use up-to-date emission factors from IPCC (2006). Palm kernel expeller also attracted a deforestation emission based on the PAS 2050 (2011) country specific defaults. Up-to-date economic and country-of-origin data were used for the allocation of the GHG emissions between the palm oil industry co-products.

In the use of LCA for carbon footprinting there are a number of important factors that affect the final estimates and these are briefly outlined in the following sub-sections as well as the calculation method.

1.3.1.1 System boundary

The system boundary refers to the range of stages of the life cycle that are used in the model and in this study it was set up for the "cradle-to-farm-gate". For dairy systems, this included:

- Production of milk on-farm, including on-farm pasture production and utilisation (thus determining methane and nitrous oxide from animals), use of farm equipment (representing diesel and petrol) and milk extraction, farm dairy effluent management and water supply (determining electricity use).
- Production of supplementary feed
- Off-farm pasture production for the dairy cow replacements
- Production and delivery of inputs to crop and pasture (e.g. fertilisers).

The above components have been found, in previous studies, to account for at least 99% of the likely life cycle emissions from cradle-to-farm-gate thereby meeting one of the key requirements of the UK PAS 2050 methodology which states that at least 95% of all constituents should be included. For sheep and beef farms the "off-farm" contributors are generally less than on dairy farms although it still includes supplementary feeds and inputs brought onto the farm. However, for sheep and beef farms it accounts for all components of the animal production and therefore accounts for animals that might have been reared on one farm and finished on another.

1.3.1.2 Functional unit

The function analysed was the milk production of dairy farms or the sheep component of sheep and beef farms. Therefore, the functional unit of the study is one kg of milksolids for dairying and 1 kg live-weight leaving the farm for sheep and beef farms.

1.3.1.3 Handling of co-products

For dairying, the impacts of GHG emissions between the co-products milk and meat were allocated according to a biological causality, based on the physiological feed requirements of the animal to produce milk and meat (calf, culled cows). The IDF (2010) methodology for allocation was used based on the relative amounts of milk and meat produced from the dairy farm system. This resulted in allocation values for milk relative to the total of between 86% and 87%. For other processes generating more than one product such as some of the brought-in feed sources e.g. PKE, an economic allocation was used. The average allocation for PKE relative to the total for all palm products was 1.55%.

For sheep and beef farming, the GHG emissions from the animal types of sheep and cattle were allocated according to biological function, i.e. based on the amount of feed eaten by sheep and cattle (Ledgard et al. 2008). This utilised an energy-based animal intake model to estimate feed dry matter intake for each of the animal types (Clark et al. 2003). For the sheep co-products of lamb, mutton and wool, an economic allocation was applied that used economic data averaged over 5 years to reduce the variability in product prices between years.

1.3.1.4 Data quality

This carbon footprint analysis used an attributional approach and therefore used average data for all processes. The technical description of dairy farm systems studied here relied mainly on DairyNZ DairyBase data for the Waikato–BOP region in the 2008/09 year. LIC statistics showed that the region supplied more than a third of the NZ milk production (36.7% of NZ MS in 2008/09; LIC 2009). Farmax modelling was used to estimate the monthly feed supplement amounts. The inventory included N fertiliser data from DairyBase augmented by lime and P and K fertiliser amounts calculated using the Overseer® nutrient budget model.

The technical description of sheep and beef farm systems relied on detailed data from the Beef+LambNZ statistics. The Beef+LambNZ statistics represent a survey of farms for each of the eight farm types. Additional survey data was also used where Beef+LambNZ data was inadequate.

The NZ-IPCC inventory was strictly applied in this carbon footprint analysis for estimating methane and nitrous oxide emissions from animals and land and CO_2 emissions after lime application. Data from the international ecoinvent v2.1 database (ecoinvent Centre 2007) was adapted, as far as possible, to the NZ situation for the carbon footprint of all inputs such as fertilisers, electricity and fuel.

1.3.1.5 Carbon footprint calculation

The inventory of GHG emissions covering CH4 from enteric fermentation by the animals, methane (CH_4) and nitrous oxide (N_2O) from excreta deposited on pasture and from farm dairy effluent (FDE), N_2O from N fertiliser, and CO_2 emissions from lime and urea application was based on the IPCC methodology (de Klein et al. 2003; Clark et al. 2003; Saggar et al. 2003; IPCC 2006).

Capital was excluded from all calculations (as recommended in the PAS 2050:2011). The estimate of emissions associated with the refrigerants HFCs and CFCs, done after discussion with a local expert (D. Grey pers. comm.), was only 0.2% of the total carbon footprint and was included for completeness.

The carbon footprint (equivalent to Global Warming Potential) for a 100 year time horizon (GWP100) was calculated according to the most recent IPCC reference in kg CO_2-equivalent, i.e. with multiplication factors of CO_2 1, N_2O 298 and CH_4 25.

1.3.2 Comparison of the carbon footprint of New Zealand and European farm systems

Information from the carbon footprint models for NZ farm systems and products were used for comparative studies with dairy farm systems in Sweden and sheep farm systems in France. The Swedish dairy system evaluation corresponded with a request for Dr Ledgard to be a co-supervisor for a PhD study based out of Aarhus University, Denmark. This resulted in Ms Anna Flysjö spending six months in Hamilton, NZ, working on a comparative study of Swedish and NZ dairy farm systems. This provided a valuable opportunity to conduct a realistic comparison between Swedish and NZ dairy farm systems. Previously, most studies were on a single farm system or country analysis and the use of differing methodologies meant that it was not possible to make direct comparisons between the different studies.

Detailed analysis of the systems using the same NZ methodology revealed that the average NZ dairy farm system had a carbon footprint for milk (to the farm-gate) that was 12% lower than that for the average Swedish dairy farm system (Flysjö et al., 2011b). However, detailed analysis using variability in input data for the different farm systems revealed a relatively large variation about the mean for each farm system. Monte Carlo analysis was applied to determine the variability in results and this is summarised in Figure 1.3.1. The Swedish farm system had relatively high CO_2 emissions associated with fossil fuel due to the use of housing of cows over an 8-month period (heated over winter) and high use of brought-in feeds. However, this was largely compensated for by the high milk production per cow resulting in lower methane emissions per kg milk associated with the relatively low maintenance component of the dairy system compared to that for the NZ dairy farm system (8274 versus 4118 kg fat-and-protein-corrected milk per cow for Swedish and NZ systems, respectively).

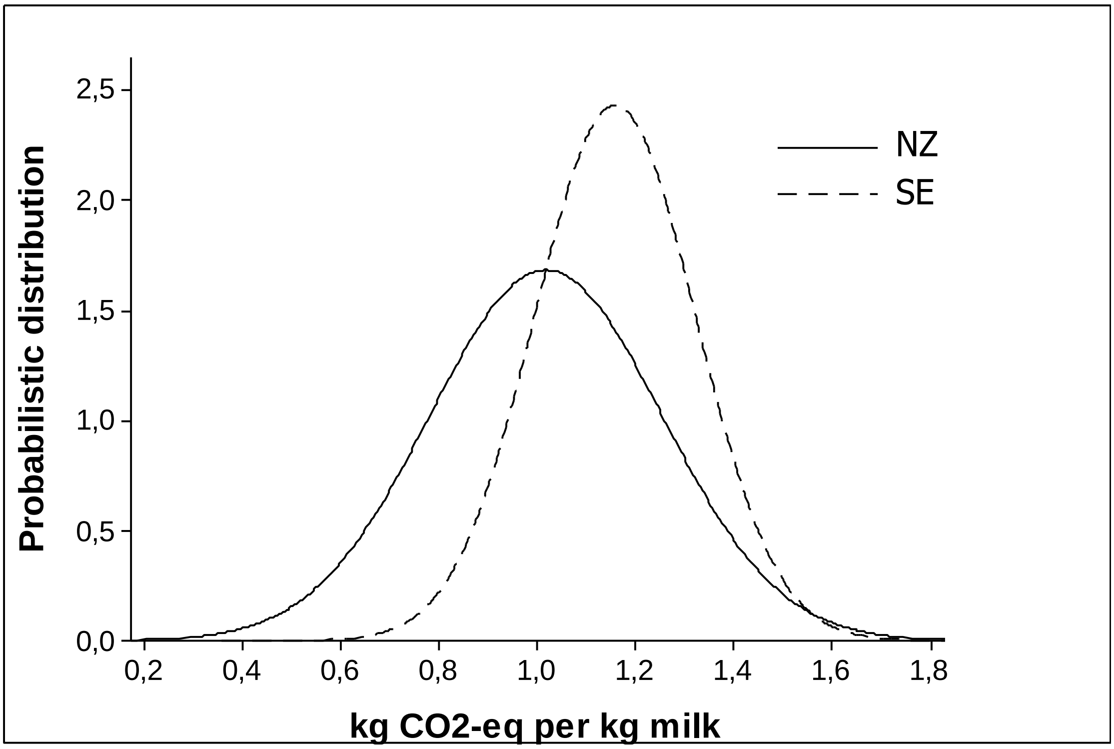

Figure 1.3.1: Probability distribution of total GHG emissions of one kg milk from the average New Zealand (NZ) or Swedish (SE) dairy farm system. This distribution was based on use of Monte Carlo simulation modelling and the average standard error of the mean for various input parameters (derived from Flysjö et al., 2011b).

This comparative research for Swedish and NZ dairy systems also revealed that the methodology had a large effect on the absolute carbon footprint value and also the difference between the systems (Flysjö et al., 2011a, 2012). A major factor was the method used to allocate GHG emissions between the co-products of milk and meat. The relative percent allocation to milk for the NZ dairy farm system was 98, 94, 86 or 63% for mass, economic, biophysical (i.e. according to feed requirements for milk or meat production) or system expansion methods, respectively. The later was based on the assumption of meat from the dairy system displacing that from a traditional beef production system. This research contributed to an international research and dairy sector group (that included Ms Flysjö and Dr Ledgard) selecting biophysical allocation as the most appropriate method for allocating GHG emission between milk and meat that was recognised in the International Dairy Federation report on a common methodology for determining the carbon footprint of milk (IDF, 2010).

A similar comparative research study was carried out with researchers from the Institut de l'Elevage (France) on the carbon footprint of French and NZ sheep production systems. Application of a common NZ-based method resulted in the carbon footprint of lamb from North Island hill country compared to a French average system (based on a northern France grass-based system and a southern France mountain-land system with extensive winter housing of sheep) of 8.5 and 12.9 kg CO_2-equivalent/kg live-weight, respectively (Gac et al., 2012).

A key aspect of this research was recognition of the effects of differences in methodology in calculation of the carbon footprint of sheep meat (Ledgard et al., 2012). For example, application of economic allocation for partitioning total GHG emissions between meat and wool accentuated the advantage of NZ sheep because of the effective use of wool in carpet-making in NZ whereas in France the wool has little use or value. Thus, the percentage allocation to meat was 78.0 and 99.7% for the NZ and French sheep, respectively.

Research from this programme, in conjunction with earlier research (Ledgard et al., 2008) resulted in Dr Ledgard being requested to draft a common methodology for assessing the carbon footprint of lamb by the international sheep meat community (led by Beef+LambNZ) and this is currently circulating through various international groups for feedback and revision before finalising on an agreed methodology.

1.3.3 Carbon footprint of NZ dairy farm systems and effects of mitigations

The methodology for determining the carbon footprint of milk from dairy farm systems developed in this project (section 1.3.1) was used to determine the carbon footprint of contrasting dairy farm systems. Data collected by DairyNZ in the DairyBase database for 2009/2010 for the Waikato region was partitioned into dairy farm systems 1-2, 3 and 4-5. These systems represent differences in farm intensity and level of brought-in feed with systems 1-2 having nil or little brought-in feed while system 5 could have approximately half of its total feed derived from brought-in feed (Hedley and Bird, 2006). This was linked with on-farm estimation of the methane and nitrous oxide analyses in Objective 2, which used the same farm system data.

Key farm data for the average of these three surveyed farm systems (Table 1.3.1) showed a 74% increase in milk solids (MS) production per on-farm hectare between farm systems 1-2 and 4-5. This was associated with increases in stocking rate (+33%), level of N fertiliser use (+122%) and brought-in feed (+16.8-fold). There was relatively little difference between farm systems in the carbon footprint (i.e. total GHG emissions per kg MS). The highest carbon footprint for farm system 3 was influenced greatly by the relatively high contribution from CO_2. This was due primarily to the source of brought-in feed (Table 1.3.2) which was predominantly palm kernel expeller (PKE) and which has a relatively high carbon footprint associated with the Land Use Change component of its production (as discussed in section 1.3.1). The lower carbon footprint from farm systems 4-5 was due in part to its greater feed conversion efficiency associated with its higher milksolids production per cow at 401 kg MS/cow compared to 307 and 340 kg MS/cow for systems 1-2 and 3, respectively. The main on-farm sources of GHG emissions were enteric methane, excreta N_2O and N fertiliser (which produced N_2O after application to soil and CO_2 mainly from manufacturing) (Table 1.3.3).

Table 1.3.1: Farm and carbon footprint data for average Waikato farms representing dairy systems 1-2, 3 and 4-5 associated with increased farm intensity and brought-in feed (data from DairyNZ DairyBase).

	Dairy farm system		
	1-2	3	4-5
Milksolids (kg/ha/yr)	824	1032	1432
Cows/ha	2.7	3.0	3.6
Nitrogen fertiliser (kg N/ha/yr)	66	105	148
Brought-in feed (kg DM/ha/yr)	238	1936	3998
Carbon footprint (kg CO_2-equiv/kg MS)	10.20	10.82	9.47
- Methane contribution	71%	64%	68%
- Nitrous oxide contribution	21%	20%	22%
- Carbon dioxide contribution	8%	16%	10%

Table 1.3.2: Contribution of various on-farm and off-farm sources to the carbon footprint of milk (values are kg CO_2-equiv/kg milksolids) for average Waikato farms representing dairy systems 1-2, 3 and 4-5.

	Dairy farm system		
	1-2	3	4-5
On-farm:			
Cow CH_4	6.21	5.84	5.50
Cow excreta+FDE N_2O	1.44	1.29	1.10
N fertiliser N_2O	0.37	0.48	0.49
Others	0.64	0.60	0.57
Off-farm:			
Replacements CH_4	0.95	0.87	0.86
Replacements excreta N_2O	0.28	0.26	0.26
Replacements others	0.08	0.08	0.08
Brought-in feeds*	0.22	1.39	0.61
TOTAL:	10.20	10.82	9.47

*including production, land use change and cartage

Table 1.3.3: Percentage contribution of various on-farm sources to the carbon footprint of milk for average Waikato farms representing dairy systems 1-2, 3 and 4-5.

	Dairy farm system		
	1-2	3	4-5

Sources of methane:			
Enteric rumen	99%	99%	99%
Dung and FDE	1%	1%	1%
Sources of nitrous oxide:			
Excreta	75%	69%	65%
N fertiliser	21%	27%	31%
Farm dairy effluent	4%	4%	4%
Sources of carbon dioxide:			
N fertiliser	45%	59%	64%
P,K,S fertilisers	18%	8%	8%
Lime	4%	4%	3%
Electricity	21%	19%	17%
Fuel	12%	9%	8%

1.3.3.1 Effects of changes in management practices and use of mitigation options

A range of different farm management practices and mitigation options were evaluated for their effects on the carbon footprint of the milk produced. These scenarios evaluated were:

1. Application of the nitrification inhibitor DCD and reduction in N fertiliser rate (by 29-37 kg N/ha) to compensate for increased N availability due to reduced N loss.
2. Use of maize silage as the only source of brought-in feed (but with no change in the total quantity of metabolisable energy in the brought-in feed).
3. No N fertiliser use on pasture and replacement of reduced pasture growth with brought-in maize silage.
4. Increasing milksolids production per cow up to the 401 kg/cow in farm system 4-5.

For dairy farm system 1-2, the largest reduction in carbon footprint of 9.4% was associated with a 30% increase in milk solids production per cow (from 307 to 401 kg MS/cow) (Table 1.3.4). Most of this reduction was due to a decrease in methane/kg milk solids due to more feed consumption partitioned to milk production relative to maintenance. The next largest reduction in carbon footprint (7.5%) was due to use of DCD resulting in a decrease in N_2O emissions. Ceasing use of N fertiliser and replacing the reduced pasture growth with maize silage produced a 4.9% decrease in carbon footprint, while changing all brought-in feed to maize silage gave only a 1.5% decrease in carbon footprint.

Table 1.3.4: Effect of mitigation or management changes on the carbon footprint of milk (values are kg CO_2-equiv/kg milk solids) for Waikato dairy farm system 1-2.

	Current	DCD	Maize only	Nil N, maize	More MS/cow
On-farm:					
Cow CH_4	6.21	6.21	6.23	6.23	5.70
Cow excreta+FDE N_2O	1.44	0.98	1.43	1.35	1.28
N fertiliser N_2O	0.37	0.21	0.37	0.02	0.39
Others	0.64	0.53	0.64	0.38	0.62

Off-farm:					
Replacements	1.32	1.32	1.32	1.32	1.04
Brought-in feed	0.22	0.22	0.05	0.39	0.23
TOTAL	**10.20**	**9.47**	**10.04**	**9.69**	**9.25**
% decrease		*-7.1%*	*-1.5%*	*-4.9%*	*-9.3%*

For dairy farm system 3, the largest reduction in carbon footprint of 9.4% was associated with changing all brought-in feed to maize silage (Table 1.3.5). This relatively large effect was due to replacing the PKE (with a relatively large carbon footprint associated with accounting for deforestation) with maize silage which had a relatively low carbon footprint. The latter is due to the high yield per hectare from maize silage (20 t DM/ha) and the low N concentration resulting in greater N efficiency, low N excretion and less N_2O emissions (e.g. Williams et al., 2007). Use of DCD or ceasing N fertiliser use and replacing lost pasture production with maize silage both gave a decrease in carbon footprint of about 6%. The smallest carbon footprint reduction was due to an 18% increase in milk solids production per cow (from 340 to 401 kg MS/cow).

Table 1.3.5: Effect of mitigation or management changes on the carbon footprint of milk (values are kg CO_2-equiv/kg milk solids) for Waikato dairy farm system 3.

	Current	DCD	Maize only	Nil N, maize	More MS/cow
On-farm:					
Cow CH_4	5.84	5.84	5.93	5.87	5.66
Cow excreta+FDE N_2O	1.29	0.98	1.24	1.18	1.22
N fertiliser N_2O	0.48	0.33	0.48	0.01	0.49
Others	0.60	0.51	0.60	0.27	0.59
Off-farm:					
Replacements	1.22	1.22	1.22	1.22	1.07
Brought-in feed	1.39	1.39	0.34	1.61	1.43
TOTAL	**10.82**	**10.18**	**9.81**	**10.16**	**10.45**
% decrease		*-5.9%*	*-9.4%*	*-6.1%*	*-3.4%*

For dairy farm system 4-5, the largest decrease in carbon footprint of 7.5% was due to ceasing N fertiliser use and replacing the reduced pasture growth with maize silage (Table 3.6). Use of DCD was estimated to decrease the carbon footprint by 5.8%. The other management option associated with changing feed to maize silage was not evaluated because most feed used in this farm system 4-5 group was maize silage and there is a limit to the extent of use of maize silage before protein limitation may become an issue (e.g. Hedley and Bird 2006).

Table 3.6: Effect of mitigation or management changes on the carbon footprint of milk (values are kg CO_2-equiv/kg milk solids) for Waikato dairy farm system 4-5.

	Current	DCD	Nil N, maize
On-farm:			
Cow CH_4	5.50	5.50	5.51
Cow excreta+FDE N_2O	1.10	0.75	0.98
N fertiliser N_2O	0.49	0.36	0.01
Others	0.57	0.51	0.27
Off-farm:			
Replacements	1.20	1.20	1.20
Brought-in feed	0.61	0.61	0.83
TOTAL	**9.47**	**8.92**	**8.76**
% decrease		*-5.8%*	*-7.5%*

The limited number of farm system analyses in this study illustrate that intensification of dairy farm production is not necessarily associated with an increase in carbon footprint. Key factors affecting the final carbon footprint were the milk solids production per cow, the source of brought-in feed and the rate of N fertiliser use. The management/mitigation options evaluated revealed that the magnitude of reduction in carbon footprint is dependent on the particular dairy farm system and the magnitude of the three key factors noted previously. It is recommended that a wider range of farm system analyses are carried out that reflect differences between different regions throughout New Zealand to get a better understanding of regional variability. It is also recommended that specific farm system analyses are carried out that test single factor changes such as intensification due to use of maize silage with other farm system inputs being kept constant. In that way, the specific effects of intensification via use of brought-in feed can be specifically examined. It is also recommended that a wider range in management practices and mitigation options are evaluated as well as optimal combinations of options.

References

Clark H, Brookes I and Walcroft A 2003. Enteric methane emissions from New Zealand ruminants 1990 and 2001 calculated using an IPCC Tier 2 approach. Report prepared for the Ministry of Agriculture and Forestry (March 2003).

De Klein C A M, Barton B, Sherlock R R, Zheng Li and Littlejohn R P 2003. Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. Australian Journal of Soil Research 42: 381-399.

Ecoinvent Centre 2007 ecoinvent data v2.1.ecoinvent reports No.1-25,Swiss Centre for Life Cycle Inventories , Dubendorf, 2007. www.ecoinvent.org

Flysjö A, Cederberg C, Henriksson M and Ledgard S 2011a. How does co-product handling affect the Carbon Footprint of milk? – case study of milk production in New Zealand and Sweden. The International Journal of Life Cycle Assesssment 16: 420-430.

Flysjö A, Henriksson M, Cederberg C, Ledgard S and Englund J-E 2011b. The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agricultural Systems 104: 459-469.

Flysjö A, Cederberg C, Henriksson M and Ledgard S 2012. The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk. Journal of Cleaner Production 28: 134-142.

Gac A, Ledgard S, Lorinquer E, Boyes M and Le Gall A 2012. Carbon footprint of sheep farms in France and New Zealand: Comparison of results and methodology analysis. Proceedings of the 8th International Conference on LCA in the Agri-food Sector, France. (October 2012). In press.

Hedley P and Bird P 2006. Achieving high profit from your farm system. Proceedings of the Dairy3 Conference 4: 167-173.

IDF 2010. International Dairy Federation. A common carbon footprint for dairy: The IDF guide to standard lifecycle assessment methodology for the dairy industry. (http://www.idf-lca-guide.org/Public/en/LCA+Guide/LCA+Guidelines+overview).

IPCC 2006. IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4: Agriculture, Forestry and other Land Use. Intergovernmental Panel on Climate Change. Paris, France. Available at: http://www.ipccnggip.iges.or .jp/public/2006gl/ vol4.htm

Ledgard S F, Luo J and Monaghan R 2003. Partitioning of excreta nitrogen from grazing animals into urine and dung nitrogen. Report to MAF. AgResearch Ruakura. 14p.

Ledgard S F, Basset-Mens C, Boyes M and Clark H 2008. Carbon footprint measurement: Carbon footprint for a range of milk suppliers in New Zealand. Report to Fonterra. AgResearch, Hamilton. 41p.

Ledgard S F, Lieffering M, McDevitt J, Boyes M and Kemp R 2010. A greenhouse gas footprint study for exported New Zealand lamb. Report for Meat Industry Association, Ballance Agri-nutrients, Landcorp and MAF. AgResearch, Hamilton. 26p.

Ledgard S F, Boyes M and Brentrup F 2011. Life cycle assessment of local and imported fertilisers used on New Zealand farms. In: 'Adding to the knowledge base for the nutrient manager'. (Eds. Currie L D, Christensen C L). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 13p.

Ledgard S F, Lorinque E, Gac A, Boyes M and Le Gall A 2012. LCA of sheep meat produced in different farm systems in France and New Zealand. Proceedings 2nd New Zealand Life Cycle Assessment Conference, Auckland. pp. 112-113.

LIC 2009. NZ dairy statistics 2008-2009. Livestock Improvement Corporation limited, Hamilton, New Zealand

PAS 2050 2011. Specification for the measurement of the embodied greenhouse gas emissions in products and services. BSi November 2011.

Saggar S, Clark H, Hedley C, Tate K, Carran A and Cosgrove G 2003. Methane emissions from animal dung and waste management systems, and its contribution to the national methane budget – A report prepared for the Ministry of Agriculture and Forestry, Wellington, New Zealand.

Schmidt J H 2007. Life cycle assessment of rapeseed oil and palm oil. (Ph.D thesis). Aalborg University, Denmark

Thomas S M, Fraser T, Curtin D, Brown H and Lawrence E 2008. Review of nitrous oxide emission factors and activity data for crops August 2008. Crop & Food Research Confidential Report No 2240. A report prepared for Ministry of Agriculture & Fisheries.

Williams I D, Ledgard S F, Edmeades G O and Densely R J 2007. Comparative environmental impacts of intensive all-grass and maize silage-supplemented dairy farm systems: a review. Proceedings of the New Zealand Grassland Association 69: 137-143.

E. Objective 1.4 Opportunities for mitigation and inventory

1.4.1 CASE STUDIES

Introduction

Considerable investments have been made in the search for sustainable land management options and opportunities for mitigation of greenhouse gas (GHG) emissions and nutrient losses from New Zealand (NZ) dairy and sheep and beef farms. However, the required reduction in environmental footprint needs to be compatible with the sustained contribution of the sector to NZ's economy and with high farm profitability to ensure continuity.

Milestones 1.4.1 and 1.4.2 of the project 'Systems analysis to quantify the role of farm management in GHG emissions and sinks for the pastoral sector', were delivered through two interconnected studies, these studies were based on actual farm data and farmer engagement. The first study, which was carried out in 2010/2011, was a small scale scoping study comprising three case studies, which sought to better understand the practices and decision making processes that one sheep and beef and two dairy farmers use in order to be able to farm in a highly productive and profitable manner while maintaining reduced GHG emissions. See attached Client Report- 'Summary report of low emission, high production farming: Three case studies'. This report was written and submitted June 2011 (Appendix 23).

The second piece of work, which was carried out 2011/2012, took the form of a further study which aimed to refine, broaden and build onto the first scoping study by investigating in greater depth, the actions and decision making processes used by a further four farmers that enabled them to achieve low greenhouse gas GHG emissions while still being highly productive and profitable. A crucial focus of both studies was to gain a better understanding about how these farmers arrived at this status in terms of their past and current practices on farm. In this respect, understanding farmers' decision making processes and their consequent actions and impacts provides insight into how farmers have achieved low emission levels on farm while remaining highly productive and profitable units.

The impetus for both pieces of work grew out of previous work carried out by AgResearch staff in the MAF/SFF project 'Raising farmer awareness and understanding of climate change and greenhouse gas impacts, adaptations and mitigations' project and accompanying case study systems modelling which identified farms that were both highly productive and profitable while maintaining reduced emissions. Farmers in the project questioned the practices and decision making processes used by the farmers who were achieving these results, as they perceived these farms to be difficult systems to manage. Therefore, the motivation for both these studies came from farmers' questions.

This report covers the second piece of work, the further four case studies made up of two sheep and beef and two dairy farm cases. Full explanation of the second study is contained in the attached papers and summary report:

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Efficiencies, productivity, nutrient losses and greenhouse gas emissions from New Zealand dairy farms identified as high production, low emission systems. In: *Advanced Nutrient Management: Gains from the Past - Goals for the Future.* (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 25. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Are high production, low GHG emission dairy farms in New Zealand possible? Oral presentation. To be presented at the 2012 ADSA-AMPA-ASAS-CSAS-WSASAS Joint Annual Meeting (July 15-19 2012), Phoenix, Arizona.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Increased productivity and reduced environmental footprint - Are high production, low GHG emission dairy farms in New Zealand possible? Poster presentation. To be presented at the Australasian Dairy Science Symposium (November 13-15 2012), Melbourne, Australia.

White, T.D., Vibart, R., and Smeaton, D. (2011) Summary report of low emission, high production farming: Three case studies. Client report for SLMACC. (Appendix 23).

Methodology

In summary, the methodology used in the second four case studies followed the approach used in the first case studies. That is:

Identification of Farms

An extensive search to identify suitable sheep and beef (S&B) and dairy farms throughout NZ. Among the resources used, farmers that had previously participated in farmer focus groups (i.e. S&B farm D) and personal communication (T. Fraser, AgResearch) were used to identify S&B potential candidates. In addition, DairyNZ's extension team and the DairyNZ-operated DairyBase data collection system (www.dairybase.co.nz) were used to identify potential dairy farms.

Criteria for the selection of these specific farms included a) predominantly pasture-based systems with low levels of imported feed and N fertiliser use, b) high meat and fibre and milk solids (MS) production per animal and per ha, c) fertile breeding flocks and herds with a certain genetic merit (i.e. high breeding worth for dairy cattle; BW), and d) farms with competitive operating profits. Expectedly, these overall criteria would aid in identifying profitable S&B and dairy farms with emissions intensity ≤ 19 kg CO_2-e/ kg meat and fibre and ≤ 9.5 kg CO_2-e/kg MS, respectively.

Once identified, potential candidates were contacted, and following farmers' approval, comprehensive on-farm interviews were conducted, followed by a brief tour of the farm. Briefly, dairy farmers were interviewed during the autumn of 2011, and S&B farmers during the spring of 2011; the data gathered included land use capabilities and carrying capacities, productive and reproductive biophysical indicators, feeding strategies, farming practices, farming philosophies and personal traits (i.e. values, risk analysis and networks used).

Models Used

The whole-farm system models Farmax® Pro and Farmax® Dairy Pro (www.farmax.co.nz; herein Farmax, versions 6.4.5.23 and 6.4.0.12, respectively) were used to set up the farms from the information gathered from the visits to farmers. Farmax was used to examine nutrients offered and required, feed flow, key physical indicators, and financial outputs from the selected S&B and dairy farms. The farms modelled were assumed to be in steady state, both in terms of opening and closing numbers of breeding ewes and cows, and corresponding body weights.

The farm-scale nutrient budget model OVERSEER® (www.overseer.co.nz; herein Overseer, version 5.4.10) was used to examine some of the environmental impacts and nutrient losses of the selected farms. Information on farm physical characteristics, stocks and management decisions from Farmax was exported and used to parameterize Overseer.

Case studies

Two farms in West Otago (farms A and B), one in Canterbury (farm C) and one in King Country (farm D) were identified as potential high production, low emission sheep and beef farming systems. Similarly, two farms in the Waikato (farms A and B) and two in Southland (farms C and D) were identified as potential high production, low emission dairy systems. Identifying suitable farms, dairy in particular, that fitted the criteria of high production, low emission proved to be a difficult task; less than 5% of the farms within the database held potential for review.

Farmer Interviews

Interviews were a process including both an interviewer and a modeller. In this way, enquiries seeking information for modelling the farm system also gave the opportunity to explore the decision making around the practices, processes and technologies undertaken on farm and vice versa.

Interviews were undertaken on farm where questions exploring the farming system and its dynamics were asked. Interviews were recorded, transcribed and the transcripts returned to the farmers for review. The quantitative information was then modelled while the qualitative descriptive information was analysed for key trends and themes.

An important part of this study focused enquiry into the cultural approaches that farmers took to practices and decision making on farm. In particular, we sought to explore if was there 'something different ' that farmers did on farm that resulted in them achieving low total emissions and high productivity or was there something in particular about the type of farmer and farming family that resulted in them meeting these criteria. Or was it a combination of both practice and farmer characteristics?

Interviews sought to understand past, current and future goals of farmers both in their family and farming situations. This provided an indication of farmers' motivations for decisions and more broadly how farmers had selected the direction they had taken with farming opportunities. It was important to understand how the farmer had set the boundaries they worked within in terms of farm size and herd size as well as choices about further investment in farming.

Pasture and stock management as well as stocking rates and resources such as nutrient use had been identified previously as important contributors towards lower emission farming. Therefore, these themes provided a focus for the interviews to seek to better understand better how the farmer decided what practices and timing they employed and why. An understanding of how farmers evolved their business strategies, market opportunities and networks were also a focus of the interviews.

Study Limitations

This study sought to examine in depth four additional examples of low emission, high producing farms in order to broaden the original scoping study. However, it must be stressed that the four case farms in this second study were selected based on emissions and production and cannot be considered indicative of all farms and farmers, and caution should be used in extrapolating the findings across farming more broadly.

Findings

In summary: the main findings from this year's case studies were:

On farm practices- Sheep and beef

Emissions intensity ranged from 14.3 to 16.3 kg CO_2-e/kg meat and fibre; these values compared favourably with other values reported in the literature and were within the lowest quartile of a greater modelling dataset provided by farmer focus groups located throughout NZ (Duchemin, 2011).

Expectedly, because of the intrinsic link between dry matter intake (DMI) and methane emissions (that made up to 72% of total GHG emissions), efficiencies in terms of feed conversion (i.e. the amount of dry matter required per unit of meat and fibre produced) are critical to the achievement of emission efficient farms. Feed conversions achieved by these farms (mean ± SD 23.9 ± 1.9 kg DMI/kg meat and fibre produced) were more efficient than those of the dataset (25.7 ± 2.6).

Similarly, ewe weaning (mean ± SD 143 ± 5%) and ewe replacement rate (25 ± 1%) were associated with lower emissions intensity. Combined, these variables were able to explain ~66% of the variation in emissions intensity. Beef ratios in the stock mix showed no relationship with emissions intensity and total emissions.

Total emissions from the selected farms ranged from 3.69 to 4.94 tonnes CO_2-e/ha. Compared with the dataset, these farms had slightly greater total emissions (4.27 vs. 3.92 tonnes CO_2-e/ha).

On farm practices- Dairy

- Emissions intensity ranged from 8.4 to 9.6 kg CO_2-e/kg MS, well below the average NZ farm range (11 – 13 kg CO_2-e/kg MS). These findings are consistent with low stocked, low N fertiliser use farming practices.

- Three out of the four selected dairy farms were particularly on target at being highly profitable, productive, and emissions efficient. Lower emissions intensity (kg CO_2-e/kg MS) farms tended to be more profitable, achieve greater feed conversion efficiencies (kg MS/kg DM consumed) and N conversion efficiencies (amount of N in product/total amount of N input), carry lower liveweights (LW) per unit of land and achieve an almost 1:1 ratio of MS production per kg LW.

- The selected farms were efficient in terms of N utilisation, farm A in particular. Low stocking policies along with reduced N fertiliser loads and high producing cows largely contributed to this achievement. Body condition score (BCS) targets (5.0 at calving and a BCS of 4.0 or above at mating) were largely met by these farms. Breeding worth, a measure of genetic merit of these herds, however, was seemingly less related to emissions intensity.

Farmer decision making rules and patterns

None of the case study farmers had intentionally farmed to achieve low total emissions and while most farmers thought that climate change was an issue for society, this was not something of focus on their farms currently beyond potential ETS impacts.

The surveyed farmers worked towards achieving simple to use systems on farm while seeking to attain maximum results. Often innovations in practice, process, or technology had been adopted or adapted.

Farmers had a very strong focus on maximising feed efficiencies through:

- Utilisation of feed made on farm through pasture and stock management as well as genetic gains.
- A strategic approach to stock type and class in relation to the business plan or market opportunities.

The farmers had rules (either formally written down or informally known from experience) where trigger points for action were identified. Key points were:

- Most rules were intuitive and the farmers found it difficult to describe these to others.
- While trigger points indicate change must occur, the actual actions may vary, providing these farmers with the opportunity for flexibility in their systems.
- Learning from past experiences is vital for farmers in these businesses.
- Farmers emphasised the need to think of the long term gains of today’s actions. This pertains to both participating in their communities as well as their businesses.

These farmers' (and their families') farming philosophy and lifestyle are very important components of their approach to farming. An example of this was evident where farmers had decided to maintain lower stocking rates, than many other farmers in their regions, because this was a better fit for how they see themselves in farming and the style of farming they find rewarding.

- Farmers' value systems are vital to their approach to farming especially in areas affecting family, animal health/welfare, work life balance and environmental care.

Managing farms within existing boundaries and with available resources is important for the types of farm systems chosen by the surveyed farmers as well as keeping an eye to achieving farm succession goals.

Discussion

In summary: the main discussion points from the additional case studies were:

1. On farm practices- Sheep and beef

Greater reproductive efficiencies and lower replacement rates are critical to emission efficient sheep and beef farms. These efficiencies are also closely linked with financial efficiencies.

Important trade-offs remain between emission intensities and total emissions. However, these farms were commercial examples of emission efficient farms in synchrony with competitive total on-farm emissions.

2. On farm practices- Dairy

The selected farms opted for nutritional diets with a high intake potential, capable of producing 1 kg MS per kg liveweight without compromising profitability.

The current scoping study provided for commercial working examples of the opportunities for highly profitable, emission efficient dairy farms, particularly farms A in the Waikato, and C and D in Southland.

Overall, the farmers selected were characterised as highly organised, committed, flexible, knew how and when to delegate farm chores to trained staff, and were open to seek new farming practices and opportunities. A highly proactive approach, along with timely decisions, was a common feature among these farmers.

3. Farmer decision making rules and patterns

The surveyed farmers were all strong strategic planners who had set long term goals that fitted their own farming philosophy. These farmers intuitively made decisions on farm, an approach that was strongly based on their own prior experiences and active learning on farm, as well as engagement in information networks. The survey participants had well defined ideas of what the land and animals were capable of producing for them with the resources available and were confident of working within these boundaries to achieve productivity goals. All of the farmers were achieving high productivity without forcing their systems.

In summary, it was difficult within this small number of case studies to identify specific actions or decision rules that the case study farmers used that differentiated them significantly from their farming peers. However, it appears that they were efficient at farming all components of their systems, rather than just some. Maybe it is this factor which differentiates them from other farming systems in their districts. But maybe if the study was extended to a larger group of participants it would be found that there are already a number of New Zealand farmers farming systems which are highly productive whilst having low total emission factors.

F. General Discussion

Two different approaches have been taken within this project to determine critical leverage points for sheep, beef and deer sectors which may be used by farmers to reduce either total GHG emissions or emissions intensity. These different approaches have enabled a deeper perspective to be gained on farm management and GHG.

Duchemin (2011) and Vibart et al. (2012, in preparation) in Objective 4 have collated whole farm system models from an extensive range of Sheep / Beef / Deer and Dairy farms throughout New Zealand. The total emissions, emissions intensity and profitability have been determined using Farmax and Overseer modelling. The farm key performance indicators have then been investigated to identify factors that are correlated with reductions in either total emissions or emissions intensity. A number of important factors have been identified, including ewe weaning percent, ewe replacement rates, and the proportion of beef animals which are trading or grazing stock as opposed to breeding. High ewe weaning percent, low ewe replacement rates, and a high proportion of trading stock were all associated with reduced emissions intensity but higher total emissions.

Wall and Dennis (2012, this report) have then taken models of representative farms, and changed each one of these factors on an individual basis to determine to what degree emissions can actually be altered using these factors on an individual farm. However they have found that some of these factors do not actually have an effect, or even have the opposite effect to what the inter-farm comparisons would indicate.

For instance, across a large number of farms, high weaning percentages are correlated with high total GHG emissions (Duchemin, 2011; Vibart et al., 2012). However when weaning percentage was increased on an individual farm, it actually reduced total GHG emissions (Wall and Dennis, 2012).

It is vital to remember that correlation does not necessarily mean causation. High weaning percentages are generally achieved on more intensive farms, often on higher production land. These farms naturally have higher than average total GHG emissions due to their high productivity, resulting in high weaning percentages being correlated with high total GHG emissions. However on an individual farm, an increase in weaning percentage causes an increase in the spring & summer pasture requirements of lambs. This requires a reduction in ewe numbers, reducing methane emissions from ewe maintenance feed intake over winter. On the individual farm, increasing weaning percentage can therefore reduce total emissions. Both study methods agree that high weaning percentages reduce emissions intensity.

Across a large number of farms, low ewe replacement rates are associated with low emissions intensity. However when ewe replacement rate was reduced on an individual farm, it did not change emissions intensity.

Farms that have achieved a low ewe replacement rate will have done so partly through efficient management. An efficient manager will achieve high production from their available pasture resource through a range of means (such as improved weaning percent), which will reduce emissions intensity. This results in low ewe replacement rate being correlated with low emissions intensity. But for an individual farm, any reduction in emissions from hoggets by reducing emissions intensity is balanced out by an increase in ewe emissions, as a higher ewe stocking rate can now be carried on the available feed. Ewe replacement does not therefore in itself greatly affect emissions intensity. Although it initially appeared to be a valuable strategy to pursue to reduce emissions based on the farm comparisons, more detailed testing contradicted this.

We have discovered that comparisons between individual farms are a useful way of identifying critical leverage points for emissions. However these studies are not able to determine whether or not this apparent leverage point will actually have an effect on an individual farm, or even conclude whether it will increase or decrease emissions. Each potential leverage point must be carefully investigated for an individual farm in the light of the implications it has for the emissions from the entire farm system, before it can be determined whether it should be promoted as a mitigation option.

Importantly, we have even discovered leverage points which initially appeared to increase total GHG emissions, but on more detailed analysis may actually be able to reduce total emissions (e.g. ewe weaning percent). These measures may have much greater scope than initially thought to assist New Zealand in meeting its Kyoto and future GHG commitments, while improving farm profitability.

So far we have tested leverage points discovered using inter-farm comparisons, and have collated a vast amount of knowledge on the factors affecting emissions from whole farm systems. However there may be other leverage points which were initially dismissed as ineffective, or not even seen in the inter-farm comparisons, that will in fact reduce emissions from an individual farm. Further work is needed on individual leverage points to discover further farm system changes which farmers may be able to use to reduce emissions from their farms.

References

Duchemin, M. *Greenhouse Gas Emissions in Dairy and Sheep & Beef Systems: a Cross-sector Analysis*. Sustainable Farming Fund project C08/008 report. Ministry for Primary Industries, 2011. http://maxa.maf.govt.nz/sff/about-projects/search/C08-008/cross-sector-analysis-ghg-emissions.pdf.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Efficiencies, productivity, nutrient losses and greenhouse gas emissions from New Zealand dairy farms identified as high production, low emission systems. In: *Advanced Nutrient Management: Gains from the Past - Goals for the Future.* (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 25. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Are high production, low GHG emission dairy farms in New Zealand possible? Oral presentation. To be presented at the 2012 ADSA-AMPA-ASAS-CSAS-WSASAS Joint Annual Meeting (July 15-19 2012), Phoenix, Arizona.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Increased productivity and reduced environmental footprint - Are high production, low GHG emission dairy farms in New Zealand possible? Poster presentation. To be presented at the Australasian Dairy Science Symposium (November 13-15 2012), Melbourne, Australia.

White, T.D., Vibart, R., and Smeaton, D. (2011) Summary report of low emission, high production farming: Three case studies. Client report for SLMACC.

G. Appendices

APPENDIX 1

MODELLING GHG EMISSIONS FROM DAIRY FARMS. REVIEW AND RECOMMENDATIONS

Prepared for the SLMACC project, Milestone 1.1.1

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MODELLING GHG EMISSIONS FROM DAIRY FARMS. REVIEW AND RECOMMENDATIONS

Introduction

The topic of GHG emission from dairy cows has been extensively reviewed recently, particularly on enteric methane emission. This report focuses on whole farm level studies, not necessarily whole farm models, which have a focus on GHGs. The idea was to see “how other people do it”, specifically overseas, in order to guide future model developments in New Zealand.
Section 0 comments on recent literature reviews on the topic. Sections 0 to 0 onwards briefly explain the methods used in nine major farm scale modelling efforts identified in the literature to estimate GHG emissions. Finally, section 0 offers some recommendations.
The objective is to identify major international whole farm modelling efforts and list the GHG considered, including their sources and methods used to calculate them.

Recent literature reviews

Ellis et al. (2010) recently evaluated eight methane prediction equations used in 6 whole farm models found in the literature (WFM, SIMS Dairy, FarmSim, Farm GHG, Phetteplace et al., 2001, Schils et al., 2005 and DairyWise). They only evaluated empirical equations. Unfortunately, in the case of DairyNZ’s WFM, Ellis et al. did not report the fact that the model included empirical equations as well as mechanistic prediction generated by Molly.
Latter in the same year, Sejian et al. (2010) published a literature review about prediction of enteric methane emissions. They mention 12 different empirical equations and 2 mechanistic models [Molly and Dijsktra et al., (1992), although they regarded the different versions these models and their publications as different models]. The paper cites two whole farm models, the Integrated Farm System Model (Rotz et al., 2009) and the DairyNZ’s WFM. The comments about the WFM are extremely inaccurate, including listing three articles (1997-1999) describing the WFM, as if they were three different models, and wrongly saying that “these models” are adequate only for predicting CH_4 production by “non-lactating” cows. They refer to the Ellis et al. (2010) paper, incorrectly implying that all currently available whole farm models only use empirical regression equations to predict methane emissions.
A non-exhaustive list of previous reviews of methane emissions from cattle include Bannink et al. (1997); Benchaar et al. (2001); Mills et al. (2003); Saggar et al. (2004); Kebreab et al. (2006); Tamminga et al. (2007) and Chianese et al. (2009b). Schils et al. (2007a) reviewed four whole farm GHG models, including their own DairyWise, plus FarmGHG, $SIMS_{DAIRY}$ and FarmSim, and discussed potential applications for each of these models.

Dairy greenhouse gas model (DairyGHG)

The Dairy Greenhouse Gas Model (DairyGHG) is a software tool for estimating the greenhouse gas emissions and carbon footprint of dairy production systems (Rotz and Chianese, 2009; Rotz et al., 2010). It is well documented in several recent publications, see detail in Table 1, and available online[1].

Table 1: GHG emission methods used in the DairyGHG model

GHG	References found	Source	Method
CH_4	Chianese et al. (2009c)	Enteric fermentation	Nonlinear model developed by Mills et al. (2003).
		Barn	Manure on housing facility floors. Adaptation of IPCC (2006) tier 2
		Manure storage	Based on Sommer et al. (2004)
		Field-applied manure	Function of VFA content in the manure (see Sherlock et al., 2002).
		Grazing	0.086 g/kg feces deposited by the animal on pastures
N_2O	Chianese et al. (2009d)	Cropland	1% of N applied IPCC (2007)
		Pasture land	2% of N applied IPCC (2007). N applied =f(DM intake, CP)
		Barn	IPCC (2006) tier 2
		Manure storage	Liquid/slurry: 0.8 g N_2O/day/ m^2 of exposed area. Stacks: IPCC (2006)
CO_2	Chianese et al. (2009a)	Cropland	Simple carbon balance
		Animal respiration	f(DM intake, $BW^{0.75}$)
		Barn floor	f(Temperature, area covered by manure)
		Manure storage	Uncovered:0.04 kg CO_2/m^3/day Covered: 0.008 kg CO_2/m^3/day
		Engine combustion	2.637 CO_2e/l of diesel consumed

Integrated Farm System Model (IFSM)

Developed by the same team as Dairy GHG, but it is a more complex tool that evaluates emissions and the footprint along with nitrogen and phosphorus losses and farm economics (Rotz et al., 2009). It represents a step up from DAFOSYM (Rotz et al., 1989). Details related with GHG are shown in Table 2. It is also well documented and available online[2].

Table 2: GHG emission methods used in the IFSM model

GHG	References found	Source	Method
CH_4	Chianese et al. (2009c)	Enteric fermentation Barn Manure storage Field-applied manure Grazing	Same as Dairy GHG
N_2O	Chianese et al. (2009d)	Cropland	DayCent model[3]: process-based, accounting for how management scenarios affect the moisture content, pH, nitrate concentration, and ammonium concentration in the soil (Del Grosso et al., 2000; Parton et al., 2001). It is the daily time-step version of the CENTURY biogeochemical model. Considers nitrification and de-nitrification losses.
		Pasture land	Not mentioned in the source
		Barn	Same as Dairy GHG
		Manure storage	Same as Dairy GHG
CO_2	Chianese et al. (2009a)	Cropland	Improvement of the DayCent model
		Animal respiration Barn floor Manure storage	Same as Dairy GHG

[1] http://www.ars.usda.gov/Main/docs.htm?docid=17355
[2] http://www.ars.usda.gov/Main/docs.htm?docid=8519
[3] http://www.nrel.colostate.edu/projects/daycent/index.html

		Engine combustion	

DairyWise

DairyWise is an empirical model, described in detail by Schils et al. (2007b), developed by the Animal Sciences Group, at Wageningen University. The model is used, for research and teaching for technical, environmental and financial simulations of dairy farms (Table 3). All the equations in the model are available online[4], and t a stand-alone version of the model can be obtained from the Animal Sciences Group.

Table 3: GHG emission sources considered in the DairyWise model

GHG	References found	Source	Method
CH_4	Schils et al. (2006)	Enteric fermentation	Empirical. Dutch emissions inventory factors. Differing factors for concentrate, grass products and maize silage
		Manure storage	Dutch emissions inventory factors.
N_2O		Manure Excreted N during grazing Manure application Fertilizer use Crop residues Mimeralization from peat soils Grassland renewal Biological N fixation NO_3 leaching (indirect) NH_3 volatilization (indirect)	
CO_2		Fossil fuel Electricity (indirect) Imported feed (indirect) Fertilizer production (indirect)	
		Energy consumption (indirect)	Dutch emissions inventory factors. Considering Buildings, machinery and contractor services

SIMS$_{Dairy}$

The *Sustainable and Integrated Management Systems for Dairy Production* (SIMS$_{DAIRY}$) is a deterministic modelling framework which simulates at the farm level the effect of the interactions between farm management, site conditions and plant/animal theoretical genetic traits on: N cycling, N and P losses, CH_4 losses, farm economics and sustainability attributes of biodiversity, landscape, product quality, soil quality and animal welfare (del Prado et al., 2010). This model is sensitive to variations in management, weather, topography and soil characteristics, and it runs in monthly time steps. It is capable of optimizing management practices to meet user multi-weighted criteria. Some details in Table 4. The publications do not mention if the model available or not.

Table 4: GHG emission sources considered in SIM$_{Dairy}$.

GHG	Source	Method
CH_4	Enteric fermentation	Empirical equation that relates animal DM intake and the degree of unsaturation of the fatty acids in the diet with CH_4 output expressed per kg of DM intake. Prediction of DM intake is calculated as a function of forage intake potential, concentrate dry matter intake, animal condition score, animal weight, milk energy output, week of lactation and forage starch concentration.
	Excreta	Using emission factors (per animal) for applied manure and dung excreted during grazing.

[4] http://library.wur.nl/way/bestanden/clc/1847073.pdf

GHG	Source	Method
N_2O	Soil	Soil emissions from each land area are simulated through nitrification and denitrification processes as described by Brown et al. (2005, NGAUGE model). Total denitrification is modelled as a function of soil inorganic N, water-filled pore space (WFPS) and temperature using a monthly time-step. Subsequently, N_2O is calculated from the N_2O:N_2 ratio, which is a function of WFPS, mineral N flux and mineralized N in the soil. Total N_2O emission from nitrification is modelled as a function of the maximum potential rate of N_2O emission from nitrification with modification factors based on nitrification rate and soil moisture.
	Manure	N_2O emissions together with NH_3, NO_x and N_2 emissions are simulated from the pool of total ammonium nitrogen in manure N according to different emission factors for different manure management stages.
CO_2	Pre-farm emissions	Purchased concentrates and manufactured inorganic fertilizers.
	Soil C balance	Considering potential change in soil stocks by adopting a system with higher or lower frequency of cultivation, including some CH_4 oxidation by soil.

FarmSim

FarmSim is a simulation framework allowing the description of mixed crop-ruminant farms and calculation of inherent emissions (Fiorelli et al., 2008). It simulates above and below ground C and N fluxes in interaction with cattle, and calculates the net balance of GHG emissions in daily time steps. In the case of grasslands, it has a fully dynamic calculation of fluxes of CO_2, N_2O and CH_4 using the PaSim model (originated from the model of Thornley, 1998)[5], which includes the effect of grazing animals. The emissions from croplands are calculated by the CERES-EGC model, also a mechanistic fully dynamic model. It uses IPCC methodology (Tier 2) for all other emissions.

According to Fiorelli et al. (2008), at the moment there is no animal production model coupled with PaSim and CERES. Emissions associated with animal wintering, livestock housing and manure storage are calculated using IPCC methodology. In the same way, direct and indirect emissions associated with the production and providing of imported feed (including transport to the farm) are also accounted for considering the use of fuel, electricity, fertilizers, veterinary products, pesticides, concentrate and other supplies.

Table 5: GHG emission sources considered in FarmSim.

GHG	Source	Method
CH_4	Enteric emissions	The publications indicate that PaSim predicts the effects of diet quality on the emissions of methane from grazing animals, but no details are provided. Ellis et al. (2010) comments that FarmSim uses IPCC (1997, Tier I), but referring to a 2004 conference article.
	Barn	IPCC
	Manure storage	IPCC
N_2O	Cropland	CERES-EGC, full N balance
	Grasslands	PaSim model, full N balance
	Barn	IPCC
	Manure storage	IPCC
CO_2	Soil carbon cropland	CERES-EGC, full C balance
	Soil carbon grasslands	PaSim model, full C balance
	Fertilizers	IPCC
	Veterinary products	
	Pesticides	
	Concentrate	
	Other supplies	

[5] https://www1.clermont.inra.fr/urep/modeles/pasim.htm

FarmGHG

FarmGHG, developed at the Danish institute of Agricultural Sciences, is a model of C and N flows on dairy farms (Olesen et al., 2004; Olesen et al., 2006), which is available for download and fully documented[6]. The model was designed to allow quantification of all direct and indirect gaseous emissions from dairy farms on monthly time steps. The model includes indirect N_2O emissions associated with N losses, and pre-chain emissions from imports of products, but not emissions after the exported products have left the farm. The imports, exports and flows of all products through the internal chains on the farm are modelled. The model thus allows assessments of emissions from the production unit and all pre-chains. FarmGHG includes C and N balances, and it allows calculation of GHG emissions (CO_2, CH_4 and N_2O) and eutrophication (nitrate and NH_3). See Table 6 for details.

Table 6: GHG emission sources considered in FarmGHG

GHG	Source	Method
CH_4	Enteric emissions	IPCC tier 1, IPCC tier 2 or the Kirchgeßner equation
	Housing	Slurry based systems, IPCC (1997, 2000) Deep litter systems, IPCC (2000)
	Manure storage and treatment	Slurry: IPCC (1997, 2000) or own (default) empirical calculations Liquid: IPCC (1997, 2000) or own (default) empirical calculations Solid: IPCC (1997, 2000) or own (default) empirical calculations Deep litter: IPCC (1997, 2000) or own empirical calculations
	Fields and crops	IPCC (1997, 2000) from faeces deposited on grazed grasslands
	Prechain emissions	Diesel, electricity, fertilizers, pesticides, imported feeds and seeds, straw for bedding, field operations (via fuel use)
N_2O	Housing	Slurry: IPCC (2000) or own (default) empirical calculations Liquid: IPCC (2000) or own (default) empirical calculations
	Manure storage and treatment	IPCC (2000) Slurry: IPCC (2000) or own (default) empirical calculations Liquid: IPCC (2000) or own (default) empirical calculations Solid: IPCC (2000) or own (default) empirical calculations Deep litter: IPCC (2000) or own empirical calculations
	Fields and crops	Direct: IPCC (1997, 2000), considers N on crop residues, N fixations, N deposited by animals.
	Prechain emissions	Diesel, electricity, fertilizers, pesticides, imported feeds and seeds, straw for bedding, field operations (via fuel use)
	Indirect N_2O loses	N leaching (2.5%). N leaching is simply 30% of all N inputs. Ammonia volatilization (1%). From manure storage and treatment (according of manure type and storage method) and from fields and crops (IPCC, 1997 or own according to type of fertilizer or applied manure and season).
CO_2	Prechain emissions	Diesel, electricity, fertilizers, pesticides, imported feeds and seeds, straw for bedding, field operations (via fuel use)

Phetteplace et al. (2001)

The model presented by Phetteplace et al. (2001) is computer spreadsheets describing current GHG emissions, soil carbon sequestration/emissions and economics of U.S. beef and dairy production systems. It can be used to test GHG

6 http://agrsci.au.dk/en/institutter/department_of_agroecology_and_environment/xxmedarbejdere_old/jeo/farmghg_a_model_for_estimating_greenhouse_gas_emissions_from/

mitigation strategies and evaluate changes in GHG emissions, meat and milk production and economics (Table 7).

Table 7: GHG emission sources considered in the model of Phetteplace et al. (2001).

GHG	Source	Method
CH_4	Enteric fermentation	Six percent of dietary energy was expended for CH_4 production in the cow-calf, stocker and dairy systems, while a CH_4 coefficient of 3.5% was used in feedlot calculations. A CH_4 coefficient of 6% for young calves was applied to the plant-derived fraction of the diet.
	Manure	IPCC (2006)
N_2O	Grazing	Direct and indirect, IPCC (2006)
	Manure	Direct and indirect, IPCC (2006)
CO_2	Fertilizer synthesis	IPCC (2006)
	Fuel	Used during animal and crop management, including transportation. IPCC (2006)
	Pesticides	IPCC (2006)

Hörtenhuber et al. (2010)

Hörtenhuber et al. (2006) developed models for different Austrian dairy production systems, using MS Excel for calculation and taking into account emissions of CH_4 and N_2O from enteric fermentation and from manure management, as well as of CH_4, N_2O and CO_2 from soil, from the use of fuels and other energy sources and from production and application of mineral fertilizers and pesticides.

Table 8: GHG emission sources considered by Hörtenhuber et al. (2006).

GHG	Source	Method
CH_4	Enteric fermentation	Empirical, using Kirchgeßner et al. (1995) (conference paper, not found). Emissions from rearing replacement and fattening of heifers (beef by-product) are also considered.
	Manure management	IPCC (2006, tier 2), with factors for slurry, farmyard manure and pasture.
N_2O	Manure management	IPCC (2006, tier 2), with factors for slurry, farmyard manure.
	Soil	Direct: based on the amount of nitrogen introduced into the soil (IPCC, 2006 tier 2), including mineral fertilizers, mineralization, manure and crop residues and N excreted by cows on pasture. Indirect: from deposited nitrogen and leaching were estimated according to IPCC (2006)
CO_2	Animals	Assumed zero, compensated by photosynthesis of plants
	Imported feed	Land use chance (i.e. forest clearance, grassland to arable): soybean from South America, rapeseed from Eastern and Central Europe, etc.
	Soil C balance	CO_2 sequestrated into soil or released from soil organic carbon stocks according to land management (following Küstermann et al., 2008, model software REPRO). Also soil carbon change emissions from imported concentrates are considered.
	Fuel Electricity Fertilizers Veterinary products Pesticides	Empirical factors, using several sources (see table 5 in source).

Moorepark Dairy System Model

O'Brien et al. (2010) developed a GHG model to quantify emissions, which is a submodel of the Moorepark Dairy System Model (MDSM, Shalloo et al., 2004). MDSM is a whole farm simulation model of grassland based dairy farm. The GHG model calculates emissions based on day-to-day farming activities (e.g. spreading of slurry) and also calculated indirect emissions (e.g. manufacture of concentrates). It does a comprehensive account of emissions of CO_2, CH_4 and N_2O (Table 9).

Table 9: GHG emission sources considered by O'Brien et al. (2010)

GHG	Source	Method
CH_4	Enteric fermentation	Different empirical equation according to animal and feed type
	Slurry application spreading	
	farmyard manure storage	
	Slurry and dirty water storage	
	Silage effluent	
N_2O	Pastorally deposited dung	Empirical factors, using several sources (see table 2 in source).
	Pastorally deposited urine	
	N fertilizer application	
	Slurry spreading	
	farmyard manure spreading	
	farmyard manure storage	
	Slurry storage	
	Nitrate leaching (Indirect)	IPCC (2006)
	Ammonia deposition (Indirect)	Indirect, 0.01 × (sum of NH_3 sources)
CO_2	Diesel combustion	Empirical factors, using several sources (see table 3 in source).
	Lime use	
	Diesel production (Indirect)	
	Electricity production (Indirect)	
	Lime production (Indirect)	
	N fertilizer production (Indirect)	
	Concentrate production (Indirect)	

Other modelling efforts

There are many other modelling efforts in the literature looking at GHG emissions from dairy at the whole farm level, but were not covered at this point due to the small amount of time assigned to this task or lack of detail in the sources. It would be worth looking at the way they do the GHG calculations in more detail in the future. Some examples are briefly introduced.

The work of Hartmann et al. (2009) describe the use a mathematical programming model, S_INTAGRAL (Swiss integrated agricultural allocation model), developed to enable the assessment of cost-effective strategies for mitigating GHG and nitrogen emissions in the agricultural sector in Switzerland. It is a recursive, linear, sectoral, supply model of Swiss agriculture. S_INTAGRAL is based on a regional farm approach and covers the Swiss agricultural sector (national level).

Sintory and Tsiboukas (2010) evaluated the GHG emissions of Greek dairy sheep farms, through the use of a whole farm linear programming model that uses farm level data and optimizes total gross margin. Their model considers all the potential sources of GHGs, including CH_4 from enteric fermentation and manure, nitrous N_2O from excreta and fertilizer and CO_2 from the use of machinery.

Zeddies et al. (2000) used a linear programming economic farm model that map the specific production structures of dairy farms in South West Germany. They consider direct and indirect CH_4, N_2O and CO_2 emissions and explore the potential of various reduction strategies and the cost associated with such measures.

In order to identify cost-effective measures to reduce emissions for dairy cattle in the Czech Republic, Havlikova et al. (2010) used a static optimization model (DAIRY). The model minimizes the total cost of realizing environmental targets at the national and subnational level. The model considers several pollutants, including N_20 and CH_4.

Also working at a regional scale, Neufeldt and Schäfer (2008) used the Economic Farm Emission Model (EFEM) to estimate possible environmental and economic

impact of different mitigation regulations for typical farming systems (including dairy) in the German federal state of Baden-Württemberg. EFEM works at the farm and regional scale, with energy and matter fluxes linked to published emission factors to estimate N_2O from soil (direct and indirect), CH_4 for enteric fermentation and manure and CO_2 form fertilizer production, fuel, agrochemicals, plant drying, heating of animal houses and additional feed. EFEM was coupled with the agro-ecosystem model DNDC, to estimate the soil GHG emissions based on land use and activity, soil parameters and weather.
Surely there are many other studies worth featuring in a more extensive literature review, as this is an extremely hot topic in the literature. Time limitations impeded to continue further, hopefully this report may serve as a starting point for a more thorough investigation.

Recommendations

We are in a good position regarding enteric CH_4, in the sense that we have a dairy whole farm model which included a highly mechanistic full cow model, while all other whole farm models found on this non-exhaustive literature review only use simple empirical equations. Having mechanistic CH_4 predictions linked to a whole farm model is important for two reasons. First, simple empirical equations do not capture dietary changes well (Tamminga et al., 2007; Ellis et al., 2010). Second, whole farm system models allow a proper consideration of aspect like herd structure and short term changes in diet. Good progress is also being made with N_20 emissions from the soil using APSIM.
However, enteric CH_4 represents between 56 to 65% of the total global warming potential on New Zealand dairy farms (Basset-Mens et al., 2009). So, being able to accounting for all the other GHG sources (e.g. CH_4 emissions from ponds, indirect N_2O from NH_3, CO_2 from electricity and fuel, and pre-farm gate emissions) is obviously important, and compared with models like IFSM or $SIMS_{DAIRY}$, we are clearly lagging behind. Schils et al. (2005) compared two case study farms with contrasting livestock density and grassland management and concluded that the inclusion of carbon sequestration factors and all indirect emissions (whole farm approach of full accounting) have a major impact on the GHG budget of the farm. More intensive dairy systems, which include more housing, more feedpads, more imported feed and more machinery, are increasing their prevalence in New Zealand. One could expect that, in these more intensive systems, a larger proportion of the GHG will be coming from sources other than enteric fermentation, like effluent ponds, manure stacks, and indirect emissions (e.g. electricity usage, supplement production and transport, etc.) (Martin et al., 2010). Leaving those sources out could bias system comparisons. Furthermore, important mitigation opportunities could be missed by focusing only on enteric fermentation (see for example Pratt et al., 2010). The recommendation of this report in to continue making progress in mechanistically predict enteric CH_4, and soil N_20 at whole farm level, but at the same time develop ways of predicting the other GHG sources from whole farm model. The most logical way would be to dynamically connect farm production models with tools like Overseer or Carbon Footprint (developed by Fonterra and MAF). It is indeed possible to extract results from farm models and manually input them into Overseer or some other model (e.g. Beukes et al., 2010), but this approach is very limiting and time consuming, particularly when trying to do optimizations, or large factorial

modelling experiments. Also, acquiring Alan Rotz's and Agustin del Prado's[7] models (IFSM and $SIMS_{DAIRY}$, respectively) and establishing collaboration links with those teams would be desirable to avoid duplications and quickly converge to common calculation procedures.

[7] BC3-Basque Centre for Climate Change, Spain

References

Bannink, A., De Visser, A., van Vuuren, A.M., 1997. Comparison and evaluation of mechanistic rumen models. British Journal of Nutrition 78, 563-581.

Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecological Economics 68, 1615-1625.

Benchaar, C., Pomar, C., Chiquette, J., 2001. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. Canadian Journal of Animal Science 81, 563-574.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G.L., Waghorn, G.C., 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agricultural Ecosystems and Environment 136, 358-365.

Brown, L., Scholefield, D., Jewkes, E., Lockyer, D., Del Prado, A., 2005. NGAUGE: A decision support system to optimise N fertilisation of British grassland for economic and environmental goals. Agriculture, Ecosystems & Environment 109, 20-39.

Chianese, D., Rotz, C., Richard, T., 2009a. Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies.

Chianese, D., Rotz, C., Richard, T., 2009b. Whole-farm greenhouse gas emissions: A review with application to a Pennsylvania dairy farm. Applied Engineering in Agriculture 25, 431-442.

Chianese, D.S., Rotz, C.A., Richard, T.L., 2009c. Simulation of methane emissions from dairy farms to assess greenhouse gas reduction strategies. Transactions of the ASABE 52, 1313-1323.

Chianese, D.S., Rotz, C.A., Richard, T.L., 2009d. Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Transactions of the ASABE 52, 1325-1335.

Del Grosso, S., Parton, W., Mosiere, A., Ojima, D., Kulmala, A., Phongpan, S., 2000. General model for N_2O and N_2 gas emissions from soils due to denitrification. Global Biogeochemical Cycles 14, 1045-1060.

del Prado, A., Chadwick, D., Cardenas, L., Misselbrook, T., Scholefield, D., Merino, P., 2010. Exploring systems responses to mitigation of GHG in UK dairy farms. Agriculture, Ecosystems & Environment 136, 318-332.

Dijkstra, J., Neal, H.D.S.C., Beever, D., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. Journal of Nutrition 122.

Ellis, J.L., Bannink, A., France, J., Kebreab, E., Dijkstra, J., 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. Global Change Biology 16, 3246-3256.

Fiorelli, J., Drouetb, J., Duretzb, S., Gabrielleb, B., Grauxc, A., Blanfortd, V., Capitainee, M., Cellierb, P., Soussanac, J., 2008. Evaluation of greenhouse gas emissions and design of mitigation options: a whole farm approach based on farm management data and mechanistic models, 8th European IFSA Symposium, Clermont-Ferrand, France.

Hartmann, M., Huber, R., Peter, S., Lehmann, B., 2009. Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model. IED Working paper.

Havlikova, M., Kroeze, C., 2010. Reducing environmental impact of dairy cattle: A Czech case study. Integrated Environmental Assessment and Management 6, 367-377.

Hörtenhuber, S., Lindenthal, T., Amon, B., Markut, T., Kirner, L., Zollitsch, W., 2006. Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change. Renewable Agriculture and Food Systems, 1-14.

Kebreab, E., France, J., McBride, B.W., Odongo, N., Bannink, A., Mills, J.A.N., Dijkstra, J., 2006. Evaluation of models to predict methane emissions from enteric fermentation in North American dairy cattle, In: Kebreab, E., Dijkstra, J., Bannink, A., Gerrits, W.J.J., France, J., . (Eds.), Nutrient Digestion and Utilization in Farm Animals: Modelling Approaches, Wallingford : CAB International., pp. 299 - 313.

Küstermann, B., Kainz, M., Hülsbergen, K., 2008. Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. Renewable Agriculture and Food Systems 23, 38-52.

Martin, C., Morgavi, D., Doreau, M., 2010. Methane mitigation in ruminants: from microbe to the farm scale. Animal 4, 351-365.

Mills, J., Kebreab, E., Yates, C., Crompton, L., Cammell, S., Dhanoa, M., Agnew, R., France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. Journal of Animal Science 81, 3141.

Neufeldt, H., Schäfer, M., 2008. Mitigation strategies for greenhouse gas emissions from agriculture using a regional economic-ecosystem model. Agriculture, Ecosystems & Environment 123, 305-316.

O'Brien, D., Shalloo, L., Grainger, C., Buckley, F., Horan, B., Wallace, M., 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. Journal of Dairy Science 93, 3390-3402.

Olesen, J., Weiske, A., Asman, W., Weisbjerg, M., Djurhuus, J., Schelde, K., 2004. FarmGHG. A model for estimating greenhouse gas emissions from livestock farms. Documentation. Danish Institute of Agricultural Sciences p.

Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agriculture, Ecosystems & Environment 112, 207-220.

Parton, W., Holland, E., Del Grosso, J., Hartman, M., Martin, R., 2001. co-authors. 2001. Generalized model for NOx and N2O emissions from soils. J. Geophys. Res 106, 403–417.

Phetteplace, H., Johnson, D., Seidl, A., 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutrient Cycling in Agroecosystems 60, 99-102.

Pratt, C., Walcroft, A.S., Tate, K.R., Ross, D.J., H, H.M., RoyR, 2010. Managing methanotrophs in an on-farm biofilter to reduce methane emissions, In: Currie, L.D., Christensen, C.L. (Eds.), 23rd Annual FLRC Workshop. Farming's Future: Minimising Footprints and Maximising Margins, Fertilizer and Lime Reaserch Centre, Massey University. Occasional Report No. 23, Palmerston North, New Zealand.

Rotz, C., Montes, F., Chianese, D., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. Journal of Dairy Science 93, 1266-1282.

Rotz, C.A., Black, J.R., Mertens, D.R., Buckmaster, D.R., 1989. DAFOSYM: A model of the dairy forage system. Journal of Production Agriculture 2, 83-91.

Rotz, C.A., Chianese, D.S., 2009. The dairy greenhouse gas model. Reference manual. Version 1.2. Pasture Systems and Watershed Management Research Unit Agricultural Research Service United States Department of Agriculture. http://www.ars.usda.gov/sp2UserFiles/Place/19020000/DairyGHGReferenceManual.pdf.

Rotz, C.A., Corson, D.C., Chianese, D.S., Coiner, C.U., 2009. The Integrated Farm System Model. Reference manual. Version 3.2. Pasture Systems and Watershed Management Research Unit Agricultural Research Service United States Department of Agriculture. http://ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.pdf.

Saggar, S., Bolan, N.S., Bhandral., R., Hedley, C.B., J., L., 2004. A review of emissions of methane, ammonia, and nitrous oxide from animal excreta deposition and farm effl uent application in grazed pastures. New Zealand Journal of Agricultural Research 47, 513-544.

Schils, R., Olesen, J., Del Prado, A., Soussana, J., 2007a. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Science 112, 240-251.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., Pol-Van Dasselaar, A., van Den, d.B., J. A., Evers, A.G., Holshof, G., van Middelkoop, J.C., Zom, R.L.G., 2007b. Dairywise, a Whole-Farm Dairy Model. Journal of Dairy Science 90, 5334-5346.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Kuikman, P.J., L.B.J., S., 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Global Change Biology 12, 382-391.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Šebek, 2005. A farm level approach to define successful mitigation for GHG emissions from ruminant livestock systems. Nutrient Cycling in Agroecosystems 71, 163-175.

Sejian, V., Lal, R., Lakritz, J., Ezeji, T., 2010. Measurement and prediction of enteric methane emission. International Journal of Biometeorology, 1-16.

Shalloo, L., Dillon, P., Rath, M., Wallace, M., 2004. Description and Validation of the Moorepark Dairy System Model. Journal of Dairy Science 87, 1945-1959.

Sherlock, R., Sommer, S., Khan, R., Wood, C., Guertal, E., Freney, J., Dawson, C., Cameron, K., 2002. Emission of ammonia, methane and nitrous oxide from pig slurry applied to a pasture in New Zealand. J. Environ. Qual 31, 1491-1501.

Sintori, A., Tsiboukas, K., 2010. Modeling Greenhouse Gas Emissions on Diversified Farms: The Case of Dairy Sheep Farming in Greece, The 84th Annual Conference of the Agricultural Economics Society., Edinburgh

Sommer, S., Petersen, S., Møller, H., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems 69, 143-154.

Tamminga, S., Bannink, A., Dijkstra, J.R., Zom, R.L.G., 2007. Feeding strategies to reduce methane loss in cattle. Report 34. Animal Science group, Wageningen UR., http://library.wur.nl/way/bestanden/clc/1855887.pdf

Thornley, J.H.M., 1998. Grassland dynamics. An ecosystem simulation model. CAB International, Wallingford, UK p.

Zeddies, J., Angenendt, E., Müller, H.U., 2000. Economic evaluation of strategies to avoid methane emissions from farming systems, Proceedings of the Second International Methane Mitigation Conference, Novosibirsk, Russia., pp. 243-248.

APPENDIX 2

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Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand

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ABSTRACT

New Zealand's commitment to the Kyoto Protocol requires agriculture, including dairy farming, to reduce current greenhouse gas (GHG) emissions by about 20% by 2012. A modeling exercise to explore the cumulative impact of dairy management decisions on GHG emissions and profitability is reported. The objective was to maintain production, but reduce GHG emissions per unit of land and product by improving production efficiency. A farm-scale computer model that includes a mechanistic cow model was used to model an average, pasture-based New Zealand farm over different climate years. A mitigation strategy based on reduced replacement rates was first added to this baseline farm and modeled over the same years. Three more strategies were added, improved cow efficiency (higher genetic merit), improved pasture management (better pasture quality), and home-grown maize silage [increased total metabolizable energy (ME) yield and reduced nitrogen intake], and modeled to predict milk production, intakes, methane, urinary-nitrogen, and operational profit. Profit was calculated from 2006/2007 economic data, where milksolids (fat + protein) payout was NZ\$ 4.09 kg^{-1}.[1] A nutrient budget model was used with these scenarios and two more strategies added: cows standing on a loafing pad during wet conditions and application of a nitrification inhibitor to pasture (DCD). The nutrient budget model predicted total GHG emissions in CO_2 equivalents and included some life cycle analysis of emissions from fertilizer manufacturing, fuel and electricity generation. The simulations suggest that implementation of a combination of these strategies could decrease GHG emissions by 27–32% while showing potential to increase profitability on a pasture-based New Zealand dairy farm. Increasing the efficiency of milk production from forage may be achieved by a combination of high (but realistic) reproductive performance leading to low involuntary culling, using crossbred cows with high genetic merit producing 430 kg milksolids yr^{-1}, and pasture management to increase average pasture and silage quality by 1 MJ ME kg dry $matter^{-1}$. These efficiency gains could enable stocking rate to be reduced from 3 to 2.3 cows ha^{-1}. Nitrogen from fertilizers would be reduced to less than 50 kg ha^{-1} yr^{-1} and include "best practice" application of nitrification inhibitors. Considerable GHG mitigation may be achieved by applying optimal animal management to maximize efficiency, minimize wastage and target N fertilizer use.

APPENDIX 3

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Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology

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ABSTRACT

The strategy for New Zealand dairy farming (DairyNZ, 2009) formulates targets for increased national milk production and a reduction in greenhouse gas (GHG) emissions, but acknowledges these two targets conflict because GHG typically increase with increased milk output. Our objective was to determine if both targets could be achieved by implementing combinations of five mitigations. A farm scale computer model, which includes a mechanistic cow model, was used to model a typical pasture based New Zealand dairy farm as the baseline farm. The five mitigations were: (1) improved reproductive performance of the herd resulting in lower replacement rates, (2) increased genetic merit of the cows combined with lower stocking rate and longer lactations, (3) keeping lactating cows on a loafing pad for 12 h/day for 2 mo during autumn, (4) growing low protein crops of grains and/or silages of maize, barley and oats on a portion of the farm and feeding this to lactating cows, (5) reducing fertilizer N use and replacing some of this with nitrification inhibitors and the plant growth stimulant gibberellins. No single mitigation strategy achieved both targets of increasing production by 10–15% and reducing GHG emissions by 20%, but when all were simultaneously implemented in the baseline farm, milk production increased by 15–20% to 1200 kg milk fat + protein/ha, and absolute GHG emissions decreased by 15–20% to 0.8 kg CO_2-equivalents (CO_2-e)/kg fat and protein corrected milk (FPCM), which is equivalent to a decrease from 11.7 to 8.2 kg CO_2-e/kg fat + protein. The synergies of the mitigations resulted in reduced dry matter intake and enteric CH_4 emissions, a reduction in N input and N dilution in feed, and, therefore, reduced urinary N excretion onto pastures, and an increase in feed conversion efficiency (*i.e.*, more feed was used for production and less for maintenance). Mechanistic CH_4 models as part of farm scale models are important because current GHG inventory methodology cannot properly evaluate CH_4 emissions for a range of potential mitigation strategies. There is also a need to develop capabilities in farm scale models to accurately simulate urine patches and N_2O emissions from these patches.

This paper is part of the special issue entitled: Greenhouse Gases in Animal Agriculture – Finding a Balance between Food and Emissions, Guest Edited by T.A. McAllister, Section Guest Editors: K.A. Beauchemin, X. Hao, S. McGinn and Editor for Animal Feed Science and Technology, P.H. Robinson.

APPENDIX 4.

Paper submitted to Journal of Dairy Science

A mathematical optimization model of a New Zealand dairy farm: the Integrated Dairy Enterprise Analysis (IDEA) framework

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ABSTRACT. Optimization models are a key tool for the analysis of emerging policies, sets of prices, and technologies within grazing systems. A detailed, nonlinear optimization model of a New Zealand dairy farming system is described. The framework is notable for its rich portrayal of pasture and cow biology that add substantial descriptive power, relative to standard approaches. Model output is shown to closely match data from a more detailed simulation model (deviations between 0 and 5 per cent) and survey data (deviations between 1 and 11 per cent), providing confidence in its predictive capacity. The case study indicates superior profitability associated with the use of a moderate level of imported supplement, with Operating Profit ($NZ ha^{-1}) of 934, 926, 1186, 1314, and 1093 when imported feed makes up 0, 5, 10, 20 and 30 per cent of the diet, respectively. Stocking rate and milk production per cow increase by 35 and 29 per cent, respectively, as the proportion of imported feed increases from 0 to 30 per cent of the diet. Pasture utilization increases with stocking rate. Accordingly, pasture eaten and nitrogen fertilizer application increase by 20 and 213 per cent, respectively, as the proportion of imported feed increases from 0 to 30 per cent of the diet.

Key words. Dairy system, farm modelling, nonlinear optimization.

APPENDIX 5.

Paper submitted to New Zealand Society of Animal Production Conference 2012

Identification of cost-effective management options for reducing greenhouse gas emissions by 10% on a Waikato dairy farm

Short title: Greenhouse gas emissions from dairy farms

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Abstract

An optimisation model of a dairy farm was built to estimate the cost of mitigation of greenhouse gas emissions. First, the Farmax and Overseer models were used to describe production, profitability, and emissions to the environment of a medium-input dairy farm system for the Waikato-Bay of Plenty region of NZ. This process allowed generation of a valid and consistent set of input data for a detailed nonlinear programming model able to optimise resource use. The optimisation model was then used to investigate how producers may best respond to the introduction of a 10% restriction on greenhouse gas emissions (GHG-e), with and without the use of strategic changes to their farm system to mitigate GHG-e. Profit decreased by 8 % when the restriction was introduced without the availability of strategic mitigation options. The variables that changed most to achieve the reduction were nitrogen fertiliser input, which was reduced by 58 %, and stocking rate reduced by 7 %. In contrast, profit increased by 5% when strategic mitigation options were used under GHG-e restrictions. Using high genetic merit cows was enough to achieve this increase in profit under the emissions constraint.

Keywords

Greenhouse gases; Dairy farm; Profit; Abatement; Systems; profile.

APPENDIX 6

C1OXO902- Systems analysis to quantify the role of farm management in GHG emissions and sinks for pastoral sectors

Milestone: 1.2.1 International review of literature and data bases
Objective: Re visit a previous internal report (Romera et al., 2008, PGGRC) on models available for testing against calorimeter data.
Authors: Pablo Gregorini, David Pacheco, Pierre Beukes and Alvaro Romera

Title: *The good, the bad and the ugly*: An overview on the available models for predicting methane emissions from grazing ruminants in pastoral systems

Summary:

- The main ***source of methane (CH_4)*** is the enteric fermentation of ruminants, thus reduction of CH_4 emissions in countries with high stocking rate of ruminant livestock presents a major challenge.
- Because of the ***complexity*** of CH_4 production, the design of mitigation strategies requires a systemic approach of gathering, analyzing and interpreting available information.
- ***Mathematical models*** are cost-effective tools to design mitigation strategies and help in the drawing of new lines of specific research from small (rumen) to larger (farm-region) spatio-temporal scales. They offer the potential to describe scenarios of complex interactions and evaluate hypothetical and 'on-practice' intervention strategies.
- Models of methanogenesis were classified in two groups: statistical models and dynamic and mechanistic models:
  - *Statistical models* have been evaluated for more than 20 years, showing a reasonable performance. Most of the evaluations showed the model of Moe and Tyrell (1979), still, as the best one. Statistical models, however, do not explain the variation in CH_4 emission with sufficient accuracy for differing nutritional treatments. This 'failure' is intimately related to their empirical nature and building up processes. Nevertheless, this type of models appear useful for a quick appraisal of the size of changes in the level of CH_4 emission that may be expected with changes in management or nutrition, in particular when information on dietary ingredients, production conditions and feed intake level is lacking. A *semi-mechanistic* approach is then proposed.
  - *Dynamic and mechanistic models* are more suitable and successful for predicting CH_4 emission from ruminants, what is the result of the mechanistic nature of its construction and description of the fermentation process in the rumen. The three major rumen models recognized in the literature: Molly, Ansje/COWPOL and Karoline seem to reasonably predict enteric CH_4 emissions. Unfortunately, and despite of the mechanistic feature of these models, the data used in the development of their stoichiometric models for VFA predictions still constraints the full/ broad context flexibility and applicability for what they were designed, at least in regards to enteric CH_4 emissions.
- ***Principles of thermodynamic*** have been suggested for developing dynamic and mechanistic models of the rumen. Although the thermodynamic approach of modelling rumen fermentation pattern and then CH_4 is promising, it is still in early stages. Even if they were a component of the rumen/ cow models, they would represent a validation challenge, since there is almost none data in this regard, and even less proper experiments set for this purpose.
- Giving attention to *scales* is important, since simple scaling-up or down leads to errors in phenomena interpretation. Thus it is suggested the incorporation of dynamic and

mechanistic models of rumen and even better whole cows to '***whole farm models***' to progress in the understanding and assessment of CH_4 at a larger scale than the rumen.

INTRODUCTION

Greenhouse gases are atmospheric gases that absorb and then re-emit long-wave radiation released by the earth back to the earth surface (Clark and Eckard, 2010). Over the last century, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), the main anthropogenic green house gases, have markedly increased as result of human activity (Clark and Eckard, 2010). Methane, for example, has doubled its contribution to the greenhouse gases, becoming the major contributor of agricultural related greenhouse gases. Globally, the livestock sector produces 37% of all human induced CH_4 emissions (Steinfeld et al. 2006). Due to the main source of CH_4 is the enteric fermentation of ruminants, reduction of CH_4 emissions in countries with high stocking rate of ruminant livestock presents a major challenge. Consequently, the research interest in reducing CH_4 emissions from ruminants has exponentially increased.

'Silver bullet' – like approaches (e.g. dietary additives, rumen defaunation or inmunization) have shown partial success in reducing the enteric CH_4 emissions from ruminants (Yan et al., 2010). The 'partial success (i.e. variable results)' of these strategies relates to their inconsistency and lack of practical demonstration of their benefits at farm system context (Yan et al., 2010; Clark and Eckard, 2010). At this level, the large variation in CH_4 emissions have been attributed to feeding regimens, and so, to feeding management and dietary factors (Ellis et al., 2007; Yan, 2009), leading most of the current experimental and modelling approaches and research efforts. Although the dietary/ feeding management approach seems to be more consistent ('higher partial successes', i.e. less variable results), emission of enteric CH_4 greatly vary between type of animal (i.e. cattle, sheep, and deer), within type of animal (even under the same diet) and within individual animal. Within individual animal variation may relate to nutritional-physiological state; while within type of animal might reflect a potential effect of genetic merit on enteric CH_4 emissions yields as an hypothetical differential capacity of energy partitioning (Yan et al., 2010). However, there is virtually no information about the two latter issues.

The complexity of CH_4 production and its evident multiple variations, therefore, requires a systemic approach of gathering, analyzing and interpreting available information, as well as cost-effective tools helping to draw new lines of specific research from small (rumen) to larger (farm-region) spatio-temporal scales. Mathematical models offer the potential to describe scenarios of complex interactions and evaluate hypothetical and 'on-practice' intervention strategies for any given situation, thereby providing a low cost and quick estimate of best management practices. Under a general objective of improving systems analysis to quantify the role of farm management in greenhouse gases emissions and sinks for pastoral farming, the present work focused on the description and conceptual evaluations of current simulation models for estimating enteric CH_4 emissions from ruminants.

MODEL TYPES

Models of the methanogenesis process (as any other process) can be classified in two groups: statistical models and dynamic and mechanistic models. Mechanistic models are based on assumptions about the mechanisms of processes represented in the model, which are thought to be important in the particular systems. Statistical models are constructed from the data, and have been used as a tool to describe empirical relationships between particular input and outputs of a system. Statistical models treat the system as a 'black box', not focusing on the underlying processes (Thornley, 1998). There are advantages and disadvantages for each type of model; the choice depends entirely on the purpose. Particular considerations and examples of each type of model, used in this case for predicting CH_4 emissions, are presented below.

***Statistical models*.**

Empirical relationships used to predict enteric CH_4 yield and production have been around for 80 years (Kriss, 1930). From the pioneer work of Kriss, 1930, several other statistical models have been developed (and published) aiming to obtain a rapid and simple estimation of enteric CH_4 at the time of assessing CH_4 emissions at larger scales. These models, in fact were and are been used to obtain values for inventory purposes (See Ellis et al., 2010). As mentioned by Mills (2008), and then corroborated by Ellis et al. (2010), Wilkerson et al. (1995) summarized the most relevant statistical models of methanogenesis. These models are presented in Table 1.

Table 1. Statistical models to predict enteric CH_4 (Mcal/d) emissions from Holstein cows (Adapted from Wilkerson et al., 1995)

Reference	Model/s
Kriss (1930)	(18 +22.5 × DMI (kg/d) × 0.013184 (Mcal/g of CH_4)
Axelsson (1949)	-0.494 + 0.629 × DMI (kg/d) – 0.025 × DMI^2 (kg/d)
Blaxter and Clapperton (1965)	(1.30 + 0.112 × energy digestibility determined at maintenance intake (% of gross energy) + multiple of maintenance × (2.37 – 0.050 × energy digestibility at maintenance intake (%of gross energy))) + 100 × gross energy intake (Mcal/d)
Bratzler and Forbes (1940)	(17.68 + 0.04012 × digested carbohydrate (g/d)) × 0.013184 (Mcal/g of CH_4)
Moe and Tyrrel (1979)	**Intake of carbohydrate fractions** 0.814 + 0.122 × nonfiber carbohydrate (kg/d) + 0.415 × hemicellulose (kg/d) + 0.633 × cellulose (kg/d) **Intake of digested carbohydrate fractions** 0.439 + 0.273 × digested nonfiber carbohydrates (kg/d) + 0.512 × digested hemicellulose (kg/d) + 1.393 × digested cellulose (kg/d)
Holter and Young (1992)	**Non lactating cows** (12.12 – 0.00542 × BW (kg) – 0.0900 × ADF (%DMI) + 0.1213 × ADF digestibility (%) – 2.472 × digestible energy (Mcal/kg DM) + 0.0417 × NDS digestibility (%) – 0.0748 × cellulose digestibility (%) + 0.0339 × hemicellulose digestibility (%)) + 100 × gross energy intake (Mcal/d) **Lactating cows fed supplemental dietary fats** 2.898 – 0.0631 × milk (kd/d) + 0.297 × milk fat (%) – 1.587 × milk protein (%) + 0.0891 × CP (5DM) + 0.1010 × forage ADF (% DM) + 0.102 × (DMI (kg/d) – 0.131 × ether extract (% DM) + 0.116 × DM digestibility (%) – 0.737 × CP digestibility (%)) + 100 gross energy intake (Mcal/d) **Lactating cows fed supplemental dietary fats** (2.927 – 0.0405 × milk (kg/d) + 0.335 × milk fat (%) - 1.225 × milk protein (%) + 0.248 × CP (% DM) - 0.448 × ADF (% DM) + 0.502 × forage ADF (% DM) + 0.0352 × ADF digestibility (%)) + 100 × gross energy intake (Mcal/d)

According to Wilkerson et al. (1995), all the equations were adequate to predict methane production from non-lactating animals. However, the one from Blaxter and Clapperton (1965) had the highest concordance correlation coefficient. For lactating animals, however, the behaviour of the models were variable and the one that performed the best was equation of Moe and Tyrrell (1979) using the intake of carbohydrates fractions. Palliser and Woodward (2002), using grass herbage-based diets, reported the same as Wilkerson et al. (1995) when comparing the statistical models of Moe and Tyrrell (1979), Blaxter and Clapperton (1965) and Kirchgeßner et al. (1995). Using more refined data set, thirty one years later, Ellis et al. (2010) arrived to the same conclusion. In this models' evaluation, Ellis et al. (2010) compared the performance of several empirical models for methane prediction for dairy cows used in some whole far models. The model models compared were: Moe and Tyrrell (1979), Blaxter and Clapperton (1965), Corre (2002), Giger-Reverdin at al. (2003), IPCC-Tier I (1997), IPCC-Tier II (1977), Kirchgeßner et al. (1995, eqn. (1 and 2)) and Schils et al. (2006).

Tamminga et al., (2007) evaluated 22 different models ranging from simple static (most of them mentioned and described before) to complicated dynamic mechanistic models in terms of their ability to accurately determine cattle methane emission from various feeding strategies. The authors grouped the models into three categories: static empirical, dynamic empirical and dynamic mechanistic models (See next section). The former performed better than dynamic empirical and dynamic mechanistic models in some circumstances, but not in others. The authors conclude that statistical models did not explain the variation in CH_4 emission with sufficient accuracy for differing nutritional treatments. According to Tamminga et al. 2007) the 'failure' of the statistical models was intimately related to their empirical nature (and building up processes). In the same line of Tamminga et al. (2007), Kebreab et al. (2006) evaluated the capability of models to predict CH_4 emission from ruminants. Kebreab, et al. (2006) tested six models; the linear model of Moe and Tyrell (Moe and Tyrell 1979), two empirical models proposed by Mills et al. (Mills et al., 2003), the dynamic model of Kebreab et al., (2004) and Tier 1 and Tier II models recommended by IPCC (IPCC 1996). Essentially, the conclusions drawn by these authors are the same as Tamminga et al. (2007), in the sense that a full assessment of mitigation options requires mechanistic models. Nevertheless, static models appear useful for a quick appraisal of the size of changes in the level of CH_4 emission in ruminants that may be expected with changes in management or nutrition, in particular when information on dietary ingredients, production conditions and feed intake level is lacking (Tamminga et al., 2007).

Unfortunately, most of the statistical models were built up on the basis of North American and /or European data (animals end diets), what in some occasions it may certainly limit their application to grass herbage-based diets, particularly in grazing feeding scenarios, as supported by the differences reported between 'in-door' feeding and grazing by Pinares-Patiño and Clark (2010).

Mills (2008) pointed out that another risk of an empirical approach is to assume nonexistent (biologically based) relationships (cause and effect) with 'only the aim of getting better correlations'. An example of these type of 'errors' is shown in the model of Holter and Young (1992) (Mills, 2008). The model of Holter and Young (1992) implies a significant effect of milk yield and milk composition on CH_4. Due to milk yield and its composition are function of nutrition and DMI, according to Mills (2008) the implications of this model could be misleading. These considerations, however, do not have to stop the use and/ or consideration of factors related to milk. For example, Yan et al. (2010) propose a simple statistical model built on the bases of calorimetric data coming from 20 studies (mainly using either fresh grass or grass silage), considering gross energy intake or energy milk outputs.

$CH_4 – E/ GEI = -0.0256 \times (E_{l(0)}/ MBW) + 0.075$

Where,

$CH_4 – E$ = Methane energy output (Mj/ d)

GEI = Gross energy intake

$E_{l(0)}$ = Milk energy output adjusted to zero energy balance(Mj/d)

$E_{l(0)} = E_l + a \times$ energy balance

Where,

E_l = milk energy output

a = 0.95 and -0.84 for positive and negative energy balance, respectively (AFRC, 1990).

MBW = Metabolic body weight ($BW^{0.75}$)

Yan et al. (2010) also showed that CH_4 output is negatively related to energy metabolizability and the efficiency of utilization of ME for lactation (see model below and Figures 1 and 2 from Yan et al. 2010). Therefore, selection for more efficient cows in using energy would offer an effective approach to reduce CH_4 emissions.

$CH_4 – E/ E_{l(0)} = -9.418 \times (E_{l(0)}/ MEI) + 10.824 \times (E_{l(0)}/ MEI)^2 + 2.193$

Where,

$CH_4 – E$ = Methane energy output (Mj/ d)

MEI = Metabolizable energy intake

$E_{l(0)}$ = Milk energy output adjusted to zero energy balance(Mj/d)

$E_{l(0)} = E_l + a \times$ energy balance

Where,

E_l = milk energy output

a = 0.95 and -0.84 for positive and negative energy balance, respectively (AFRC, 1990).

The models of Yan et al. (2010) seem to be quite simple and promising for cows consuming grass-based diets. However, as any other empirical model it may in fact restricted to the data set it was built on. Such data set average an intake of concentrates of 498 g/kg DM (range = 198 -869 g concentrate/ kg DM) and have not grazing animals in it; consequently, it applicability to New Zealand pastoral systems may be still limited.

A semi -statistical approach.

In an attempt to keep simplicity of estimation and gather the benefit of a more mechanistic approach, Mills et al. (2003) proposed the following model:

CH_4 (MJ/ d) = a – (a + b) × $e^{-c \times x}$

Where,

a and b = upper and lower bounds of CH_4 production, respectively.

c = shape parameter determining the rate of change of CH_4 production with increasing ME intake.

Where,

c = - 0.0011 × [starch concentration of the diet/ acid detergent fibre concentration of the diet] + 0.0045

The application of this non-linear, semi-mechanistic, approach enabled Mills et al. (2003) to represent the typical diminishing response observed as DMI increases, and predicted by the mechanistic models of Danfer et al., (2005), Bannink et al. (2010) and Baldwin's (1995, within the Whole Farm Model of DairyNZ). Such an approach is quite interesting since it tackles ease of use and some complexity of mechanistic relationships; therefore amplifies the applicability of evolving statistical approaches. However, the major barrier for this approach is that most of the statistical models and some of the mechanistic ones require a defined input of intake (Mills, 2008), which in general is poorly described and even poorer under grazing feeding environment.

Gregorini et al. (2009) used a the same non linear approach of Mills et al. (2003) when attempting to predict herbage intake from grazing dairy cows differing in genetic merit (Breeding worth) at different levels of herbage allowance, during the entire lactation. In this model the level of intake is shaped (diminishing response) by a factor k. This factor represented the hunger drive of grazing dairy cows modulated by genetic merit and stage of lactation. Based on the non-linear approach and suggestions, as well as concerns related the lack of intake inputs; it is raised here, the potential of linking the model of Gregorini et al. (2009) with one of the equations (see above) of Yan et al. (2010) or Ellis et al. (2007) to generate a non linear semi-statistical model to ease predict CH_4 production base on pasture intake level (and herbage allowance) . Ellis et al. (2007) compiled a large amount of data, comprising 83 beef and 89 dairy datasets from the literature. Although the data was exclusively for northern United States or Canadian research, they developed several simple and multiple linear equations using diet information indicating that the best predictor was the simple linear regression with DMI. Moreover, their tables show the percentage of forage in the diet one of the best predictors. The study also analysed five extant models, including Moe and Tyrell (1979) and Blaxter and Clapperton (1965). Ellis et al. (2007) model performed slightly better than the extant models.

Although not as simple as the model of Mills at al., (2003), or even the proposed link mentioned above, a good example of this semi-mechanistic approach is the recently published work of Volden (2010). NorFor is a semi-mechanistic model of gastro intestinal digestion to optimize cattle nutrient supply, Volden (2010), demonstrated the usefulness of this semi-mechanistic approach to rapidly assess the effectiveness of different feeding strategies aiming at reducing CH_4, based on rapidly and easy to get data inputs.

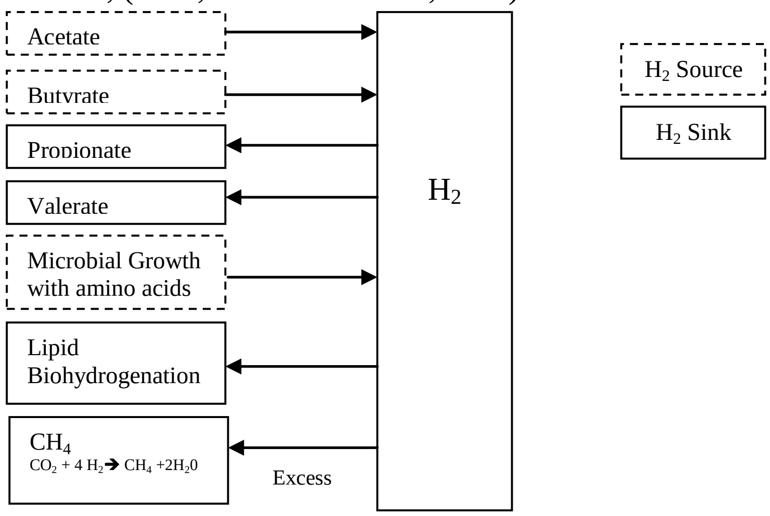
Mechanistic and dynamic models.

Empirical models are set to describe, while mechanistic not only describe the process in question, but also provide (by their nature) understanding (France and Thornley, 1984). Such understanding is mainly given by the nature (*per se*) of mechanistic model to construct relationships (equations) between levels of the organizational hierarchy. For example, as (France and Thornley, 1984) explain, a mechanistic model describe the behaviour of the level *i* attributes in term of the attributes of the level *i-1*. The two levels are connected by a process. The dynamicity to these types of models is given by simply including the time as variable.

According to Tamminga (2007) dynamic mechanistic models are more suitable and successful for predicting CH_4 emission from ruminants, what is the result of the mechanistic nature of its construction and description of the fermentation process in the rumen (Mills, 2008). There are four major rumen (standing alone or within a cow model) models recognized in the literature: Molly (Baldwin, 1995), Ansje/ COWPOL (Dijkstra, 1992; Mills et al., 2001), Karoline (Danfaer et al. 2006) and the model of Martin and Sauvant (2007), with Molly, Anja/ COWPOL and Karoline predicting enteric CH_4 emissions.

The common ancestor. The product of rumen fermentation results in the formation of CH_4 as a sink for excess of hydrogen (Baldwin, 1995). This process of CH_4 formation is described by the following scheme, referred and used by (Baldwin, 1995), Benchaar et al. (1998) and Mills et al. (2001).

Figure 1: The mechanistic scheme for methane production in the rumen from Baldwin et al., (1987, taken from Mills, 2008).



Basically, the CH_4 production is predicted based on the hydrogen balance, which is calculated as follows:

Hy_{rumen} (mol/d) = $Hy_{Hex} + Hy_{AA} - Hy_{MiGr} - Hy_{FA}$

CH_4 (mol/d) = $Hy_{rumen} / 4.0$

Where,

Hy_{rumen} = hydrogen balance in the rumen

Hy_{Hex} = amount of hydrogen resulting from the fermentation of carbohydrates (hexoses) to VFA.

Hy_{AA} = amount of hydrogen resulting from the fermentation of amino acids in the rumen.

Hy_{MiGr} = amount of hydrogen used for microbial growth

Hy_{FA} = amount of hydrogen used for biohydrogenation of unsaturated fatty acids.

4.0 = mol of hydrogen used to for a mol of CH_4

The main source of hydrogen in this scheme is the amount of hydrogen resulting from the fermentation of nutrients (hexoses and amino acids) to volatile fatty acids (VFA). This amount, pretty much depends on the nutrients fermentation, stoichiometrical coefficients and statistical models describing the rumen conversion of carbohydrates and protein to VFA (Dijkstra et al., 2008). Baldwin et al. (1995) used the stoichiometrical models reported by Murphy et al. (1982), when developing Molly. Ansje/ COWPOL uses the scheme for methane production from Baldwin et al. (1995), inserted by Benchaar et al. (1998), with a revised (by Bannink et al., 2006) version of the coefficients for the VFA stoichiometrical models reported by Murphy et al. (1982). Karoline's coefficients for the stoichiometrical models were calculated using in principle the approach of Murphy et al. (1982) for acetate, propionate and butyrate (Dijkstra et al., 2008). And in order to calculate VFA production, the French cow of Martin and Sauvant (2007) uses a table of estimations 'inspired' from the data of Murphy et al. (1982) and transformed to equations.

Short description of Karoline, Ansje and Molly.

Karoline. The simulation model Karoline, which is a dynamic, deterministic and mechanistic whole animal model of lactating cows, has been described by Danfer et al. (2006). In brief, Karoline consists of two sub-models, a digestion and a metabolism model. The digestive model of Karoline comprises the forestomachs (rumen) and the intestines (small and large). The metabolism model is represented by the portal drained viscera, live, mammary gland, muscle, connective and adipose tissue. Karoline is fed with (inputs) crude protein and fat, potentially degradable NDF, starch, fermentation products (silage related) and 'the rest' (other components of OM not accounted for). The crude protein fraction is further detailed by NH_3, amino acids, peptides and soluble and insoluble protein, as well as indigestible protein. Degradation rates of NDF protein and starch need to be provided to Karoline. The ruminal degradation of carbohydrates and protein and their correspondents' passage rates trough the rumen are describes by two-compartmental models. The later is regulated by the level of NDF intake and the former is regulated by the ratio of non-structural and structural carbohydrates. The VFA patterns in Karoline were based on equations derived from a Nordic database (Sveinbjörnsson et al., 2006). These equations are adjusted by level of intake and fat content of supplements fed to Karoline. The methane production in Karoline is calculated on the basis of stoichiometric fermentation equations for both nutrients fermented in the rumen and the hindgut. The predicted methane formation is corrected for the use of reduction equivalents for microbial cell synthesis, synthesis of microbial fatty acids and hydrogenation of unsaturated dietary fatty acids.

Karoline has been used previously by Weisbjerg et al. (2005) to predict the CH_4 production from different feed rations. In all cases, the model simulated higher values of CH_4 production than two selected empirical regression equations (IPCC, 1997; Kirchgeßner et al., 1994, taken from Olesen et al., 2005). This observation matches the results of Uden and Danfer (2008), who reported that Karoline, for example, predicts considerably less propionate from sugars, starch and hemicellulose in comparison with Molly. The latest version of Karoline has been changed further from the published version to better represent changes in the stoichiometric fermentation equations for starch and sugar (lower acetate and higher propionate and butyrate formation from starch; lower propionate and higher butyrate formation from sugar). According to Huhtanen (Pekka Huhtanen pers. comm.), Karoline predicts reasonably well changes in CH_4 in response to changes in DMI, proportion of concentrate in the diet, efficiency of microbial protein synthesis and fat supplementation, especially with typical Nordic grass silage-based diets. However, Karoline's CH_4 module still needs further development (Pekka Huhtanen pers. comm.).

Ansje (Acid and nitrogen supply jolly estimator). This model is originated from the model of Dijkstra et al. (1992). The later is a dynamic and mechanistic model to simulate the digestion, absorption, and outflows of nutrients in the rumen. Ansje does not have the complexity of Karoline (see Danfer et al., 2006) or Molly (see below and Baldwin, 1995). The rumen of Ansje (Dijkstra et al., 1992) consists of 17 state variables representing nitrogen, carbohydrate, lipid, and VFA pools. The flux equations are described by Michaelis-Menten or mass action forms. This model includes several specific aspects of rumen metabolism, in particular microbial metabolic activity differentiated by particular populations (amylolityc, fibrolytic and protozoa) and pH-dependent absorption of VFA and ammonia. The model also includes intra-ruminal recycling of microbial matter as a result of protozoa activity (predation) and N recycling via saliva (Bannink et al., 2010). As stated by Benchaar et al. (1998), originally, the model of Dijkstra et al. (1992) did not predict CH_4 emissions. Therefore, Benchaar et al. (1998) incorporated in it the Baldwin's scheme described above. The input parameters to this model are daily DMI, chemical composition of the diet, solubility of protein and starch, degradability and degradation rates of feed components, ruminal passage rates, rumen volume, and rumen pH (Benchaar et al., 1998).

The original improvements (CH_4 production related [Benchaar et al., 1998]) of Ansje rumen have been continued by carried out by Mills et al., (2001), Bannink et al. (2006; 2010). Mills et al., (2001) added to Ansje a module of hindgut CH_4 and revised and incorporated the coefficients for rumen VFA yield described by Bannink et al. (2000). As it was mentioned above, being the latter a revised version of the coefficients generated by Murphy et al. (1982). Bannink et al. (2008) improved Mills et al., 2001 work by introducing pH-dependent VFA yields from fermentable soluble carbohydrates and starch.

When comparing Ansje (Dijkstra et al., 1992) and Molly (Baldwin, 1995). Tamminga et al. (2007) mention two studies Bannink et al. (1997) and Benchaar et al. (1998) showing better prediction quality for Ansje. Tamminga et al. (2007) conclude that Ansje, and subsequent adaptations (e.g. Mills et al., 2001), is of a highly mechanistic nature and represents the influence of many key mechanisms in the literature, suggesting Ansje as a useful research instrument to study the effectiveness of nutritional measures to reduce CH4 by cattle.

Recently, Ansje was used to investigate the effect of type and quality of grass forage, DMI and proportion of concentrates in dietary DM on variation in CH_4 emission. Effects of type and quality of fresh and ensiled grass were evaluated by distinguishing two N fertilization rates of grassland and two stages of grass herbage maturity. Simulation results indicated a strong impact of the amount and type of herbage consumed on CH_4 emission, for diets with a proportion of concentrates in dietary DM from 0.1 to 0.4. The lowest emission was established for early cut, high fertilized herbage silage and high fertilized herbage. The highest emission was found for late cut, low-fertilization rate. The N fertilization rate had the largest impact, followed by stage of herbage maturity at harvesting. Simulation results were evaluated against independent data obtained at three different laboratories in indirect calorimetry trials with cows consuming grass herbage mainly. Ansje predicted the average of observed values reasonably, but systematic deviations remained between individual laboratories and root mean squared prediction error was a proportion of 0.12 of the observed mean. Ansje predicted that emission expressed in g CH_4/ kg DMI decreased upon an increase in dietary N: organic matter ratio. According to Bannink et al. (2010), Ansje reproduced reasonably well the variation in measured CH_4 emission in cattle sheds on Dutch dairy farms. Ansje's prediction power of CH_4 emissions still needs to be assessed on pastoral systems as the New Zealand one.

Molly. *"... Molly will provide me and associates with a continuum opportunity to learn"* (R. L. Baldwin, 1995). Molly is a mechanistic and dynamic model representing the digestion and metabolism, as well as production of a dairy cow (Baldwin, 1995). The first version of the model (Cow1) was published in 1987 (Baldwin *et al.*, 1987a). Later Cow1 became Myrtle, when the digestion model (Baldwin *et al.*, 1987b) was joined to Cow1. Myrtle could not simulate full lactations. To do so, Myrtle's pool sizes were inflated (see Baldwin 1995) and integration interval was set to 1 day, then becoming Daisy till 1992. Three years later and as a product of Daisy's structural reorganizations, parameter corrections and code reformatting, Molly came to the scene. Since then, Molly has evolved considerably. In brief, the current Molly has evolved to better simulate lipid metabolism (McNamara *et al.*, 2000), lactation curves of New Zealand grazing dairy cows (Palliser *et al.* 2001), photoperiod effect and milk production in grazing dairy cows (Beukes *et al*. 2005), lactation potential (Hanigan *et al.*, 2008), and to properly represent anabolic and catabolic hormone dynamics, and gestational metabolism (Hanigan *et al.*, 2009), as well as the bioenergetics of walking and harvesting herbage while grazing (Gregorini et al., unpublished). Furthermore, the work of Nagorcka et al. incorporated significant elements in Molly. Although never fully published (John McNamara pers. com.), this work expanded bacterial pools, particle dynamics and VFA productions in Molly's rumen (Nagorka *et al.*, 2000).

In the rumen, Molly describes degradation and fermentation of feedstuffs, including cellulose, hemicellulose, starch, soluble sugars, organic acid, and proteins and amino acids. Within the carbohydrate degradation and fermentation processes, production of volatile fatty acids is explicitly described, as well as hydrogen production that is not trapped in VFA. From these equations and the context described in the previous paragraph (and following section), the New Zealand's (DairyNZ) Molly mechanistically predicts enteric CH_4 production.

Previous evaluations of Molly (Baldwin, 1995) under pasture-based diets have indicated under-prediction of enteric CH_4 emissions (Palliser and Woodward, 2002). In the models comparison referred by Tamminga et al. (2007), Benchaar et al. (1998) reported that Molly (Baldwin, 1995) and the rumen model from Dijkstra et al. (1992) were better predictors of enteric CH_4 compared to the empirical models. According to Benchaar et al. (1998) Molly and Dijkstra et al. (1992) had similar R^2 (0.7), however, the prediction error for Molly was higher (37 vs.19.9%), which according the Benchaar et al. (1998) could be eliminated by a correction factor. Both Molly and Ansje (Dijkstra et al. (1992)) have the same mechanistic module of CH_4 production described above (Figure 1). Therefore, any errors in description of VFA production from any dietary component are compounded in the production of H_2 and thus CH_4. Nevertheless, in fact Molly describes production of CH_4 within the observed ranges for the diets tested and also within 1 to 2 standard deviations of the measurement of CH_4 (John P. McNamara, pers. com).

Recently, Gregorini et al. (2010) tested New Zealand Molly's predictions of enteric CH_4 and urinary N in response to different dietary characteristics determined by grazing and feeding managements (i.e. N fractions, structural and non-structural carbohydrates, maize silage feeding, leaf stage of the sward, etc) under New Zealand farming conditions. The results indicate that despite differences between Ansje and Molly models; Molly, as a component of a whole farm model (DairyNZ, Beukes et al., 2010), predicts the right and similar trends in enteric CH_4 compared to the model of Ansje.

Improvements in DairyNZ Molly's CH_4 descriptions will mostly derive from a better description of degradation and fermentation of ingested feedstuffs. In this regard Hanigan et al. (unpublished) used a dataset constructed from the literature to solve for a set of parameters that corrected bias in ruminal pH, ruminal nutrient degradation, microbial growth, and post-ruminal digestion of Molly. These adjustments had a large impact on model performance as ruminal pH determines the rates of fiber degradation and microbial growth and the latter influences degradation of all nutrients and VFA production. The adjustments also reduced (slightly) overall prediction error and the removal or reduction in slope bias for each of the individual VFA. The balance of VFA dictates the H supply which, in turn, dictates CH_4 production. Thus, such an improvement is promising with respect to improving predictions of CH_4 production and required further evaluation.

Nagorcka *et al*. (2000) extended the rumen processes in Molly to include three bacterial pools (similarly to Dijkstra et al., 1992), an additional particle size pool, and morphological representation of the herbage consumed by Molly, plus an updated data set on VFA production on higher grass and pasture diets. This extension resulted in more accurate descriptions of nutrient utilization coming from pasture, however full and systemic analysis of this model has not been possible. Therefore, the latest DairyNZ's Molly (Hanigan et al., unpublished) would benefit and it is nowadays adopting some of Nagorcka *et al*. (2000) approach.

Mixed blessing of Karoline, Ansje and Molly

These models offer the potential to describe scenarios and evaluate the intervention strategies for a spectrum of situations, thereby providing a low cost and quick estimate of best practices to mitigate CH_4 emissions. Unfortunately, and despite of the mechanistic feature of these three renown models, the data used in their development (i.e. stoichiometric factors among others) still constraints, somehow, the full/ broad context flexibility and applicability for what they were designed, at least in regards to enteric CH_4 emissions. Such constraints increase considerably not only according to diet and feeding environment, but also type of cow or even animal (i.e. See Ellis et al. 2009; Kebreab et al., 2008; Levy et al., unpublished). This issue creates imprecision and thereby confounding judgments for each particular model when they evaluated/ challenged to a common data set. At the time of validation, however, Molly, Ansje and Karoline generally face experimental works with imprecise measurements and results derived from confounding effects, especially under grazing situations. Furthermore, in grazing environments, most of the potential good data sets 'experiments' lack of a proper experimental design and replication. The later, being generally related to errors/ confusion at the time of determining the experimental unit of the experiment (see Rook, 1999; Lean and Lean, 2010). Consequently, it may not be fair to entirely blame the models when errors of predictions observed.

Anyway... what is ***the good, the bad*** and ***the ugly*** of Molly, Ansje and Karoline for New Zealand's pastoral systems and the GHG research around it?

Briefly, the *good* of Molly is 'her metamorphosis' from the American Holstein TMR fed cow designed by Baldwin et al. in the late 80' to the more flexible (Holstein-Friesian, Jersey and crosses) pasture fed Molly as described before. Such a metamorphosis lead the pasture fed Molly play a major role in a pastoral whole farm model (WFM, Beukes et al., 2010a) dynamically interacting with climate driven qualitative and quantitative changes in pasture, quality and amounts of bought-in supplements, and her own metabolic capacity to absorb and convert nutrients into milk as determined by age, breed, and genetic merit. This Molly not only behaves according to feed inputs and animal characteristics, but also to common and specific farm management policies and decisions. Recently the WFM was upgraded to include reproductive modeling capability, based on relationships between cow factors, physiology and mating management (Beukes et al. 2010b); and the grazing behavior of Molly according to sward condition and grazing management (Gregorini et al., unpublished). The *bad* of Molly still holds on the old stoichiometric coefficient/ models for rumen fermentation pattern (Murphy et al., 1982), the lack of a mechanistic representation of rumen outflows rates, the lack of representation of ionospheres and probiotics, the poor representation of the effects polyunsaturated fatty acids, and the lack of representation of other H_2 sinks (i.e. sulfur) with their consequent impact in CH_4 production. The need of the representation of the last four issues in mechanistic models of rumen was raised already by Tamminga et al. (2007) and Ellis et al., (2008). The *ugly* side of Molly comes along with 'her' lack of modularity and thus 'spaghetti' features from a software engineering standpoint, which complicates the easiness of working with 'her'. The latter is potentiated by the software in which Molly is commonly run, ACSL Xtreme.

Karoline's *good* for New Zealand pastoral systems resides not only in the fact that 'she' is a 'whole' cow, but also in 'her' quite advanced mechanistic approach of 'her' digestive and metabolism modules, as well as the set used to build up the stoichiometric models for rumen fermentation patters. Such data set is built on the basis of experiments feeding cows with diets mainly composed by grass silage and fresh grass (Sveinbjorsson et al., 2006). Furthermore, as stated by Sveinbjorsson et al. (2006) and Danfer et al., (2006), Karoline was built on inputs that would not be too difficult to attain in practice, aiming to serve advisory services (Danfer et al., 2006). The latter, in fact, could but not necessary should lead researchers to discard

Karoline as a detail research tool, showing a relative *bad* side 'her'. Moreover, despite of showing better behaviour than the stoichiometric models coefficients of Murphy et al. (1982), Karoline's stoichiometric models coefficients still need more refinement, updating and independent evaluation (Dijkstra et al., 2008). As it was mentioned the Karoline's stoichiometric models were built on VFA database is mainly from typical Nordic diets (based on grass silage), while nowadays more whole-crop silages, barley/oats based concentrates with some by-products and protein supplements are fed to cows (Pekka Huhtanen pers. comm.). With these diets the ranges in fermentation pattern are small, and surprisingly, lactic acid is the most important factor influencing acetate (not starch or proportion of concentrate in the diet). Karoline's old empirical regression equations make 'a better job' in predicting VFA than stoichiometric models used by the newest Karoline (Pekka Huhtanen pers. comm.), which may show the price of keeping Karoline purely mechanistic. An *ugly* face of Karoline is that it is written with POWERSIM software. This software is similar to Stella (modelling software), but does not communicate with it. POWERSIM communicate Excel spreadsheet, but the recent versions of POWERSIM are made mainly for commercial applications and Karoline does not run in it, at least without some modifications (Pekka Huhtanen pers. comm.).

Ansje's rumen is nowadays the most advanced mechanistic rumen model; the *good*. As it was mentioned above the most interesting and differentiating features of Ansje's rumen is the representation of microbial populations (specially protozoa) and the new VFA stoichiometric coefficients from Bannink et al., (2006), as well as the pH dependency of VFA yield from fermented soluble carbohydrates and starch, incorporated by Bannink et al. (2008). The *good* of Ansje is also related to the replication of the module of CH_4 production in the hindgut (Mills et al., 2001). Although Ansje is been referred as a cow, the metabolic complexity of Molly and Karoline makes Ansje look like a rumen with accessories; what could be referred as 'the' *bad* of Ansje. Ansje, also lacks of a representation of ionophores and other additives (Tamminga et al., 2007) and still need refinement at the time of assessing the effects of diets with high fat contents (Jan Dijkstra pers. com.). According to Ellis et al. (2009), even the improved coefficient of the stoichiometric models of VFA pattern (Bannink et al. 2006) require adjustment for predicting CH_4 in high grain diets. Moreover, Ansje, as Karoline are not incorporated into whole farm models (see below). The *ugly* of Ansje is that 'she' required some 'manual' setting dependent of user/researcher knowledge of the simulation context (Andre Bannink, pers. com. SLMACC meeting, Ruakura Research Centre, 2010). Ansje's code inaccessibility, when compared with Karoline's and Molly's code accessibility, also presents a *downside* side from 'her'.

RUMEN THERMODYNAMICS

Does rumen thermodynamics represent a step forward?

Nutrition science comes from medicine, physiology, biochemistry, genetics microbiology, agriculture, home economics and behavioural sciences. Although thermodynamics plays an integral role in the calorimetry of the energy content of the ingested food; paradoxically, thermodynamics is not generally included in such a list (Welch, 1991 at the Symposium on 'History of research in Human energy nutrition'). This absence is also evidenced by the fact that few works in the ruminant nutrition literature (compared to the bulk of literature regarding with rumen function) deals with rumen thermodynamics. Perhaps, it is not the lack of knowledge of the thermodynamics science existence, as demonstrated by several works in energetic of rumen bacteria and rumen redox capacity (See Russell and Cook, 1995, Janssen, 2010), but a simple delay on its incorporation and utilization in modelling of rumen fermentation pattern.

It seems that the awakening of rumen thermodynamics in the modelling side of the story started with the doctoral dissertation of Hoh (1996), as referred by Kohn and Boston (2000). Hoh (1996) integrated equilibrium thermodynamics principles into kinetics models in attempt to explain shifts in the reactions of anaerobic digesters. Due to the level of inconsistency of the stoichiometric model of Murphy et al. (1992), the common ancestor (see above) (Kohn and Boston, 2000; Offner and Sauvant, 2006), Kohn and Boston (2000) developed a dynamic model of glucose fermentation to demonstrate the potential for thermodynamic control of rumen fermentation. The reason behind this development resides not only in the inconsistencies the stoichiometric model of Murphy et al. (1992), but also in that a thermodynamic approach would provide ‘a fundamental’ understanding of the factors altering ruminal fermentation patterns.

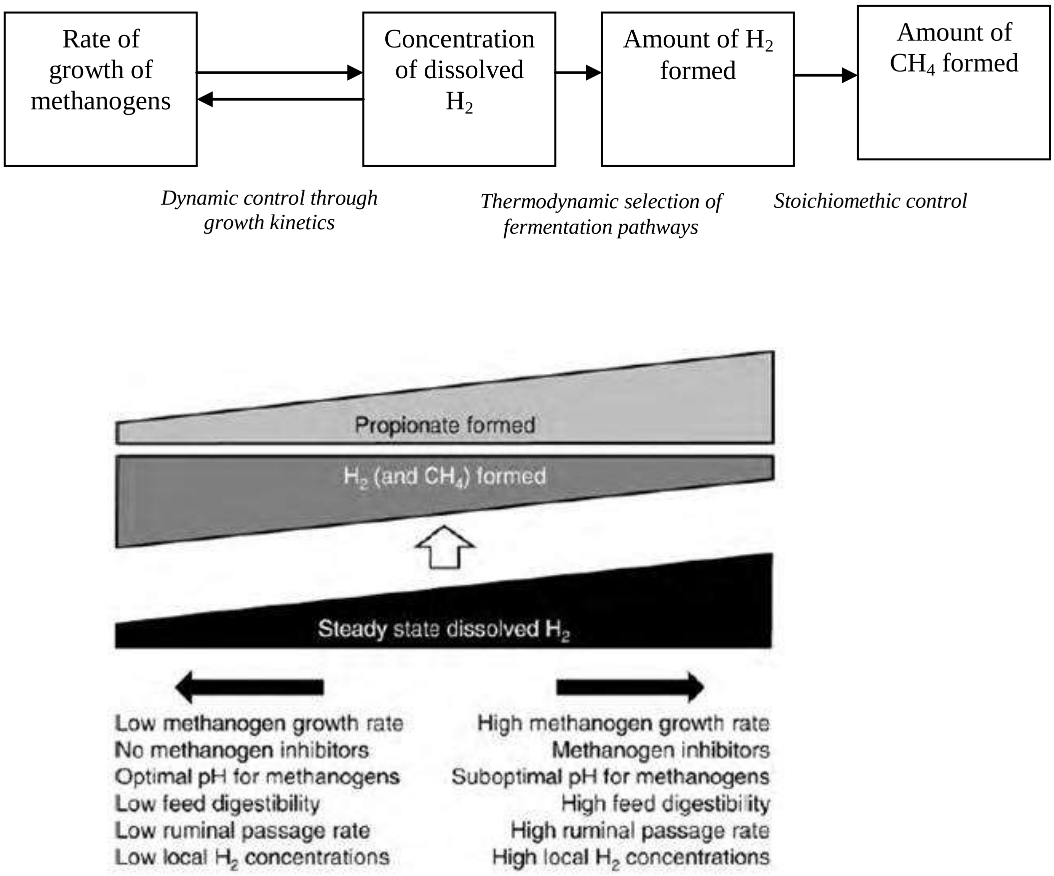
Chemical reactions (pathways) are controlled by either thermodynamic or kinetic principles (Chang, 1981, cited by Kohn and Boston, 2000). Thermodynamic principles are based on that substances tend to achieve the lowest energy state, offering the possibility to determine processes direction (pathways) and strength, as well as which process is likely to occur (Welch, 1991, Offner and Sauvant, 2006, Janssen, 2010). While kinetics laws only describe the rate of the reactions (Offner and Sauvant, 2006) and only controls them when they are thermodynamically favourable (Kohn and Boston, 2000) and apply to a monoculture (Offner and Sauvant, 2006). Therefore, in a complex environment/ ecosystem like the rumen, with a quite diverse and dynamics microflora and many options for metabolic pathways, thermodynamic laws will probably dictate the success of species, particular metabolic pathways (Janssen, 2010), and consequently rumen fermentation pattern at any point in time.

Although the glucose fermentation model of Kohn and Boston (2000) predicts realistic concentration of VFA and gasses, the thermodynamic efficiencies of this model were considered static at steady-state (Offner and Sauvant, 2006). Offner and Sauvant (2006) took a step forward from Kohn and Boston (2000) and developed a thermodynamically driven model representing the variation in carbon flows between the VFA, gasses and microbial biomass. This model predicted a satisfactory post-prandial evolution of VFA patterns; however, predictions of pH, and redox potential were less reliable, and predictions of CH_4 were too low.

In a recent thorough literature review, Janssen (2010) evaluated the influence of hydrogen on rumen CH_4 formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. In this work Janssen (2010) proposed a quite integrative and challenging conceptual model (Figure 2), which cries for validation. The model explains the control of CH_4 formation in the rumen by kinetics and thermodynamic laws. Methanogens growth kinetics determines the H_2 concentration, and thermodynamics of the rumen fermentation is controlled by the H_2 concentration. Jenseen’s approach is exiting and has created huge expectations, especially in the arena of model development.

Neither the model of Kohn and Boston (2000) not the one from Offner and Sauvant (2006) are incorporated into whole rumen (then whole cow) models. And the model of Janssen is still conceptual. Consequently, although the thermodynamic approach of modelling rumen fermentation pattern and then CH_4 is promising, it is still in early stages. Even if they were a component of the rumen/ cow models, they would represent a validation challenge, since there is almost none data in this regard, and even less proper experiments set for this purpose. Recently, and based on a thermodynamic principles, Laporte and Gregorini (unpublished) proposed a quite simple approach to asses real-time rumen thermodynamics parameters and then rumen function efficiency using ‘easy to get’ data (i.e. pH, redox capacity and temperature). If applied, this approach will facilitate data collection not only to evaluate the spatio-temporal efficiency of rumen function, but also validation and model building data

Figure 2. Janssen’s (2010) conceptual model of methanogenesis (Taken from Janssen, 2010).



THE NECESSITY OF SCALING-UP: A FINAL NOTE

Methane predictions through whole farm modelling

Giving attention to scales is important, since simple scaling-up or down leads to errors in phenomena interpretation (Wiens, 1989, Wu, 1999). The integration of CH_4 production from small (rumen) to large (farm) spatio-temporal scales can lead to such a common errors, especially when empirical/ statistical models are used for this purpose, as demonstrated by Ellis et al., (2010). As it was mentioned before; statistical models cannot deal with farm dynamism and complexities. Therefore, and as suggested by Dijkstra et al. (2007) and recently by Ellis et al. (2010), the incorporation of dynamic and mechanistic models of rumen and even better whole cows to 'whole farm models' is imperative if 'we' want to progress in the understanding and assessment of CH_4 at a larger scale than the rumen.

Ellis et al. (2010) mentioned the few whole farm models with capabilities to predict CH_4 emissions. For example, FarmGHG (Olsen et al. (2006), DairyWise (Schils et al., 2007a), FarmSim (Saletes et. al., 2004), SIMS Dairy (Schils et al., 2007b) and the WFM (Whole farm model of DairyNZ). From these models, the WFM is the only one that uses a mechanistic and dynamic model of a whole cow, the rest utilize an empirical approach to estimated enteric CH_4 production. The WFM was created more than 10 years ago (Sherlock et al., 1997) using Molly (Baldwin, 1995) as the cow model. The versions of actual Molly used in the WFM and his current improvements were mentioned before. The WFM has already and is currently being used in New Zealand to set pathways of research, and also by policy makers to re designing pastoral dairy systems for environmental protection (Dave Clark, pers. com.). Readers are referred to Beukes et al., 2010, Gregorini et al., 2010 and Beukes et al. In Press).

REFERENCE

Axelsson. 1949. The amount of produced methane energy in the European metabolic with adult cattle. Ann. Royal Agric. Coll. Sweden. 16: 404-419.

Baldwin, R. L., J.H.M. Thornley, and D. E. Beever. 1987b. Metabolism of the lactating cow. II. Digestive elements of a mechanistic model. J. Dairy Res. 54: 107-131.

Baldwin, R.L., J. France, and Gill, M. 1987b. Metabolism of the lactating cow. I. Animal elements of a mechanistic model. J. Dairy Res. 54: 77-105

Baldwin, R. L. 1995. Modeling Ruminant Digestion and Metabolism. Chapman & Hall, London.

Bannink, A., De A. Visser, and van A. M. Vuuren, 1997. Comparison and evaluation of mechanistic rumen models. British Journal of Nutrition 78: 563-581.

Bannink A., J. Kogut, J. Dijkstra, J. France, E. Kebreab, A. M. Van Vuuren, and S.Tamminga. 2006. Estimation of the stoichiometry of volatile fatty acid production in the rumen of lactating cows. J. Theoretical Biol. 238: 36–51.

Bannink, A., C. J.Smiths, E. Kebreab, J.A.N. Mills, J. L. Ellis, A. Klop, J. France J. Dijkstra. 2010. Simulating the effects of grassland management and grass ensiling on methane emission from lactating cows. J. Agric. Sci. 148: 55-72.

Benchaar, C., C. Pomar, and J. Chiquette. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. Canadian J. Anim. Sci. 81: 563-574.

Benchaar, C., J. Rivest, and J. Chiquette. 1998. Prediction of methane production form dairy cows using existing mechanistic and regression equations. J. Anim. Sci. 76: 617-627.

Beukes P.C., Thorrold B.S,. Wastney M.E., Palliser C.C., Macdonald K.A., Bright K.P., Lancaster J.A.S., Palmer C.A.J., Auldist M.J. 2005. Modelling the bi-peak lactation curves of summer calvers in New Zealand dairy farm systems. Aus. J. Exp. Agric. 45: 1-7.

Beukes, P. C., P. Gregorini, A. J. Romera., G. L. Levy and G. C. Waghorn. 2010a. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agri. Ecosystems Environ.136:358-365

Beukes, P.C., Burke, C.R., Levy, G., Tiddy R.M. 2010b. Using a Whole Farm Model to determine the impacts of mating management on the profitability of pasture-based dairy farms. Anim. Rep. Sci. 121:46-54.

Beukes, P. C., A. Romera, and P. Gregorini. 2011a. Estimating greenhouse gasses emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. In: Greenhouse gasses and animal agriculture conference. Anim. Feed Sci. Technol. (in Press).

Blaxter, K. L. and J. L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. British J. Nutr. 19: 511-522.

Chang, R. 1981. The second law of thermodynamics. Pages 129-163, in: Physiscal chemistry with applications to biological systems (2nd Ed.) Macmillan, New York.

Clark, H., and R. Eckard. 2010. Mitigating methane in a system context. Pages 79-85, in: Proc. IVth Australasian Dairy Science Symposium. Lincoln University, Lincoln, New Zealand, September 2010.

Corre, W. J. 2002. Agricultural Land Use and Emissions of Methane and Nitrous Oxide in Europe. Plant Research International, Wageningen, the Netherlands.

Danfaer, A., P. Huhtanen, P. Uden, J. Sveinbjornsson, and H. Volden. 2006. The Nordic dairy cow model, Karoline-description. Pages 407-415, in: Nutrient digestion and utilization in farm animals. Modelling approaches. E. Kebreab, J. Dijkstra, A. Bannink, W.J.J. Garrits, and J. France (eds). CAB International, Wallingfords, UK.

Dijkstra, J., H. D. Neal, D. Beever, and J. France, 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J. Nutr. 122: 2239-2255.

Dijkstra, J., A Bannink, K. W. Hoek, v. d., and W. Smink. 2006. Simulation of variation in methane emissions from enteric fermentation in Dutch dairy cattle. J. Dairy Sci. 89: 259.

Dijkstra J., E. Kebreab, J.A.N. Mills, W. F. Pellikaan, S. Lopez, A. Bannink, and J. France. 2007. Predicting the profile of nutrients available for absorption: from nutrient requirement to animal response and environmental impact. Anim. 1: 99–111.

Dijkstra, J., E. Kebreab, J. France, and A. Bannink. 2008. Pages 171-188, in: France J and E. Kebreab (eds). Mathematical modelling in animal nutrition. CAB International.

Ellis, J. L., E. Kebreab, N. E. Odongo, B. W McBride, E. K. Okine, and J. France. 2007. Prediction of methane production from dairy and beef cattle. J. Dairy Sci. 90: 3456-3467.

Ellis, J. L., J. Dijkstra, E. Kebreab, A. Bannink, N. E. Odongo, B. W. McBride, and J. France. 2008. Aspects of rumen microbiology central to mechanistic modelling of methane production in cattle. J. Agric. Sci. 146: 213–233.

Ellis, J. L., J. Dijkstra, E. Kebreab, S. Archibeque, J. France, and A. Bannink. 2009. Methane prediction with an improved representation of volatile fatty acids in a rumen model. Page 29, in: Proc. VII Int. Workshop. Modelling Nutrient digestion and utilization in farm animals. Paris September, 2009.

Ellis, J. L., A. Bannink, J. France, E. Kebreab, and J. Dijkstra. 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. Global change Biol. 16:3246-3256.

France, J., and J.M.H. Thornley. 1984. Mathematical models in agriculture. Butterworths, London.

Giger-Reverdin. S., P. Morand-Fehr, and G. Tran. 2003. Literature survey of the influence of dietary fat composition on methane production in dairy cattle. Livest. Prod. Sci. 82: 73–79

Gregorini, P., A. J., Romera, P. Beukes, J. L. Rossi, K.A. MacDonald. 2009. Using an existing intake model to demonstrate relationships between herbage allowance, hunger drive, days in milk and actual intake in grazing dairy cows. Proc. New Zealand. Soc. Anim. Prod. 69:27-31.

Gregorini, P., P. Beukes, R. Bryant, A. J. Romera. 2010. Simulating the effect of feeding strategies on nitrogen excretions and methane emission from grazing dairy cows. Pages 29-43, in: Proc. IVth Australasian Dairy Science Symposium. Lincoln University, Lincoln, New Zealand, September 2010.

Hanigan, M. D., H. G. Bateman, J. G. Fadel, and J. P. McNamara. 2006. Metabolic models of ruminant metabolism: recent improvements and current status. J. Dairy Sci. 82: E52-E64.

Hanigan M. D., C. C. Pallisser, and A. G. Rius, 2008. Modelling lactation potential in an animal model. Pages 486-507, in: J. France and E. Kebreab (eds.) Mathematical modelling in animal nutrition. CAB International.

Hanigan, M.H., Palliser, C., Gregorini, P. 2009. Altering the representation of hormones and adding consideration of gestational metabolism in a metabolic cow model reduced prediction errors. J. Dairy Sci. 92:5043-5056.

Hoh, C. 1996. Modelling reaction kinectics in anaerobic ecosystems with consideration of thermodynamic prioncipIes. PhD Diss. Murdoch University, Australia.

Holter, J. B., and A. J. Young. 1992. Methane prediction in dry and lactating Holstein cows. J. Dairy Sci. 75:2165-2175

IPCC, 1996. Chapter 4, Agriculture. In: S. Eggelston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (Eds.) Revised 1996 Guidelines For National Greenhouse Gas Inventories. Published by the Institute for Global Environmental Strategies (IGES) for the IPCC.

IPCC (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.
Intergovernmental Panel on Climate Change, Bracknell, UK.

Janssen P. H. 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. Anim. Feed Sci. Technol. 160:1-22.

Kebreab, E., K.Clark, , C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: a review. Canadian J. Anim. Sci. 86: 135-158.

Kebreab, E., J.A.N. Mills, L. A. Crompton, A. Bannink, J.Dijkstra, W.J.J. Gerrits, and J. France. 2004. An integrated mathematical model to evaluate nutrient partition in dairy cattle between the animal and its environment. Anim. Feed Sci. Technol. 112: 131-154.

Kebreab, E., K. A.Johnson, S. L. Archibeque, D. Pape, and T. Wirth. 2008. Model for estimation of enteric methane emissions from United States dairy cows and feedlot cattle. J. Anim. Sci. 86: 2768-2748.

Kohn, R.A., Boston, R.C. 2000. The role of thermodynamics in controlling rumen metabolism. Pages 11-24, in: J. P. McNamara, J. France and D. E. Beever (eds.). Modelling Nutrient Utilization in Farm Animals. CAB International. Wallingford, UK.

Kirchgeßner, M., W. Windisch, and H. L. Müller. 1994. Methane release from dairy cows and pigs. In: Proc. 13th symposium on Energy metabolism of farm animals (ed. J.F. Aguilera). EAAP publ. No. 76. CSIC Publ.Service, Spain, 399-402.

Kirchgeßner, M., W. Windisch, H. L. Muller. 1995. Nutritional factors for the quantification of methane production. Pages 333–348, in: W. Von Engelhardt, S. Leonhard-Marek, G. Breves, and D. Giesecke (eds.). Ruminant physiology: digestion, metabolism, growth and reproduction: Proc. VIII Int. Symp. Ruminant Physiology Ferdinand Enke Verlag, Stuttgart.

Kriss, M. 1930. Quantitative relations of dry matter of food consumed the heat production, the gaseous outgo and the insensible loss in body weight of cattle. J. Agric. Res. 40:283-295.

Lean, I. J., and C. H. Lean. 2010. Improving the specific credibility of farm systems and on farm dairy research. Pages 126-143, in: Proc. IVth Australasian Dairy Science Symposium. Lincoln University, Lincoln, New Zealand, September 2010.

McNamara, J. P., and Baldwin, R.L. 2000. Estimation of parameters describing lipid metabolism in lactation: challenge of existing knowledge described in a model of metabolism. J. Dairy Sci.83: 128-143.

Martin, O. and Sauvant, D. 2007. Dynamic model of the lactating dairy cow metabolism. Animal 1: 1143-1166.

Mills, J. A. N., J. Dijkstra, A. Bannink, S. B.Cammell., E. Kebreab, and J. France. 2001. A mechanistic model of whole-tract and methanogenesis in the lactating dairy cow: model development, evaluation, and application. J. Anim. Sci. 79: 1584-1597.

Mills, J.A.N. 2008. Modelling methane emissions from farm livestock. Pages 189-203, in, France J and E. Kebreab (eds). Mathematical modelling in animal nutrition. CAB International, Wallingford, UK.

Mills, J.A.N., E. Kebreab, C. M. Yates, L. A. Crompton, S. B. Cammell, M. S. Dhanoa, R. E. Agnew, and J. France. 2003. Alternative approach to predicting methane emissions from dairy cows. J. Anim. Sci. 81:3141-3150.

Moe, P. W., and H. F. Tyrell, 1979. Methane production in dairy cows. J. Dairy Sci. 62:447-454

Nagorka, B. N., G.L.R. Gordon, and R. A. Dynes. 2000. Towards a more accurate representation of fermentation in mathematical models of the rumen. In: J.P. McNamara et al. (eds) Modelling nutrient utilization in farm animals. CAB International. pp. 37-48.

Palliser C. C., M. E. Wastney, K. B. Bright, K. A. Macdonald, J. P. Penno 2001. Modelling the lactation curves of New Zealand Cows. Modelling and Simulation Society of Australia and New Zealand MODSIM 2001. Ghassemi F. White D, Cuddy S, Nakanishi T.(Eds), 4: 1853-1858,.

Offner, A. And D. Sauvant. 2006. Thermodynamic modelling of ruminal fermentations. Anim. Res. 55:343-365.

Olesen, J. E., H. Jørgensen, A. Danfær, S. Gyldenkærne, M. H. Mikkelsen, W.A.H. Asman, and S. O. Petersen. 2005. Evaluering af mulige tiltag til reduktion af landbrugets metanemissioner. Arbejdsrapport fra Miljøstyrelsen Nr. 11, 2005

Olesen J. E., K. Schelde, A. Weiske, M. R. Weisbjerg, W.A.H. Asman, Djurhuus J (2006). Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agriculture, Ecosystems and Environment, 112, 207–220.

Pinares-Patiño, C. S., and H. Clark. 2010. Rumen function and digestive parameters associated with methane emissions in dairy cows. Pages 66-93, in: Proc. IVth Australasian Dairy Science Symposium. Lincoln University, Lincoln, New Zealand, September 2010.

Rook, A. J. 1999. The use of groups or individuals in the design of grazing experiments (reply to Phillips, 1998). Appl. Anim. Behave. Sci. 61:357-358.

Russell, J. B. And G. M. Cook. 1995. Energetics of bacterial growth: balance of anabolic and catabolic reactions. Microbiol. Rev. 59:48-62.

Saletes S., J. Fiorelli, N. Vuichard, J. Cambou, J. E.Olesen, S. Hacala, M. Sutton, J. Fuhrer, J. F Soussana. 2004. Greenhouse gas balance of cattle breeding farms and assessment of mitigation options. Pages 203–208, in: Greenhouse Gas Emissions from Agriculture, Mitigation Options and Strategies (M. Kaltschmitt and A. Weiske eds.). Institute for Energy and Environment, Leipzig.

Schils, R.L.M., A. Verhagen, H.F.M. Aarts, P.J. Kuikman, and L.B.J. Sebek. 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Global Change Biol. 12: 382–391.

Schils, R. L. M., d M.H.A.e Haan, J.G.A. Hemmer, A. Pol-Van Dasselaar, B.J.A. van Den, A.G. Evers, G. Holshof, J.C. van Middelkoop, and R.L.G. Zom, 2007a. Dairywise, a Whole-Farm Dairy Model. J. Dairy Sci. 90: 5334-5346.

Schils RLM, Olesen JE, del Prado A, Soussana JF (2007b) A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Science, 112, 240–251.

Sherlock, R. A., K. P. Bright, and P. G. Neal. 1997. An object-oriented simulation model of a complete pastoral dairy farm. Pages 1154-1159. Proc. Int. Cong. on Modelling and Simulation. Vol 3. University of Tasmania, 8-11 Devcember.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. De Haan. 2006. Livestock long shadow-Environmental issues and options. Food and Agricultural Organization of the United Nations, Rome, Italy.

Sveinbjornsson, J., P. Huhtanen, and P. Uden. 2006. The Nordic dairy cow model, Karoline-development of volatile fatty acids sub-model. Pages 1-14, in: E. Kebreab, J. Dijkstra, A. Bannink, W.J.J. Garrits, and J. France (eds). Nutrient digestion and utilization in farm animals. Modelling approaches. CAB International, Wallingford, UK.

Tamminga, S., A. Bannink, J. Dijkstra, and R.L.G. Zom. 2007. Feeding strategies to reduce methane loss in cattle. Report 34. Animal Science group, Wageningen UR. 46pp. http://library.wur.nl/way/bestanden/clc/1855887.pdf

Thornley, J. H. M. 1998. Grassland dynamics. An ecosystem simulation model. CAB International, Wallingford, UK.

Uden, P., and A. Danfaer. 2008. Modelling glucose metabolism in the dairy cow: A comparison of two dynamic models. Anim. Feed. Sci. Technol. 143:59-69

Volden, H. 2010. The potential of using the NorFor model to evaluate dietary strategies to reduce methane production and nitrogen excretion in cattle. Pages 65-70 in: Proc. I Nordic feed science conf. Uppsala, Sweden, June 2010.

Weisbjerg, M. R., T.Hvelplund, , P.Lund, and J. E Olesen. 2005. Metan frahusdyr: Muligheder for reduktion ved ændret fodring. In Olesen, J.E (red):Drivhusgasser fra jordbruget – reduktionsmuligheder, DJF rapport Markbrugnr. 113: 67-83.

Welch, G. R. 1991. Thermodynamics and living systems: problems an paradigms. J. Nutr. 121: 1902-1906

Wiens, J.A. 1989. Spatial scaling in ecology. Functional Ecology, 3: 385-397.

Wilkerson, V. A. and Casper, D. P. 1995. The prediction of methane production of Holstein cows by several equations. Journal of Dairy Science 78: 2402-2414.

Wu, J. 1999. Hierarchy and scaling: Extrapolating information along a scaling ladder. Can. J. Remote. Sensing. 25:367-380.

Yan, T. Development of dietary and animal approaches to reduce methane emission from dairy cattle. Pages 29-30 in Proc. XV Intern. Silage. Conf, Univ Wisconsin-Madison.

Yan, T., C. S. Mayne, F. G. Gordon, M. G. Porter, R. E. Agnew, D. C. Patterson, C. P. Ferris, D. J. Kilpatrick. 2010. Mitigation of enteric methane emissions through improving efficiency of energy utilization and productivity in lactating dairy cows. J. Dairy Sci. 93: 2630-2638.

APPENDIX 7 Abstract for American Dairy Science Symposium 2012

Comparison of methane prediction for pasture fed dairy cows using a simulation model (Molly) incorporating revised VFA stoichiometry and microbial pools

McNamara, J. P., P. C. Beukes, P. Gregorini, M. D. Hanigan and G. Waghorn.

This study compared the outcomes of three versions of DairyNZ's metabolic model, Molly, with two different VFA stoichiometry constructs, to describe ruminal VFA pattern and methane (CH4) production (g/d). The models' outputs were validated using data from 16 dairy cattle (26 months old, 82 DIM, 17 kg milk/d) fed fresh cut ryegrass (DMI 12.3 kg DM) in respiration chambers. The model versions were DairyNZ's Molly4 (similar to Baldwin, 1995); Molly84, which includes updated ruminal fiber digestive parameters and animal hormonal parameters (Hanigan et al., J. Dairy Sci.); and Molly85, a revised version of Molly84 with new digestive and rumen parameters. The original forage diet VFA construct was compared to a new VFA stoichiometry based on a more recent and larger set of data, including lactate and valerate production and, amylytic, cellulytic bacteria, as well as protozoal pools. Average observed CH4 production was 266 ± 30 SD (g/d). Mean predicted values for CH4 production were 287 and 258 (g/d) for Molly4 without and with the new VFA construct, respectively. Molly84 predicted 295 and 288 (g CH4/d) with and without the new VFA construct, respectively. Molly85 predicted the same CH4 production (276 g CH4 /d) with or without the new VFA construct. The incorporation of the new VFA construct did not consistently reduce the mean relative prediction error (RPE %) across the versions of Molly evaluated in the present study. The improvements in the Molly versions from 4, 84 to 85 resulted in a decrease in RPE from 8.6, 8.3 to 4.3%, respectively. The majority of the root mean square prediction error was apportioned to random bias, e.g. 43, 71 and 70% in Molly4, 84 and 85, respectively. The slope bias was 2% in all cases. It is concluded that DairyNZ's present version (Molly85) has the capability to predict CH4 production of pasture fed dairy cows with acceptable accuracy.

KEY WORDS: cow model, VFA, methane prediction

APPENDIX 8. In preparation for Journal of Dairy Science

RUNNING HEAD: MECHANISTIC MODELING OF METHANE PRODUCTION

Comparison of updates to the Molly mechanistic, dynamic model of metabolism to describe VFA patterns and methane production.

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Interpretive Summary

Use of dynamic, deterministic models of metabolism in dairy cattle can be used to ask questions about the effect of feeding strategies on efficiency, including production of VFA and methane. Three updated versions of the UCDavis (Molly) metabolic model accurately predicted methane production from cows fed fresh grass in respiration chambers. Recent updates improved the precision of VFA production response and methane production, demonstrating utility of the model in helping to formulate research questions and compare methane mitigation strategies.

ABSTRACT

The multifaceted challenges facing the dairy industry demands a systems approach to integrate our knowledge for faster and more effective research and application. Use of biological models provides such an approach to answer questions concerning efficiency of dairying practices across a range of animal genetics and feeding systems. Mechanistic models can be used to ask questions about the underlying control of animal performance, including ruminal metabolism and loss of methane. One such model (Molly, UC Davis) has been used extensively to ask research questions and describe the digestion and metabolism of the cow, and updates to the model equations and parameter values have been published in recent years. Therefore, our objective was to use an existing mechanistic, dynamic model of rumen and animal metabolism in three different updates, to compare performance of the versions of rumen and metabolic parameter values in the model, including an alternative set of coefficients for VFA production in the rumen, on the ability of this model to describe observed ruminal processes including methane production in one specific situation representative of feeding grass based pasture. A study of 30 dairy cattle fed fresh grass in respiration chambers was used as the challenge study, providing a wide range of methane production. All versions of the models described methane production within 12 % of the mean observed, which is within the observed coefficient of variation. The newest version with updated fiber and protein degradation and acetate absorption parameter values was within 0.4 to 4 % of the observed. The newest model version using updated ruminal VFA data based on microbial pools may provide more flexibility in describing products of fermentation. The work illustrates the utility of using metabolic dynamic models to describe ruminal and metabolic processes altering efficiency of dairy cattle and production of waste products such as methane.
Keywords: metabolic models, dairy efficiency, methane, systems biology

APPENDIX 9.

Gregorini, P., Beukes, P.C., Bryant, R.H., Romera, A.J., 2010. A brief overview and simulation of the effects of some feeding strategies on nitrogen excretion and enteric methane emission from grazing dairy cows. In: Edwards, G.R., Bryant, R.H. (eds). Meeting the challenges for pasture-based dairying. Proceedings of the 4th Australasian Dairy Science Symposium, 31 August – 2 September 2010, Lincoln University, Christchurch, New Zealand. Pp 29-43.

A brief overview and simulation of the effects of some feeding strategies on nitrogen excretion and enteric methane emission from grazing dairy cows

Short title: Modelling dairy environmental impact

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ABSTRACT

Dairy farming is under increasing pressure to reduce its environmental impact; foremost of these being nitrogen (N) discharges in urine and enteric methane (CH_4) emissions. This work reviews the literature supporting specific feeding strategies on reducing urinary nitrogen (UN) and scales each strategy up to a farm level using a mechanistic cow model (Molly) within a whole farm model (WFM). It then explores the capacity of each strategy to reduce UN and collateral enteric-methane (CH_4) emissions from those on a baseline all-pasture dairy farm (BL) from Waikato, New Zealand (3.45 cow/ha; 1300 kg milksolids/ha/yr). The feeding strategies simulated were: 1) N fertilisation level; 2) Use of high sugar ryegrass cultivars; 3) Timing of pasture allocation; 4) Timing of defoliation at specific leaf stage; and 5) Maize silage supplementation at the beginning and end of lactation. The simulations showed different effectiveness on UN reductions according to feeding strategies. Except for the lowest and highest levels of N fertilisation (100 and 300 kg N/ha/yr) all feeding strategies increased enteric-CH_4 emissions/kg dry matter intake (DMI). Such increments were small, but had a large impact on CO_2 equivalent (CO_2-e) emissions/DMI and per unit of milksolids (MS). The biggest reduction of CO_2-e/herbage DMI, (6.3%) from BL, was obtained with the lowest level of N fertilisation (100 kg N/ha/yr). This work highlights an important trade-off: feeding strategies aimed to reduce UN may result in concurrent increases in CH_4 emissions, with an overall increase in environmental impact measured in CO_2-e.

Keywords: Feeding strategies; urinary nitrogen; methane; pastoral dairy systems

APPENDIX 10. In preparation for Journal of Dairy Science

Revised digestive parameter estimates for the Molly cow model

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ABSTRACT

The Molly cow model (Baldwin, 1995) represents nutrient digestion and metabolism based on a mechanistic representation of the key biological elements. Initial digestive parameters were derived ad hoc from literature observations or were hand estimated. Preliminary work determined that a number of these parameters did not represent the true relationships. The current work was undertaken to derive ruminal and post-ruminal digestive parameters and to use a meta-analysis approach to assess interactions among nutrients and identify areas of model weakness. The ruminal pH prediction equation generated predictions with substantial mean bias which caused problems in fiber digestion and microbial growth predictions. The pH prediction equation was re-parameterized simultaneously with the a number of ruminal and post-ruminal digestion parameters resulting in more realistic parameter estimates for ruminal fiber digestion, and moderate reductions in prediction errors for pH; NDF, ADF, and microbial N outflow from the rumen; and post-ruminal digestion of NDF, ADF, and protein. Prediction errors are still large for ruminal ammonia and outflow of starch from the rumen. Residuals analyses indicated additional progress could be made in predicting microbial N outflow, VFA production and concentrations, and cycling of N between blood and the rumen. These additional corrections should lead to a robust representation of the effects of dietary nutrients on ruminal metabolism and nutrient absorption. This will lead to better predictions of animal performance and the environmental impact of dairy production which could be leveraged to identify novel or existing management practices that could be used to reduce environmental loading per unit of product while maintaining the economic performance of the industry.

APPENDIX 11

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ORIGINAL ARTICLE

A urine patch framework to simulate nitrogen leaching on New Zealand dairy farms

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Abstract On New Zealand dairy farms, it is the nitrogen excreted directly onto pasture, particularly urine, that drives nitrogen (N) leaching from the farm. A new framework (UPF: Urine Patch Framework) is presented that post-processes the results of a whole farm model and runs a mechanistic soil model to simulate the urine patches. Two alternative methods to simulate the spatial distribution of urine patches were implemented and compared (*Grid*: spatially explicit, and *Probabilistic*: based on the probability of different temporal urination patterns). This paper describes the implementation of these two methods in connection with a Whole Farm Model; and compares the N leaching predictions with observed data. Two examples are provided, one analyzing the impact of urine patch overlap and another, the relative risk of N leaching at different times of urinary N deposition. The model showed good correlation and predictive ability between simulated annual N leaching results and observed data [$R^2 = 94$ %, mean relative prediction error (MRPE) = 10 % for *Grid* and $R^2 = 72$ %, MRPE = 20 % for *Probabilistic*]. The two methods produced similar results across an 8-year period for monthly and annual N leaching ($R^2 = 96$ %, MRPE = 10 % and $R^2 = 86$ %, MRPE = 8 %; respectively). Only 8 % of the paddock area was covered with multiple urinations during 1 year, but as much as 39 % of the total urine volume was deposited on overlapped patches. Systematically removing all urinary N for 1 month in either May or June reduced N leaching by approximately 20 %. Avoiding urinary N deposition during autumn or early winter could be highly effective in mitigating N leached during the following winter.

Keywords Whole farm model · Soil model · Nitrogen excretion · Nitrogen leaching

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Introduction

Agricultural fertiliser, stock manure and urine are the major non-point-sources of nitrogen (N) in rural New Zealand (Ministry for the Environment 2007). On New Zealand pastoral dairy farms, it is the nitrogen excreted on pasture, particularly urine patches, that drives environmental impact, and not nitrogen fertilizer inputs per se (Decau et al. 2004). This has wide relevance beyond New Zealand dairy farms, since the majority of the world's ruminants still urinate at pasture rather than inside a building. Furthermore, managed grazing is the single most extensive form of land use on the planet (Asner et al. 2004). Even for extensive systems where rotational grazing is not practiced, there are still important issues of animal concentration around water holes and camping areas

APPENDIX 12

CSIRO PUBLISHING

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Estimating nitrous oxide emissions from a dairy farm using a mechanistic, whole farm model and segregated emission factors for New Zealand

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Abstract. Nitrous oxide (N_2O) emissions from agriculture are generally estimated using default IPCC emission factors (EFs) despite the large variation in measured EFs. We used a classification and regression tree (CART) analysis to segregate measured EFs from direct emissions from urine patches and fertiliser and effluent applications, based on temporal and site-specific factors. These segregated EFs were linked to simulations from the DairyNZ Whole Farm Model to obtain N_2O emissions for a typical pasture-based dairy farm in New Zealand. The N_2O emissions from urine patches, dung pads, and fertiliser and effluent application, as well as from indirect sources, were aggregated to obtain total N_2O emissions for the farm-scale. The results, based on segregated EFs, were compared with those obtained using New Zealand-specific EFs. On-farm N_2O emissions based on these segregated EFs were 5% lower than those based on New Zealand-specific EFs. Improved farm management by avoiding grazing, effluent, and N fertiliser application during periods of high risk for N_2O emissions, or by the use of mitigation technologies such as nitrification inhibitors, could reduce annual farm scale N_2O emissions.

Additional keywords: CART analysis, fertiliser, nitrous oxide emission factors, N_2O database NZ, urine.

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APPENDIX 13

Prepared for submission to Special Issue on 'Soil as a Source and Sink for Greenhouse Gases' in *Science of the Total Environment*

Comparison of APSIM and DNDC to simulate nitrogen transformations and N_2O emissions

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APPENDIX 14

Evaluation of mitigation strategies for nitrate leaching on pasture-based dairy systems

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Abstract

Dairy farms are under pressure to increase productivity while reducing environmental impacts. We used the DairyNZ Whole Farm Model (WFM) and APSIM to evaluate the effect of mitigation strategies within an efficient farm (EF) in the Waikato region, NZ, on these targets. Mitigation strategies compared with the baseline farm (BF) included the use of fewer more efficient cows, low nitrogen (N) feed supplements, loafing pads, less N fertiliser and nitrification inhibitor (DCD). To encompass climate affects three different years with average, high and low annual rainfall were modelled. The WFM predicted number of urinations and urinary N loads deposited during individual grazing events were used as an input for APSIM to simulate N leaching from urine patches, as well as from non-urinated areas. Results were aggregated to obtain total N leached on a paddock and farm scale. For all three years, farm averaged N leaching was lower, by 20 to 55%, in the EF compared with the BF farm. DCD reduced leaching in two of the three years by 12 and 15%. N leaching was lowest for N deposited in the wet year and highest for the dry year. Milk production was consistently greater for the EF compared to the BF, with an increase in milksolids (MS)/ha ranging from 8% in the wet, to 17% in the dry year.

Keywords: Modelling, Whole Farm Model, APSIM, N leaching, DCD

APPENDIX 15

Abstract for 17th International Nitrogen Wrokshop 27-29 June 2012 Wexford Ireland

Comparison of APSIM and DNDC for simulating nitrogen transformation and N2O emissions from urine patches

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1. Background & Objectives

Nitrogen transformation rates and nitrous oxide (N_2O) emissions from urine patches are notoriously variable, both in space and time, due to the variability of controlling environmental factors. Thus annual N_2O losses are often made up by a few emission peaks. Effective mitigation of N_2O emissions from pastoral systems requires better understanding of the factors that control the interconnected N cycling processes, including nitrification, denitrification and gaseous emissions.

Computer simulation models provide a cost effective method of estimating N_2O emissions from soils and for evaluating how heterogeneity in climate and soil affect these emissions. Various simulation approaches are in use or being developed to predict N_2O emissions. The models vary in the level of detail or number of nitrogen pools and transformation processes considered, as well as on how the processes are described. Other processes within the models, such as water and heat transport within the soil also affect the modelled N transformations and losses. And while most models have been tested and validated for certain aspects, there is a lack of information on how models compare in other aspects. The objective of this paper is to compare the APSIM (Agricultural Production Systems Simulator; (Keating et al., 2003),), and DNDC (DeNitrification DeComposition; (Li et al., 1992)) model for simulating N transformation processes and N_2O emissions from urine patches.

2. Materials & Methods

N transformations and N_2O emissions from urine patches from the two different simulation approaches, APSIM and DNDC, were compared by setting up simulations comprising two different regions of NZ, two different soils, 4 different N deposition times, (Spring, summer, autumn and winter), and four different N deposition loads (250, 500, 750, and 100 kg N/ha). The simulations were run for 3 months and simulation output included cumulative and daily values of nitrification, denitrification, volatilisation, and N_2O emissions. Simulation results were also compared to different datasets comprising N_2O emissions from urine patches.

3. Results & Discussion

Simulated N transformation rates as dependent on environmental conditions were quite different for the two models, APSIM and DNDC. APSIM simulated denitrification in a silt loam in the Waikato region of NZ increases nearly linear with increasing N load (Figure 1), whereas denitrification simulated by DNDC reaches a plateau at an N load of 250 kg/ha and thereafter remains almost constant. DNDC also shows little seasonal affect to denitrification, whereas APSIM predicts much higher denitrification in autumn compared to summer and spring. This model difference is partly due to the higher sensitivity of denitrification in APSIM to soil water content, and of DNDC on soil temperature. Simulated N2O emissions by APSIM show a similar trend to denitrification, whereas those simulated by DNDC show a linear increase over the entire range of N load simulated. This suggests that in DNDC at high N loads nitrification becomes a major source for N2O emissions.

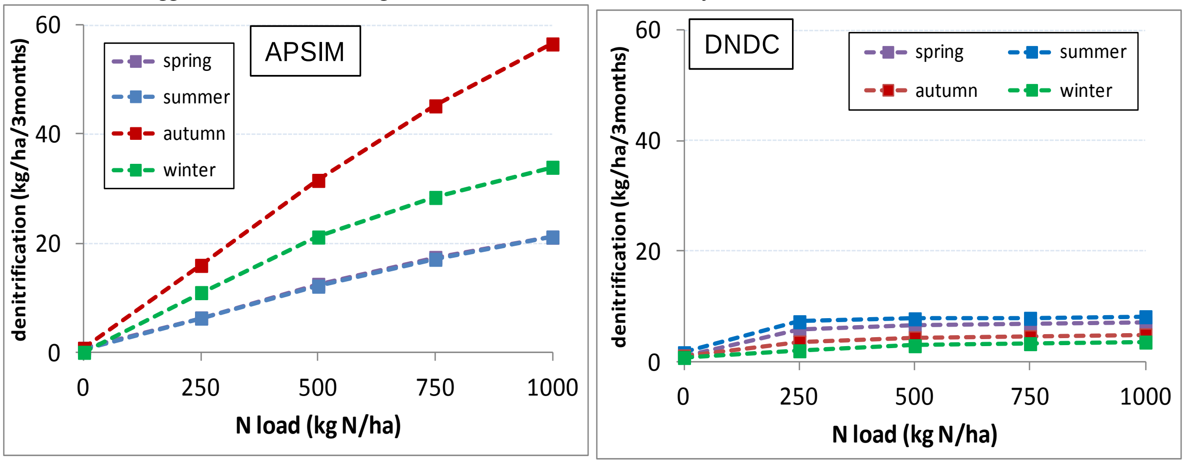

Figure 1. APSIM and DNDC simulated denitrification rate as dependent on N load and time of deposition in a silt loam in the Waikato region of NZ.

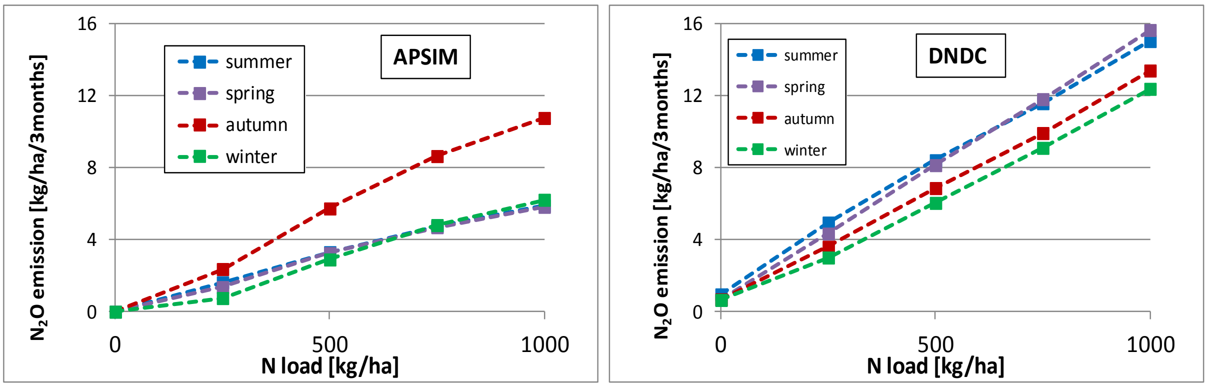

Figure 2. APSIM and DNDC simulated N_2O emission as dependent on N load and time of deposition in a silt loam in the Waikato region of NZ.

4. Conclusion

5. Acknowledgments
This project is jointly funded by the New Zealand Agricultural Green House Gas Research Centre (NZAGRC) under "Integrated Systems" and MAF under "Sustainable Land Management Mitigation & Adaptation to Climate Change".

References

Keating, B., Carberry, P., Hammer, G., Probert, M., Robertson, M., Holzworth, D., Huth, N., Hargreaves, J., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J., Silburn, M., Wang, E., Brown, S., Bristow, K., Asseng, S., Chapman, S., McCown, R., Freebairn, D., and Smith, C., 2003, An overview of APSIM, a model designed for farming systems simulation: European Journal of Agronomy, v. 18, p. 267-288.

Li, C., Frolking, S., and Frolking, T.A., 1992, A model of nitrous oxide evolution from soil driven by nitrous oxide evolution from soil driven by rainfall events. Model structure and sensitivity.: Journal of Geophysical Research, v. D9, p. 9776-9799.

APPENDIX 16

19th International Congress on Modelling and Simulation, Perth, Australia, 12–16 December 2011
http://mssanz.org.au/modsim2011

Comparison of models for predicting nitrification, denitrification and nitrous oxide emissions in pastoral systems

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Abstract: Intensification of agricultural systems has resulted in remarkable increases in productivity. However in grazed systems only about 10-20% of the N ingested by grazing animals is retained in animal products. The reminder is returned in excreta to the paddock in a spatially non-uniform fashion as dung and urine and then either accumulates in the soil or is lost via leaching or gaseous emissions. The amount of N lost from these patches via leaching and gaseous emissions is highly dependent on site-specific factors. Routine direct measurements are impractical given the scale and variability so simulation models are an essential alternative to estimate likely N losses. Various simulation approaches are in use or are being developed to predict N leaching and N_2O emissions. The models vary in the level of detail or number of nitrogen pools and transformation processes considered, as well as on how the processes are described. Other processes within the models, such as water and heat transport within the soil also affect the modelled N transformations and losses. While most models have been tested and validated for some processes or outputs in a particular range of systems, soils and climates, there is a lack of information on how models compare in other aspects. We discuss key differences and similarities between the N transformation components of the APSIM and DNDC models with respect to their simulation of nitrification, denitrification and N_2O emissions under pastoral systems.

Agreement between daily N_2O emissions from urine patches simulated by APSIM and DNDC was variable, Figure 1. For the Horotiu soil the index of agreement (IA) between measurements and APSIM or DNDC were 0.4 and 0.13, and for the Templeton soil 0.77 and 0.47. Agreement between total emissions over the experimental period was better for the APSIM model than the DNDC, based on default model parameters. For the Horotiu soil, N_2O emissions over 3 months were 4.9 kg/ha, and simulations with APSIM and DNDC gave values of 7.4 and 13.7 kg/ha. For the Templeton soil over 1 year measurements were 2.8 kg/ha and simulations with APSIM 1.9 kg/ha and with DNDC 16.3 kg/ha. Adjusting default values to NZ conditions can, however, improve the prediction capacities of the models.

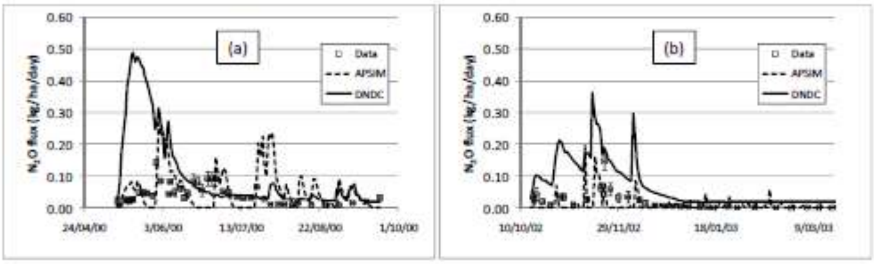

Figure 1. Measured and simulated N_2O emission from a urine patch by APSIM and DNDC a) Horotiu silt loam over 4 months and b) Templeton silt loam over 1 year from New Zealand (data taken from de Klein et al., 2003)

Keywords: *APSIM, DNDC, nitrous oxide, nitrification, denitrification*

884

APPENDIX 17

NZAGRC Abstract 2012

Modelling nitrous oxide emissions from urine patches: Comparison of different approaches

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There are many different modelling approaches that can be used to predict N_2O emissions from agricultural systems. They vary somewhat in the way they describe soil processes such as nitrogen transformations. This paper provides a comparison of alternative process based N_2O modelling approaches and discusses key differences. N_2O emissions from urine patches were simulated using the APSIM model based on the default procedure for simulating N_2O, a simplification of the DayCent approach. Additional nitrification-denitrification-N_2O procedures based on DayCent, WNMM or NEMIS were evaluated by linking them with the soil nitrogen module of APSIM. Simulation results were compared to datasets comprising N_2O emissions from urine patches. For a urine patch deposited in May in the Hamilton region the annual nitrification simulated by the various approaches was very similar. Simulated denitrification and N_2O emissions, however, showed a high variability of one magnitude between these approaches.

APPENDIX 18

Compilation of a N_2O database for NZ pastoral systems

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The compilation and analysis of a N_2O emissions database from pastoral systems is discussed. It covers about 150 measurement sets done under a wide range and combination of environmental and site specific conditions, including variations in climate, soil type, topography, and N source. Measured data were processed into a common framework within a spreadsheet (xlsx) format that enables easy analysis and comparison. The database includes measurements of soil water content and mineral N concentrations, soil temperature and pH, where available, as well as climate and soil descriptions, either measured on site, obtained from the literature, or from known reference datasets, such as the National Soils Database (Landcare) and the Virtual Climate Station database (NIWA). The database also contains calculations of emission factors, and a quality control procedure of measured data. The database, which will be updated regularly, is extremely valuable for testing and fine tuning models for more accurate estimation of N_2O emissions from pastoral systems.

Abstract NZAGRC Conference January 2012

Comparison of models for simulating N_2O emissions from urine patches

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Nitrous oxide (N_2O) emissions from urine patches are notoriously variable, both in space and time, due to the variability of controlling environmental factors. Computer simulation models provide a cost effective method for evaluating how heterogeneity in climate and soil affect N_2O emissions. Various simulation approaches are in use or being developed to predict N_2O emissions. The models vary in the level of detail or number of nitrogen pools and transformation processes considered, as well as on how the processes are described. We discuss key differences and similarities between the N transformation components of the APSIM and DNDC models. Simulation results were compared to N_2O datasets from different regions within NZ, different soil types and various urine deposition times. Using default model parameters, agreement between total emissions was generally better for the APSIM model than the DNDC. Adjustment of default values to NZ conditions improved the prediction capacities of both the models.

Abstract NZAGRC Conference January 2012

APPENDIX 19

CAN WE IMPROVE INTERPOLATION OF N_2O EMISSION MEASUREMENTS BY USING ENVIRONMENTAL FACTORS?

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Abstract

Determining nitrous oxide (N_2O) emissions is highly uncertain due to their large spatial and temporal variability. This variability is caused by the many biological processes involved, each responding in a different way to environmental conditions. Also the various processes are often associated with non-linear relationships to gaseous emissions. The objective of this study was to analyse N_2O emission from a recently compiled New Zealand N_2O database and to verify the possibility of using environmental factors to improve the currently used linear interpolation of measurements. The database comprises a collection of data from 21 trials carried out in New Zealand since 2000, under different climates, with different soils and N loads and sources. Gaseous and soil data collection were performed according to NZ's Ministry of Agriculture and Forest (MAF) protocols. In this work, we analyzed all data from urine patches treatments (N application ranging from 49 – 1,000 kg/ha) using stepwise multiple regression to select significant variables and to determine their relationship with N_2O emissions. Daily measurements of soil water-filled pore space, volumetric water content, soil porosity, sum of rain recorded in the two previous days of gas measurement, soil temperature, air temperature, solar radiation as well as soil organic carbon content and inorganic soil N content were used as environmental variables. Prediction of N_2O emissions using environmental parameters resulted in a poor agreement when fitting was done using the whole dataset (R^2=0.16). Improvement of fitting (R^2=0.39) was achieved after filtering the data according to the soil's nitrate content (soil NO_3 content higher than 70% of total inorganic N). This separates the N_2O values obtained when denitrification was the dominating process on the production of N_2O. For the remaining data, the emissions come from both nitrification and denitrification, and could not be related to environmental factors in a more precise way. Next the data were analysed region specific. For the Waikato region, stepwise regression indicated four variables as significant: rainfall, air temperature, radiation, soil's clay content, and NO_3 amount; while for Otago only rainfall and NO_3 amount were significant. Predictive functions based on these variables were used to interpolate N_2O emissions and these were compared with the Intergovernmental Panel on Climate Change (IPCC) interpolation approach. Preliminary results suggest that the above procedure is promising and specific tests will be carried out in the future. The relationship between estimated gaseous emissions and environmental factors at the time of high ammonium contents also need to be further investigated.

APPENDIX 20

Abstract NZAGRC Conference January 2012

Temporal trends of nitrous oxide emissions from pastoral systems of NZ

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Estimation of nitrous oxide (N_2O) emissions is highly uncertain due to their large spatial and temporal variability. This variability is caused by the large variation in biological processes involved, which each respond differently to environmental conditions in soils, and are often associated with non-linear relationships to N_2O emissions. The objective of this study was to analyse measured seasonal variations of N_2O emissions from pastoral systems. Selected N_2O data from the NZAGRC compiled N_2O database were used, comprising two different regions, with two contrasting soils each, and also different urine deposition timings and N loads (ranging from 340-540 kg ha^{-1}). Trends of N_2O emissions and their correlation to some soil attributes and controlling environmental factors are discussed.

APPENDIX 21

Outputs objective 1.4

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Efficiencies, productivity, nutrient losses and greenhouse gas emissions from New Zealand dairy farms identified as high production, low emission systems. In: *Advanced Nutrient Management: Gains from the Past - Goals for the Future.* (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 25. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Are high production, low GHG emission dairy farms in New Zealand possible? Oral presentation. To be presented at the 2012 ADSA-AMPA-ASAS-CSAS-WSASAS Joint Annual Meeting (July 15-19 2012), Phoenix, Arizona.

Vibart, R., White, T., Smeaton, D., Dennis, S., Dynes, R., and Brown, M. (2012). Increased productivity and reduced environmental footprint - Are high production, low GHG emission dairy farms in New Zealand possible? Poster presentation. To be presented at the Australasian Dairy Science Symposium (November 13-15 2012), Melbourne, Australia.

White, T.D., Vibart, R., and Smeaton, D. (2011) Summary report of low emission, high production farming: Three case studies. Client report for SLMACC June 2011.

APPENDIX 22

Identification of a Model for predicting N_20 production from farming systems in New Zealand

November 2010

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Table of Contents

Executive Summary

From a detailed model screening of denitrification and gaseous N emission models in the literature we selected various models that have the potential to be integrated into a Farm System Model for predicting N_2O production for NZ's pastoral systems. The selection was based on choosing different approaches with regard to model complexity and ensuring that the model is (i) publicly available, (ii) is mechanistically sensible, (iii) can be tested with datasets from NZ spanning a range of soils and climates, (iv) adequately describes NZ farming systems including urine patches, and (v) can be used to evaluate mitigation options such as nitrification inhibitors and their effect on the whole farm system. We selected the following models: APSIM, DayCent, DNDC, NEMIS, VISIT and WNMM. The submodules of these models describing either denitrification and/or gaseous N losses will be integrated into a Farm System Model such as APSIM.

Introduction

Importance of gaseous N emissions from grazed pasture systems on environmental quality is well recognised. Agricultural land has been identified as the major anthropogenic source of nitrous oxide, N_2O (IPCC 2007), and also as an important source of nitric oxide (NO) emissions. Nitrous oxide is an important GHG and NO emissions contribute to the destruction of stratospheric ozone.

The IPCC currently uses a fixed N_2O emission rate of 1.25% for all N applied as fertiliser, manure, green manure or fixed by leguminous crops. In addition NZ uses a country specific modified IPCC methodology to produce its annual emission inventory. These IPCC guidelines are very simplistic and generalised, and do not necessarily represent the spatial and temporal patterns of emissions nor consider site specific factors or management practices. As such it does not provide the flexibility to assess mitigation options and their affect on the whole farm system. More complex models that simulate the processes controlling emissions have the potential to better represent how grazing intensity and microbial dynamics interact to control nitrogen cycling and N_2O emissions.

Nitrification is the microbiological conversion of ammonium (NH_4^+) to nitrite (NO_2^-) and then nitrate (NO_3^-). In the absence of available oxygen some microorganisms progressively reduce NO_3^- to NO_2^- , nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen gas (N_2) in a process known as denitrification. Thus, oxides of nitrogen, NO and N_2O are intermediate products of the processes of nitrification and denitrification. Both these processes, and the ratios of the products, are affected by environmental conditions such as soil oxygen and moisture contents, temperature, mineral N content, available carbon and pH.

Models for predicting N2O emissions

Accurate estimates of regional N_2O emissions from agricultural soils are very difficult due to spatial and temporal variability in N gas emissions. To address the variability in N_2O emissions various models, including simple regression and mechanistic models have been developed. Regression models have some substantial deficiencies, lack important variables and do not consider interaction of the various processes in the nitrogen cycle, and only apply within the range of situations for which they were developed. Thus these models cannot be used for testing mitigation scenarios. In addition, regression models will only predict the effects on N_2O emissions. More mechanistic models can look at multiple impacts such as N_2O emissions, NO_3 leaching, plant growth etc. Various mechanistic models of soil C and N cycling with varying degrees of complexity have been published. Such process based models can help to better understand the processes governing N_2O emissions and their dependence on environmental conditions, and are essential for estimating long term effects of management strategies and climate change on emissions from pastoral farming systems. Processes such as nitrification and denitrification are generally represented as functions of substrate and available carbon, and modified by dimensionless factors for soil water content and temperature (Li 1992; Parton *et al.* 1996). All of the models have strengths and weaknesses in different areas, especially in the description of the denitrification processes and the processes producing gaseous N emissions. Differences include:

- The processes of denitrification and nitrification can either be described via a microbial growth model, a chemical reaction or an empirical reaction (either first order or Michaelis Menten).
- Some models consider gaseous N emissions from denitrification only and neglect those from nitrification

- Denitrification can either be driven by the water content of the soil, e.g. the water filled pore space, or the redox potential.
- Only some models partition denitrified N into N_2O and N_2. This partition is either based on simulating the separate processes during denitrification or by simply partitioning denitrification between N_2O and N_2 depending on environmental conditions, such as soil water content and Nitrate/Carbon ratio.

The objective of this model screening exercise is to identify and/or develop an improved model for predicting N_2O production for NZ's pastoral systems which is (i) publicly available, (ii) is mechanistically sensible, (iii) can be tested with datasets from NZ spanning a range of soils and climates, (iv) adequately describes NZ farming systems including urine patches, and (v) can be used to evaluate mitigation options such as nitrification inhibitors and their effect on the whole farm system.

Model screening

A literature search on publicly available N_2O models has been done, from which 23 deterministic models, of varying complexity governing the carbon and nitrogen cycling in the soil plant atmosphere continuum, were selected. We identified the processes considered in these models and how they are described and quantified. A summary of the model descriptions, as relevant for N_2O modelling, is given in Table 1.

From the initial screening 10 models (highlighted in Table 1) were selected for a more detailed screening and for identifying the best candidate(s) for further development and testing. These 10 models were chosen to cover a range of different approaches for N_2O modelling (including denitrification processes and gaseous N emissions), as well as different model complexities. A more detailed description of these models is given below.

Detailed Model Description

Agricultural Production Systems Simulator - APSIM

The Agricultural Production Systems Simulator (APSIM; www.apsim.info), developed by the Agricultural Production Systems Research Unit in Australia, is a framework of biophysical modules that simulate biological and physical processes in farming systems (Keating *et al.* 2003), with an emphasis on cropping systems. A simulation engine is used to drive the simulation processes, and control all messages and data transfer from independent modules that simulate soil water balance and solute movement. Movement, transformation and losses of nitrogen and phosphorus (Probert *et al.* 1998) erosion and incorporation of plant litter are modelled (Keating *et al.* 2003). The framework is designed to allow addition of different modules as they are developed. APSIM models a diverse range of crops (Wang *et al.* 2002) pastures and trees (Huth *et al.* 2001). It is possible to carry out multi-paddock simulations where each paddock can have different soil properties or crops. APSIM has been used extensively worldwide for a broad range of cropping applications including modelling soil water, nitrogen balance and nitrogen leaching, growth of a wide range of arable crops. APSIM's application in New Zealand is also increasing. Publications include simulations of drainage and runoff in tile-drained soils (Snow *et al.* 2007), pasture simulation (Li *et al.* in press), and climate change impact on plant growth (Asseng *et al.* 2004).

The APSIM-SoilN model (Probert *et al.* 1998) simulates the dynamics of N and C on a daily time-step in soil layers, the number and thickness of these are set by the user. N mineralisation, N immobilisation and nitrification are explicitly described in each layer, as are the N losses from denitrification and leaching. The last two are controlled by soil water content and flow which are simulated within the APSIM-SoilWat model (Probert *et al.* 1998), or alternatively by APSWIM.

Nitrification

Nitrification in the APSIM-SoilN model follows Michaelis–Menten kinetics and is modified by pH, soil moisture and temperature (Meier *et al.* 2006; Probert *et al.* 1998).

Denitrification

Within the APSIM-SoilN module denitrification rate is calculated by:

$$R_{denit,i} = k_{denit}\ NO_{3,i}\ C_{A,i}\ F_{moist,i}\ F_{temp,i}$$

where, R_{denit} is the denitrification rate (kg N ha^{-1} day^{-1}) of the ith soil layer, k_{denit} is the denitrification coefficient (=0.0006), NO_3 the amount of NO_3 -N present in the ith soil layer (kg N ha^{-1}), C_A is the active carbon (ppm) and F_{moist} and F_{temp} are factors (scaled from 0 to 1) accounting for the limitations to denitrification imposed by moisture and temperature, respectively. Active carbon is defined as by Rolston (Rolston *et al.* 1984):

$$C_{A,i} = 0.0031 SOC_i + 24.5$$

where SOC is the soil organic C (ppm) which is defined as the sum of the carbon concentrations of the humus (HUM_C) and fresh organic matter (FOM_C) soil C pools.

The functions defining the factors F_{moist} and F_{temp} in each soil layer are:

$$F_{moist,i} = \frac{SW_i - DUL_i}{SAT_i - DUL_i}$$

$$F_{temp,i} = 0.1 \exp\left(0.046\, ST_i\right)$$

where, SW_i ($m^3\ m^{-3}$) is the water content, DUL_i ($m^3\ m^{-3}$) is the water content at the drained upper limit, SAT_i ($m^3\ m^{-3}$) is the water content at saturation and STi is the soil temperature (8C) in the ith soil layer. The above equation results in a straight line relationship between Fmoist and soil water content between DUL and SAT. However, the relationship between Fmoist and soil water content may be curvilinear (Weier *et al.* 1993). Also, the equation results in no denitrification at water contents at and below DUL, whereas it is possible that microsites that can cause denitrification at water contents below the DUL (Barton *et al.* 1999). Thus, to encompass these denitrification processes, an alternative function for F_{moist} has recently been suggested (Thorburn *et al.* 2010):

$$F_{moist,i} = \left[\frac{SW_i - SW_{\lim,i}}{SAT_i - SW_{\lim,i}}\right]^x$$

where $SW_{lim,i}$ ($m^3\ m^{-3}$) is the water content at which denitrification ceases and x is an empirical exponent.

Other denitrification models often use the water-filled pore space (WFPS, unit less) as a scalar for soil water content (e.g. (Parton *et al.* 2001), which can be related to SW_{lim} by (Thorburn *et al.* 2010):

$$SW_{\lim} = WFPS \cdot SAT$$

The default representation of F_{moist} in APSIM-SoilN is with x =1, and SW_{lim} defined by the value of WFPS at DUL.

Nitrous oxide emissions during denitrification

Thorburn et al. (2010) used the approach in the model of Del Grosso (Del Grosso *et al.* 2000) with APSIM to predict nitrous oxide emissions from fertilised sugarcane during denitrification (N_2O_{denit}) base on an N_2 to N_2O ratio

$$\frac{N_2}{N_2O_{denit}} = Max\left[\left(0.16k_1\right),\left(k_1 \exp\left(\frac{-0.8\,NO_3}{CO_2}\right)\right)\right]Max\left[0.1,\left(\left(1.5WFPS\right)-0.32\right)\right]$$

where, k_1 is related to the gas diffusivity in the soil at field capacity, NO_3 (mg g^{-1}) is the nitrate concentration of the soil on a dry weight basis, and CO_2 is the heterotrophic CO2 respiration (mg C g $soil^{-1}$ day^{-1}). They selected the model because it has been widely tested (Del Grosso *et al.* 2009) and is compatible with the N cycle and denitrification routines in APSIM-SoilN. Predicted N_2O emissions agreed well with data provided that the default denitrification rate in APSIM was substantially increased.

Nitrous oxide emissions during nitrification

Thorburn et al. (Thorburn *et al.* 2010) calculated N_2O emissions during nitrification (N_2O_{nit}) as a proportion (k_2) of nitrified N Li, 2000 (Li *et al.* 2000; Li *et al.* 2007; Parton *et al.* 2001):

$$N_2O_{nit} = k_2\,R_{nit}$$

where R_{nit} is the rate of nitrification (kg N ha^{-1} day^{-1}). A wide range of values have been adopted for k_2 in agricultural soils in other models, potentially reflecting the uncertainty in the process resulting in N_2O emissions during nitrification (Parton *et al.* 2001).

CoupModel

The CoupModel (Jansson and Karlberg 2004a) has a kitset structure which combines several submodels with often multiple choices to describe various relationships, and includes the SOILN model. The model was originally developed for forest soils but is now independent of plant cover, and uses a variable time-step that can be daily or sub-daily. The CoupModel simulates water and heat processes as well as carbon and nitrogen cycles. The ability to simulate NO, N_2O and N_2 gases from soils was added by adopting the nitrification and denitrification submodels from PnET-N-DNDC (Norman *et al.* 2008).

The soil is divided into several organic pools for C and N. Some of these pools are always present (humus, soil litter, and surface litter) while others are optional (faeces, dissolved organics, microbes, optional 2nd litter pool). Mineral N is divided into NH_4^+ and NO_3^- pools.

Denitrification

Input Requirements for simulating denitrification in the CoupModel include: (i) Soil NH_4^+ and NO_3^- pools, (ii) Soil water content, (iii) soil pools NO_2^-, NO, N_2O and N_2, (iv) denitrifying microbial N, (v) dissolved organic carbon, (vi) temperature, (vii) pH, and (viii) O_2 concentration.

Denitrification can either be simulated using a simplified approach or a microbial approach. In the simplified approach only the total amount of NO_3^- denitrified is calculated and the relative amount of N_2O/N_2 produced is not calculated. Therefore only the microbial approach is described here.

In the microbial model the following additional N pools are considered: denitrifying microbes (N_{micrDN}), anaerobic NO_2 (N_{AnNO2}), anaerobic NO (N_{AnNO}), anaerobic N_2O (N_{AnN2O}) and anaerobic N_2 (N_{AnN2}). The concentrations of anaerobic NO_3^-, NO_2^-, NO and N_2O are used in several calculations. For NO_3^- the concentration is calculated by dividing the amount of NO_3 by the soil water content for each layer. For the other species the amount is divided by the soil water content and the anaerobic volume fraction (f_{AnVol}).

The denitrifying microbes consume nitrogen for maintenance and growth from all anaerobic N pools except N_2. Microbial growth causes the assimilation of mineral N to the denitrifier microbial pool. The formula for N consumption from pool N_i is given by:

$$N_{N_i \rightarrow micrDN} = d_{growthN_i} \cdot f\left(C_{DO,dnCons}\right) . f\left(N_{N_xO_yConc}\right) . M_{activity} . N_{micrDN}$$

where $f\left(C_{DO,dnCons}\right)$ and $f\left(N_{N_xO_yConc}\right)$ are response functions for dissolved organics and nitrogen concentrations respectively, and $d_{growthN_i}$is a growth parameter. For N_2O consumption there is an additional term to account for NO_3^- inhibition:

$$f\left(N_{NO_3Concinhib}\right)=\frac{d_{inhirate}}{d_{inhirate}+N_{NO_3Conc}}$$

The response functions for dissolved organics and nitrogen concentrations are:

$$f\left(C_{DO,dnCons}\right)=\frac{C_{DO}/\theta}{d_{hrateDOC}+\left(C_{DO}/\theta\right)}$$

$$f\left(N_{NxOyConc}\right)=\frac{N_{NxOyConc}}{d_{hrateNxOy}+N_{NxOyConc}}$$

where $d_{hrateDOC}$, $d_{hrateNxOy}$ are the half rates for DOC and nitrogen concentrations respectively and θ is the soil water.

Each anaerobic N pool loses N through microbial maintenance and growth respiration. These fluxes are calculated as:

$$N_{NO_3\rightarrow AnNO_2}=\left(N_{rgNO_3}+N_{rmNO_3}\right).M_{activity}.N_{micrDN}$$

where $N_{rgNO_3}$and $N_{rmNO_3}$are the growth and maintenance requirements. Similar equations exist for $N_{AnNO_2\rightarrow AnNO}$ $N_{AnNO\rightarrow AnN_2O}$, and $N_{AnN_2O\rightarrow AnN_2}$. However, $N_{AnN_2O\rightarrow AnN_2}$ also includes a term for inhibition by NO_3^-. CoupModel also simulates the flow of the created gases out of the soil.

Total denitrification is the sum of the production of N_2, N_2O and NO. The growth respiration and maintenance respiration are calculated as:

$$N_{rgN_i}=\frac{N_{N_i\rightarrow micrDN}}{d_{effN_i}}$$

$$N_{rmN_i} = \frac{d_{rcN_i}.N_{N_i}}{N_{AnTot}}$$

where d_{effN_i} is an efficiency factor, d_{rcN_i} is a respiration coefficient and N_{AnTot} is the total nitrogen in the N_2O, NO, NO_2^- and NO_3^- pools. N_i can represent NO_3^-, N_2O, NO and NO_2^-.

The change in denitrifier biomass N is given by the difference in the growth and death rate. The death rate is calculated as:

$$M_{death,DN} = d_{denitrdie}.M_{activity}.N_{micrDN}$$

where $d_{denitrdie}$ is the death rate coefficient.

Microbial activity ($M_{activity}$) is calculated using multiplicative response functions:

$$M_{activity} = f(T).f(pH).f(N_{AnTot}).f_{AnVol}(z).d_{actratecoef}$$

where $d_{actratecoef}$ is the activity rate coefficient.

The pH response function is:

$$f(pH) = 1 - \frac{1}{1+e^{(5-d_{pHrate})/d_{pHshape}}}$$

where d_{pHrate} is the pH half rate and $d_{pHshape}$ is a shape coefficient. The response function for total nitrogen content is a Michaelis-Menten form:

$$f(N_{AnTot}) = \frac{N_{AnTot}}{d_{hrateNxOy} + N_{AnTot}}$$

There are multiple options that can be selected for the temperature response:

1. Q10 whole range

$$f(T) = t_{Q10}^{(T-t_{Q10bas})/10}$$

where t_{Q10} and t_{Q10bas} are parameters.

2. Q10 threshold

As for Q10 whole range except that below a threshold temperature $t_{Q10thres}$ the response function is recalculated as:

$$f(T) = \frac{1}{t_{Q10thres}} f(T)$$

(The response function is set to 0 when T<0)

3. O'Neill Function

Uses 3 parameters t_{ONmax} (maximum temperature), t_{ONopt} (optimum temperature) and n_{ONform} (form coefficient).

$$f(T) = \left(\frac{t_{ONmax} - T}{t_{ONmax} - t_{ONopt}} \right)^{n_{ONform} \cdot f_{ON}(T)}$$

$$f_{ON}(T) = e^{\left(\frac{T - t_{ONopt}}{t_{ONmax} - t_{ONopt}} \right)}$$

4. Ratkowsky function

Uses two parameters t_{max} and t_{min}

$$f(T) = \begin{cases} 0, T < t_{\min} \\ \left(\dfrac{T - t_{\min}}{t_{\max} - t_{\min}} \right)^2, t_{\min} < T < t_{\max} \\ 1, T > t_{max} \end{cases}$$

Anaerobic volume fraction

The anaerobic volume fraction is calculated as:

$$f_{anvol} = \exp\left(-g_{aporshape} . O_{volcons}^2\right)$$

where $g_{aporshape}$ is a shape parameter and $O_{volcons}$ is the volumetric oxygen concentration calculated as:

$$O_{volcons} = \frac{O_{O_2Conc}}{O_{ratioair} . \rho_a(T)}$$

where O_{O_2Conc} is the oxygen concentration, $O_{ratioair}$ is the ratio of oxygen to air and $\rho_a(T)$ is the air density temperature function.

Default Parameters

The following table lists the default values for a number of parameters.

Parameter	**Description**	**Default**
n_{ONform}	Shape coefficient in O'Neill temperature response	4.28
t_{ONmax}	Maximum temperature in O'Neill temperature response	42 ˚C
t_{ONopt}	Optimum temperature in O'Neill temperature response	27.5 ˚C
t_{Q10}	Response to a 10˚C temperature increase in Q10 temperature response	2
t_{Q10bas}	Base temperature for microbial activity. Q10 temperature response function	20˚C
$t_{Q10thres}$	Temperature threshold for microbial activity in Q10 threshold temperature response function	5 ˚C
t_{max}	Temperature at which response on denitrification is 1 using Ratkowsky function	20 ˚C
t_{min}	Temperature at which response on denitrification is 0 using Ratkowsky function	-8˚C
$d_{inhihrate}$	Denitrification inhibition half rate of NO_3^- on growth of denitrification microbes during N_2O formation	0.3 mg/l
$d_{pHhrate}$	pH half rate for denitrification	4.25
$d_{pHshape}$	pH shape coefficient in denitrification response fct	0.5
$d_{actratecoef}$	Denitrification activity rate coefficient	0.5 /day
$d_{denitrdie}$	Death rate coefficient	0.09 /day
d_{effNO}	Efficiency parameter for growth respiration function for NO	0.428
d_{effNO2}	Efficiency parameter for growth	0.428

	respiration function for NO_2	
d_{effNO3}	Efficiency parameter for growth respiration function for NO_3^-	0.401
d_{effN2O}	Efficiency parameter for growth respiration function for N_2O	0.151
$d_{growthNO}$	Growth parameter describing loss of NO due to microbial growth	8.2 /day
$d_{growthNO2}$	Growth parameter describing loss of NO_2^- due to microbial growth	16 /day
$d_{growthNO3}$	Growth parameter describing loss of NO_3^- due to microbial growth	16 /day
$d_{growthN2O}$	Growth parameter describing loss of N_2O due to microbial growth	8.2 /day
d_{rcNO}	respiration coefficient for maintenance respiration for NO	0.84 /day
d_{rcNO2}	respiration coefficient for maintenance respiration for NO_2^-	0.84 /day
d_{rcNO3}	respiration coefficient for maintenance respiration for NO_3^-	2.2 /day
d_{rcN2O}	respiration coefficient for maintenance respiration for N_2O	1.9 /day
$i_{denitrmc}$	Initial biomass of denitrifying microbials (whole soil profile)	2 g N/m^2
$g_{aporshape}$	shape parameter of the anaerobic volume fraction equation	100

Model Use

The CoupModel has been used to simulate of NO_3^- leaching from temperate grassland and grass/crop rotations (Conrad and Fohrer 2009a; b; Korsaeth *et al.* 2003), forest systems (Christiansen *et al.* 2006), and plant uptake and soil N in temperate grass/crop rotations (Nykanen *et al.* 2009). Apart from the study by (Norman *et al.* 2008), who compared N_2O and NO predictions from the CoupModel and the original PNET-N-DNDC in a forest system the model has not been used to simulate N_2O emissions.

DAISY

Daisy (Hansen *et al.* 1990) is a Soil-Plant-Atmosphere system model designed to simulate water balance, heat balance, solute balance and crop production in an agro-ecosystems. The water balance model comprises a surface water (e.g., snow melting) and a soil water balance. Special emphasis is given to the nitrogen dynamics. Mineralization-immobilization, nitrification and denitrification, sorption of ammonium, uptake of nitrate and ammonium, and leaching of nitrate and ammonium are simulated. The model has a website (http://code.google.com/p /daisy-model), and the model details are well documented. N_2O emissions are only calculated from the process of denitrification, not from nitrification.

Denitrification

Denitrification is simulated using a simple index model taking into account the decomposition of organic matter, volume of anaerobic micro sites (expressed in terms of soil water content), soil temperature, and the concentration of nitrate in the soil solution.

The potential denitrification rate of the soil, ξ_d^*, is expressed as a linear function of the CO_2 evolution rate in accordance with Lind (Lind 1980):

$$\xi_d^* = \alpha_d^* \xi_{CO_2}$$

where ξ_{CO_2} is the CO_2 evolution rate (simulated by the MIT-model), and α_d^* is an empirical constant (default value 0.1 g Gas-N/g CO_2-C). The values of ξ_{CO_2} are derived from the organic matter model as the evolution of CO_2 from the decomposition of organic matter.

The actual denitrification rate is determined either by the transport of nitrate to the anaerobic micro sites or the actual microbial activity at these sites. Transport of nitrate to the denitrifying micro sites is a diffusion process. Hence the maximum transport will take place when the micro sites act as zero sinks. The maximum transport of nitrate to micro sites can therefore be assumed to be proportional to the nitrate concentration in the soil ($N_{ni}=\theta C_{ni}$, where C_{ni} is the concentration in the soil solution). The increased tortuosity when the soil dries is of little consequence as denitrification is very limited in dry soil. In the case of ample supply of nitrate, the actual denitrification rate is determined by multiplying the potential denitrification rate by a modifier function. Hence, the actual denitrification is simulated as:

$$\xi_d = \mathrm{Min}\left\{F_d^{\theta}(\theta)\,\xi_d^{*};\, K_d\, N_{ni}\right\}$$

where ξ_d is the actual denitrification rate, $F_d^{\theta}(\theta)$ is a modifier function, and K_d is an empirical proportionality factor (default value: d^{-1}). The modifier function is assumed to be a function of the soil water content and is adopted from Rolston et al. (1984).

Daisy has been used extensively (Hansen et al, 1990), both in scientific research and for decision support. To simulate crop production and nitrogen and water processes. Olesen et al (2004) used the model for estimating CO_2 emissions but the model has not been used to estimate N_2O emissions.

DayCent

The DayCent model is the daily time step version of the CENTURY biogeochemical model (Parton et al. 1994), and was developed to simulate trace gas fluxes that results from short term rainfall, snowmelt or irrigation events (Del Grosso *et al.* 2001). The model has been used to provide site-specific and regional scale estimates of N_2O emissions from NZ soils (Saggar *et al.* 2008).

The N gas sub-model uses the NO_3^- and NH_4^+ concentrations to predict N_2O and NO_x emissions from nitrification and denitrification, and N_2 from denitrification. The N gas flux from nitrification is a function of NH_4^+ concentration, water content, temperature, and pH. Denitrification is a function of NO_3^- concentration, labile C availability, water filled pore space (WFPS), and soil physical properties related to texture that influence gas diffusivity. Denitrification increases exponentially with increasing soil NO_3^- concentrations at low concentrations (< 50ppm), and linear at higher concentrations. It increases linear with soil heterotrophic respiration (proxy for labile C availability), and equals zero up to about 50-60% WFPS, and then increases exponentially until WFPS of 70-80%. N_2 and N_2O are calculated from denitrification by assuming that process is controlled by most limiting factor (NO_3^-, respiration, WFPS), with the ratio of N_2/N_2O increases with decreasing ratio of NO_3/labile C, and decreasing soil gas diffusivity and O_2 availability. Gas diffusivity is calculated as function of PFPS and soil physical properties (bulk density and field capacity). NO_x emissions from soils are a function of total N_2O emissions, a NO_x/N_2O ratio equation and a precipitation initiated pulse multiplier.

The model has been tested for cropping in USA, for both field data and regional N_2O emissions (Del Grosso *et al.* 2005), and for a dry short grass steppe in Colorado, a ryegrass pasture in Scotland and perennial cropping in Germany (Frolking *et al.* 1998). The DayCent model has been shown to not always simulate observed variability in N_2O fluxes, mainly due to failure to simulate WFPS correctly (Del Grosso *et al.* 2008).

DNDC

The DeNitrification DeComposition (DNDC) model (Li 1992; Li *et al.* 1994) was originally developed in the US to determine the evolution of N_2O, CO_2 and N_2 from agricultural soils. It has since been modified and updated to include a number of other systems (e.g. perennial pastures, forests, wetlands, rice paddies) and issues (e.g. CH_4 and NO fluxes, NO_3^- leaching). The model consists of several sub-models: thermal-hydraulic flows, plant growth, aerobic decomposition, fermentation and denitrification. The model usually operates on a daily time-step, except following a rainfall event where denitrification is calculated on an hourly time-step. As the DNDC model has been frequently modified it is important to note the version being referred to. The most recent version on the website is 9.2

C and N Pools:

DNDC divides organic carbon and nitrogen into eight pools: very labile, labile and resistant litter; labile and resistant microbial biomass; labile and resistant humads and passive humus. These pools vary in their C/N ratios and turnover times. Soil pools of Urea, NH_4^+, NO_3^-, NH_3, NO, N_2O and N_2 are tracked.

Denitrification Description

For simulating denitrification the following input parameters are required: (i) Soil NO_3^-, NO_2^-, N_2O, N_2, (ii) microbial biomass, (iii) dissolved organic carbon, (iv) soil temperature, (v) pH, and (vi) oxygen partial pressure. DNDC simulates the reduction sequence $NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$. The steps in this sequence are performed by different microbial populations which compete for the available C.

The consumption of species N_i (nitrate, nitrite or nitrous oxide) is given by:

$$\frac{dN_i}{dt} = \left(\frac{u_{N_i}}{Y_{N_i}} + M_{N_i} \frac{N_i}{N_{tot}} \right) .B(t).\mu_{pHN_i} \cdot \mu_{T,DN}$$

where $u_{N_i}$is the relative growth rate of N_i denitrifiers, Y_{N_i} is the maximum growth yield on N_i (kg C/kg N), M_{N_i} is maintenance coefficient (in kg N/kg/h), N_{tot} is the sum of NO_3^-, NO_2^- and N_2O, B is the microbial biomass of denitrifier, and μ_{pHN_i} and $\mu_{T,DN}$ are the reduction factors for pH and temperature respectively. The growth term results in the transfer of mineral N to the denitrifier N pool while respiration results in the reduction of N_i to the next species in the denitrification sequence.

The growth rates of the denitrifier populations are calculated as:

$$u_{N_i} = u_{N_i,\max} \left(\frac{C}{C + K_{c,1/2}} \right) \cdot \left(\frac{N_i}{N_i + K_{N_i,1/2}} \right) .\mu_{T,DN} \cdot \mu_{pHN_i}$$

where C is the dissolved carbon concentration in the soil, $K_{c,1/2}$ and $K_{N_i,1/2}$ are the half-saturation values for soluble C and N_i respectively. The microbial population death rate is given by:

$$\frac{dB}{dt}_d = M_c Y_c B(t)$$

where M_c is the maintenance coefficient of carbon (kg C/kg/h) and Y_c is the maximum growth yield on soluble carbon.

The temperature response function for denitrification and growth of denitrifiers as:

$$\mu_{T,DN} = \begin{cases} 2^{(T-22.5)/10}, T < 60℃ \\ 0, T \geq 60℃ \end{cases}$$

DNDC uses different pH response functions for the different denitrifiers:

$$\mu_{pHNO3} = \frac{7.14\left(pH - 3.8\right)}{22.8}$$

$$\mu_{pHNO2} = 1$$

$$\mu_{pHN2O} = \frac{7.22\left(pH - 4.4\right)}{18.8}$$

Thus these models cannot be used for testing mitigation scenarios. Originally DNDC used a simple switch to turn denitrification on when the soil WFPS exceeded 40%. However, this did not allow nitrification and denitrification to occur simultaneously. Li et al. (2000) moved to considering the anaerobic volume fraction with the nitrogen and carbon pools being split into anaerobic and aerobic fractions and denitrification occurring only within the anaerobic fraction. The volume fraction of anaerobic microsites is calculated using a simplified linear correlation with oxygen partial pressure

$$f_{anvol} = a\left(1 - b\frac{p_{O_2,layer}}{p_{O_{2,air}}}\right)$$

The following table lists some of the default parameters in the decomposition sub-model

Parameter	Description	Default
$u_{max,NO3}$	Maximum growth rate of NO_3^- denitrifier	0.67 /h
$u_{max, NO2}$	Maximum growth rate of NO_2^- denitrifier	0.67 /h
$u_{max, N2O}$	Maximum growth rate of N_2O denitrifier	0.34 /h
K_C	Half-saturation value of soluble carbon	0.017 kg C/m^3
K_N	Half-saturation value of N-oxides	0.083 kg N/m^3
M_c	Maintenance coefficient on C	0.0076 kg C/kg/h
M_{NO3}	Maintenance coefficient on nitrate	0.09 kg N/kg/h
M_{NO2}	Maintenance coefficient on nitrite	0.035 kg N/kg/h
M_{N2O}	Maintenance coefficient on nitrous oxide	0.079 kg N/kg/h
Y_c	Maximum growth rate on soluble carbon	0.503 kg C/kg C
$Y_{max,NO3}$	Maximum growth rate on nitrate	0.401 kg C/kg N
$Y_{max,NO2}$	Maximum growth rate on nitrite	0.428 kg C/kg N
$Y_{max,N2O}$	Maximum growth rate on N_2O	0.151 kg C/kg N
R	C/N ratio in denitrifiers	3.45
RBO	Ratio of microbial to total organic C	0.01-0.025
FD	Ratio of denitrifiers to microbial biomass	0.001-0.5

Model Use

When DNDC was first published it was validated against five field studies: N_2O emissions from a US prairie, N_2O emissions from a cultivated organic soil in Florida, denitrification losses (N_2+N_2O) in a UK fertilised grassland, CO_2 emissions from a grassland soil in Germany, CO_2 emissions from a tilled and fertilized winter wheat field in the US (Li *et al.* 1992). The model has been updated to account for a greater number of systems. Major changes include: using an "anaerobic balloon" method for denitrification rather than switching at a fixed WFPS (Li *et al.* 2000), adding a phenomenological crop growth (Zhang *et al.* 2002b), impacts of soil freezing and thawing (Li *et al.* 2000; Xu-Ri. *et al.* 2003), improved N adsorption and water drainage to improve simulation of nitrate leaching (Li *et al.* 2006), adding perennial pasture as a crop type (Saggar *et al.* 2004), simulating CH_4 fluxes in rice paddies.

The DNDC model has been combined with PnET model to simulate forests (Li *et al.* 2000) and a Wetland-DNDC was created where water table dynamics were also simulated (Li *et al.* 2004; Zhang *et al.* 2002a). The DNDC model has been used widely for various systems including:

- New Zealand: N_2O emissions from dairy-grazed pasture in New Zealand (Saggar *et al.* 2004); CH_4 consumption in sheep-grazed pastures in New Zealand (Saggar *et al.* 2007); N_2O emissions from urine application with nitrification inhibitor (Giltrap *et al.* 2010).
- USA: Drainage and leaching in grain systems (Li *et al.* 2006; Tonitto *et al.* 2007; Tonitto *et al.* 2010); N_2O from prairie and drained cultivated organic soil, CO_2 from tilled and fertilised wheat (Li *et al.* 1992), N_2O from arid rangeland (Frolking *et al.* 1998), N_2O emissions and soil NO_3^-, in bare soil, grass and sugar cane (Li *et al.* 1994)
- Australia: long-term SOC dynamics in permanent rotation crops (Li *et al.* 1997), CO_2 and N_2O from legume pasture (Wang *et al.* 1997)
- Canada: N2O emissions from crops (Smith *et al.* 2002)
- China: N_2O emissions from grasslands (Xu-Ri. *et al.* 2003; Zhang *et al.* 2010); N_2O and CO_2 emissions from arable crops (Li and Snow 2010); Soil

CO_2 emissions from a sub-alpine forest (Lu and Cheng 2009); N_2O, CO_2 and CH_4 soil-atmosphere exchange from forest systems (Werner *et al.* 2006)

- Czech Republic: long term SOC dynamics in crop system (Li *et al.* 1997)
- Ireland: N_2O emissions from barley and cut and grazed pasture (Abdalla *et al.* 2009)
- India: grain yield, N uptake, NH_3 volatilization, NO_3^- leaching and denitrification in rice and wheat (Pathak et al. 2006); CH_4 and N_2O from rice (Babu *et al.* 2006) + CO_2 (Pathak *et al.* 2005)
- Japan: long term SOC changes in paddy soils (Shirato 2005)
- UK: denitrification loss (N_2O + N_2) from grassland soil (Li *et al.* 1992); N_2O emissions from grasslands and crops (Brown *et al.* 2005; Frolking *et al.* 1998); long-term SOC dynamics in crop systems (Li *et al.* 1997)
- Germany: CO_2 emissions from uncultivated grasslands (Li *et al.* 1992), N_2O from forest (Lamers *et al.* 2007), N_2O from crops (Frolking *et al.* 1998), long term SOC dynamics in crop systems (Li *et al.* 1997)
- Kenya: N_2O, CO_2 and CH_4 fluxes in a rain-forest soil (Werner *et al.* 2007)
- CH_4 from rice paddies in Japan, China and Thailand (Fumoto *et al.* 2008; Smakgahn *et al.* 2009)
- Eucalyptus plantation growth (Brown *et al.* 2005; Miehle *et al.* 2009).

NEMIS

Nemis (Henault and Germon 2000) is a simple denitrification model, based on soil potential denitrification rate and dimensionless response functions to account for water content (f_s), temperature (f_T), pH (f_{pH}) and soil nitrate concentration (f_{NO3}). Bacterial activity in the soil is related to the soil nitrate concentration via a Michaelis-Menton function.

The actual denitrification rate is given by:

$$D_a = D_p \; f_{NO_3} \; f_T \; f_w \; f_{pH}$$

where D_p is the potential denitrification rate, measured in the laboratory under standardized conditions. Values for D_p measured in the literature are given in the table below. The response function for nitrate concentration, water content and temperature can be described via:

$$f_{NO_3} = \frac{[NO_3]}{K_m + [NO_3]}$$

$$f_w = \left[\frac{WFPS - 0.62}{0.38}\right]^{1.74}$$

$$f_T = \begin{cases} \exp\left[\frac{(t-11)\ln(89) - 9\ln(2.1)}{10}\right] & t < 11 \\ \exp\left[\frac{(t-20)\ln(2.1)}{10}\right] & t \geq 11 \end{cases}$$

where $[NO_3]$ is the soil nitrate concentration (mg N/kg), K_m is the Michaelis-Menten half saturation constant (mg N/kg), and WFPS is the water filled pore space.

Alternatively the following response functions have been used:

$$f_T = \begin{cases} 0 & T_s \leq 0 \\ Q_{10}^{0.1(T_s - T_r)} & 0 < T_s < T_r \\ 1 & T_r \leq T_s \end{cases}$$

$$f_w = \begin{cases} 0 & W \leq W_{FC} \\ \left(\frac{W - W_{FC}}{1 - W_{FC}}\right)^n & W_{FC} \leq W \leq W_s \\ 1 & W_{FC} \leq W \end{cases}$$

$$f_{pH} = \begin{cases} 0 & pH \leq 3.5 \\ pH - 3.5/3 & 3.5 < pH < 6.5 \\ 1 & pH \geq 6.5 \end{cases}$$

where T_r is a reference temperature at which D_p is determined, T_s is the soil temperature, Q_{10} is an increase factor for a 10^oC increase in temperature, W is the soil water content, W_{FC} and W_s the soil water contents at field capacity and saturation, and n a dimensionless parameter.

NEMIS has been applied successfully to two independent datasets.

Potential denitrification rates (D_p) found in literature

Reference	**Cover**	**Soil**	**D_p g N m^{-2} d^{-1}**	**Method**
(Sánchez *et al.* 2001)	crops		0.6-1.2	Acetylene inhibition

(D'Haene *et al.* 2003)	Pasture/crops	Clay/sand	0.0026-0.008	Acetylene inhibition
(Oehler *et al.* 2007)	Riparian		0-0.4	Acetylene inhibition
(Machefert and Dise 2004)	Pasture		0.002-0.5 (D_a)	Acetylene inhibition
(Henault and Germon 2000)			0.56±0.5	Database
(van der Salm *et al.* 2007)	Pasture		0.03	Acetylene inhibition

PaSim

The Pasture Simulation Model (PaSim) is a process-based grassland biogeochemical model derived by Riedo et al (Riedo *et al.* 1998b) from the Hurley Pasture Model (HPM) (Thornley 1998). It simulates fluxes of carbon, nitrogen, water and energy at the soil-plant-animal-atmosphere interface for managed grasslands at the plot scale. Vegetation is represented by a mixed sward, with grasses and legumes co-existing.

PaSim is composed of submodels for plant, animals, microclimate, soil biology and soil physics. It was extended by (Schmid *et al.* 2001a) to simulate N_2O production and emission, by (Riedo *et al.* 2002) in relation to the exchange of ammonia with the atmosphere, by (Vuichard *et al.* 2007) concerning water stress, senescence and the effects of diet quality on the emissions of methane from grazing animals. The French INRA/UREP group did some model improvements with respect to calculating water stress, and for the N_2O diffusion process, and incorporated it into a system for greenhouse gas accounting at farm scale, FarmSim.

Nitrification

Nitrification is described using the first-order reaction of ammonium:

$$N = kT \times k\theta \times fN_{20} \times NH_4$$

where fN_20 is the nitrification rate at 20°C and field capacity (default = 0.2), and kT and $k\theta$ are temperature and soil moisture factors;

N_2O production is described by a daily conversion rate (fraction) of NH_4-N to N_2O during nitrification given by:

$$fN_2O = fN_2O_{20} \times kT \times k\theta$$

where fN_2O_{20} is maximum conversion rate at 20°C (fraction: default = 0.02), kT and $k\theta = (\theta/\theta_{sat})^2$ are temperature and soil moisture factors;

Denitrification

To simulate denitrification within PaSIM (Schmid *et al.* 2001a) is in accordance with the approach in Daisy (Hansen et al (1991), where the potential denitrification is assumed proportional to the CO_2 production during soil organic matter (SOM) decomposition (*Rsom*):

$$Dinitrif = fDN_{max} \times F\theta \times Rsom \times (5/d \times \theta) \times (1/0.0012)$$

where fDN_{max} is maximum molar ratio of denitrified NO_3 to *Rsom* (default = 0.1), and:

$$F\theta = F\theta_{dul} \times exp\left[-5(\theta_{dul} - \theta)/\theta_{dul}\right] \qquad \theta < \theta_{dul}$$

$$F\theta = F\theta_{dul} + (1 - F\theta_{dul}) \times (\theta - \theta_{dul})/(\theta_{sat} - \theta_{dul}) \qquad \theta \geq \theta_{dul}$$

The default value for fDN_{max} is 0.1, and for $F\theta_{dul}$ *0.05*

Turnover of SOM is modelled as in the Century model (Parton *et al.* 1994).

The actual denitrification process is described as a three step conversion of nitrate to molecular nitrogen with nitrite and N_2O as intermediates (Cho *et al.* 1997). Nitrite and N_2O compete with nitrate as electron acceptors:

$$\left.\frac{dNO_3}{dt}\right|_{denit} = \text{Denitrif}\ \frac{-a_{NO3}\left[NO_3\right]}{q} d_{Ah}\ \theta_{S,Ah}\ \frac{0.014 kg\ N}{mol}$$

$$\left.\frac{dNO_2}{dt}\right|_{denit} = \text{Denitrif}\ \frac{-a_{NO3}\left[NO_3\right]-2\,a_{NO2}\left[NO_2\right]^2}{q} d_{Ah}\ \theta_{S,Ah}\ \frac{0.014 kg\ N}{mol}$$

$$\left.\frac{dN_2O}{dt}\right|_{denit} = \text{Denitrif}\ \frac{-a_{NO2}\left[NO_2\right]^2 - a_{N2O}\left[N_2O\right]_{denit}}{q} d_{Ah}\ \theta_{S,Ah}\ \frac{0.028 kg\ N}{mol}$$

$$\left.\frac{dN_2}{dt}\right|_{denit} = \text{Denitrif}\ \frac{a_{N2O}\left[N_2O\right]_{denit}}{q} d_{Ah}\ \theta_{S,Ah}\ \frac{0.028 kg\ N}{mol}$$

with

$$q = 2\,a_{NO3}\left[NO_3\right] + 4\,a_{NO2}\left[NO_2\right]^2 + 2\,a_{N2O}\left[N_2O\right]_{denit}$$

Where a_{NO3} is the affinity of NO_3 as electron acceptor during denitrification with a default value of 1 m^3/mol, a_{N2O} is the affinity of N_2O as electron acceptor during denitrification with a default value of 200 m^3/mol, a_{NO2} is the affinity of NO_2 as electron acceptor during denitrification with a default value of 1000 m^6/mol^2, d_{Ah} is the depth of main the rooting zone, and θ_{sAh} is the soil moisture content in main rooting zone.

Diffusion between the denitrification N_2O pool (N_2O_{denit}) and the soil N_2O pool is simulated using:

$$\left.\frac{dN_2O}{dt}\right|_{diff} = \frac{\left(N_2O_{denitri} - N_2O\right)}{tDiffN_2O}$$

where $tDiffN_2O$ is the time constant for the exchange between denitrification and soil N_2O pool, the default value is 1 day.

The emission of N_2O to the atmosphere is based on a resistance model approach:

$$N_2O\ flux = \frac{\left[N_2O\right]_{soil} - \left[N_2O\right]_{atm\ )}}{r}$$

with:

$$r = \frac{0.5\ d_{Ah}}{D_{s,N2O}}\ r_{sa} + r_{aa}$$

where $D_{s,N2O}$ is the diffusion coefficient in root zone, r, r_{sa} and r_{aa} are the resistances for N_2O exchange soil air and atmosphere, soil surface and canopy height, and canopy height and atmosphere.

PaSim is being used intensively in a set of European research projects (CarboEurope IP, NitroEurope IP, CARBO-Extreme and (French) CLIMATOR, VALIDATE) aiming at understanding the C and N cycles, carbon sequestration, greenhouse gases emissions (GHG) and the effects of climate variability and climate change. However simulation of N_2O fluxes in european grasslands (Hungary, UK, Ireland, France, Switzerland) overestimated measured emissions (Calanca *et al.* 2007).

TOUGHREACT-N

TOUGHREACT-N (Maggi *et al.* 2008) is a modification of the coupled reactive transport model TOUGHREACT. The TOUGHREACT-N model includes biochemical kinetic reactions, microbial biomass dynamics, soil moisture dynamics, advective and diffusive transport, partitioning of N species between gaseous and aqueous phases and several equilibrium and kinetic reactions that link the C and N cycles.

TOUGHREACT-N solves a series of partial differential equations to calculate gaseous emissions. In addition to the microbially mediated reactions (including nitrification), it also accounts for aqueous complexation, gas dissolution/exsolution, and advective and diffusive transport.

Within the C and N pool the model considers the following aqueous primary species: H^+, HCO_3^-, NH_4^+, NO_2^-, NO_3^-, O_2(aq), H_2O, CH_2O, NO(aq), N_2O(aq), N_2(aq). Secondary species are formed by aqueous complexation, gas dissolution and exsolution, and solute adsorption/desorption occurring at equilibria. The microbial populations considered are ammonia oxidising bacteria (AOB), nitrate oxidising bacteria (NOB), denitrifying bacteria (DEN) and aerobic bacteria (AER).

Denitrification

The aqueous concentrations of secondary species and gas dissolution/exsolution are calculated using differential equations based on the reaction stoichiometry, equilibrium constant and (for dissolution/exsolution) partial pressures. These equations include thermodynamic activity coefficients that have to be solved for during numerical integration.

All microbially mediated transformations of N species are aqueous reactions and the rate depends on the rate of production of species *i* from substrate *p* by biomass (B_p) and the consumption of *i* during metabolism of biomass (B_c).

$$\left.\frac{\partial C_{wi}}{\partial t}\right|_B = \sum_p \hat{\mu}_{ip} M_{ip} B_{ip} - \sum_c \hat{\mu}_{ic} M_{ic} B_{ic}$$

where C_{wi} is the aqueous concentration of species *i*, $\widehat{\mu_{ip}}$ and $\widehat{\mu_{ic}}$ are the maximum specific consumption rates and M_{ip} and M_{ic} are Michaelis-Menten functions:

$$M_i = \frac{C_{wi}}{K_{Cwi} + C_{wi}} \frac{e_i}{K_{ei} + e_i} \frac{K_{Ii}}{K_{Ii} + I_i} f\left(S_\theta\right) g(pH)$$

where the K terms are constants and f and g are functions accounting for microbial water and acidity stress given by:

$$f\left(S_\theta\right) = \min\{2S_\theta, 1\}$$

$$g\left(pH\right) = \begin{cases} \min\left\{\frac{1}{4}pH - \frac{3}{4}, -\frac{1}{4}pH + \frac{11}{4}\right\}, 3 < pH < 11 \\ 0, otherwise \end{cases}$$

The dynamics of the microbial biomass pools satisfy the equation:

$$\frac{\partial B_i}{\partial t} = B_i \sum_c \hat{\mu}_{ic} M_{ic} Y_{ic} - \delta_i B_i$$

where Y_{ic} are the yield coefficients for B_i growing on substrate *c*, M_{ic} is the Michaelis-Menten equation given above, and δ_i is the biomass death rate.

Values for $\widehat{\mu_{ic}}$ K_c, K_e, K_I and Y for each biologically mediated reaction and microbial death rates are listed in a table in (Maggi *et al.* 2008).

The TOUGHREACT-N paper was published relatively recently, so the model has not yet been widely tested in a range of systems. (Maggi *et al.* 2008) parameterised the model using data from a furrow irrigated tomato field. The microbial reactions do not appear to have any temperature dependency. This could be because the experiment was performed for only 20 days in July and therefore experienced little temperature variation.
(Gu and Riley 2010) tested the TOUGHREACT-N against data from 2 tropical soils with varying water inputs, but N_2O emissions were only examined over a 30 day period.

VISIT

The Vegetation Integrative Simulator for Trace Gases (VISIT) is based on the carbon cycle model SimCYCLE. (Inatomi *et al.* 2010) expanded the model to include nitrogen cycling and trace gas exchange processes. The N_2O flux estimation, F_{N2O}, is based on the semi-empirical scheme NGAS (Parton *et al.* 1996), that adopts the "hole in the pipe concept". N_2O is released during nitrification and denitrification with:

$$F_{N_2O} - nit = \beta_{WFPS-nit}\ \beta_{pH}\ \beta_t \left(K_{\max} + F_{\max}\ N_{NH_4}\right)$$

where $\beta_{WFPS\text{-}nit}$, β_{pH}, and β_t are the effects of moisture of WFPS, soil pH and soil temperature on nitrification, K_{max} is the soil specific N turnover coefficient, F_{max} is the maximum nitrification gas flux, and N_{NH4} is the effect of soil NH_4 concentration on nitrification.

The gas emission rate due to denitrification is a function of soil moisture, heterotrophic respiration and NO_3 concentration. The total nitrogenous gas emission is calculated based on the NGAS scheme as:

$$F_{den} = \beta_{WFPS-den} \min\left[F_{den}\left(N_{NO_3}\right), F_{den}\left(RH\right)\right]$$

where $\beta_{WFPS\text{-}den}$ is the effect of WFPS on the denitrification rate, and $F_{den}(N_{NO3})$ and $F_{den}(RH)$ are the maximum total gas fluxes for a given NO_3 concentration and heterotrophic respiration rate. F_{den} is then separated into N_2O and N_2 fluxes using a fractionation coefficient, $R_{N2/N2O}$,

$$F_{N_2O-den} = F_{den} / \left(1 + R_{N_2/N_2O}\right)$$

$R_{N2/N2O}$ is also a function of WFPS, N_{NO3}, and RH.

VISIT has been used to simulate carbon and nitrogen cycling in a Japanese forest, including GHG emissions. Simulated N_2O emissions were within the range reported for similar forests, but much lower compared to observed rates in other areas of the world. This was attributed to low nitrification and denitrification rates in the volcanic ash soil.

WNMM

The Water and Nitrogen Management Model (WNMM) developed by (Li *et al.* 2007) runs on a daily time step at any spatial scale. The source code is available from the authors on request. The model has been tested in Australia and China, but denitrification under wet conditions has not been well-tested.

Soil organic matter is divided into 3 pools: fresh organic matter (FOM), microbial biomass (BIOM) and humus (HUM). The microbial biomass is further partitioned into dead and alive, and the humus is divided into passive and active fractions. The C:N ratios of these pools are assumed to remain constant.

Denitrification:

WNMM uses a simple empirical relationship to calculate denitrification. Denitrification is limited to the top 20cm of the soil and only occurs when WFPS >0.8.

$$R_{den} = \begin{cases} 0, WFPS < 0.8 \\ WNO_3\left[1 - \exp\left(-1.4 f_{sw\_den} f_T OC\right)\right], WFPS \geq 0.8 \end{cases}$$

where R_{den} is the denitrification rate, WNO_3 is the NO_3^--N content in the soil layer, OC is the soil organic carbon fraction, WFPS is the fractional water-filled pore space, and f_{sw_den} and f_T are the soil water and temperature factors given by:

$$f_{sw\_den} = \exp\left(-23.77 + 23.77 wfps\right)$$

$$f_T = 0.9 \frac{T_{soil}}{T_{soil} + \exp\left(9.93 - 0.312 T_{soil}\right)} + 0.1$$

The amount of N_2O-N produced by denitrification is given by:

$$N_2O_{den} = \begin{cases} 0.05R_{den}, wfps \geq 1 \\ \alpha_{den} R_{den} \left(1 - f_{sw\_den}\right), wfps < 1 \end{cases}$$

where α_{den} is a parameter determined from the fraction of N_2O emitted at 0.8 WFPS, with a default value for α_{den} of 0.5.

(Li *et al.* 2007) parameterised and tested the model on a Chinese cropping system. WNMM has since been compared with N_2O emissions from Australian dairy and crop systems (Li *et al.* 2008), Chen et al. 2010), total denitrification and N_2O emissions from crop systems in the North China Plain (Li et al. 2005), and leaching under irrigated maize desert oasis conditions and sub-tropical crop rotations in China (Sun *et al.* 2008).

Conclusions

From the above denitrification and N_2O models the following models were chosen as potential candidates for predicting N_2O production for NZ's pastoral systems. This was based on selecting models based on different approaches, the likely ability to parameterize the model/modules (as such the models TOUGHREACT-N and PaSIM were excluded as they were found to be too detailed), and the likely ability to integrate the model with a Farm System model.

- APSIM
- DayCent
- DNDC
- NEMIS- for denitrification only
- VISIT
- WNMM

From the above list the best suited denitrification and gaseous N loss modules will be integrated into a farm system model. This is likely to be the Agricultural Production Systems Simulator APSIM, as the model is (i) publicly available, (ii) is mechanistically sensible, (iii) can be tested with datasets from NZ spanning a range of soils and climates, (iv) can describe farming systems including urine patches, and

(v) can be used to evaluate mitigation options such as nitrification inhibitors and their effect on the whole farm system.

As a next step the SoilN submodule of APSIM will be assessed in detail to see if the above modules could potentially be integrated into SoilN. Either a few modules will be chosen for integration and testing, or approaches from various models will be combined to develop a suitable model for estimating N_2O production and mitigation strategies in NZ farm systems.

References

Abdalla M, Wattenbach M, Smith P, Ambus P, Jones M, Williams M (2009) Application of the DNDC model to predict emissions of N2O from Irish agriculture. *Geoderma* **151**, 327-337.

Aggarwal PK, Kalra N, Chander S, Pathak H (2006) InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agricultural Systems* **89**, 1-25.

Asseng S, Jamieson PD, Kimball B, Pinter P, Sayre K, Bowden JW, Howden SM (2004) Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. *Field Crops Research* **85**, 85-102.

Babu YJ, Li C, Frolking S, Nayak DR, Adhya TK (2006) Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. *Nutrient Cycling in Agroecosystems* **74**, 157-174.

Barton L, McLay CDA, Schipper LA, Smith CT (1999) Annual denitrification rates in agricultural and forest soils: A review. *Australian Journal of Soil Research* **37**, 1073-1093.

Bradbury NJ, Whitmore AP, Hart PBS, Jenkinson DS (1993) Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertiliser to winter wheat. *Journal of Agricultural Science* **121**, 363-379.

Brown L, Scholefield D, Jewes EC, Lockyer DR, del Prado A (2005) NGAUGE: A decision support system to optimise N fertilisation of British grassland for economic and environmental goals. *Agriculture, Ecosystems & Environment* **109**, 20-39.

Calanca P, Vuichard N, Campbell C, Viovy N, Cozic A, Fuhrer J, Soussana JF (2007) Simulating the fluxes of CO2 and N2O in European grasslands with the Pasture Simulation Model (PaSim). *Agriculture, Ecosystems & Environment* **121**, 164-174.

Chatskikh D, Olesen JE, Berntsen J, Regina K, Yamulki S (2005) Simulation of effects of soils, climate, and management on N2O emissions from grasslands. *Biogeochemistry* **76**, 395-419.

Cho CM, Burton DL, Change C (1997) Kenetic formulation of oxygen consumption and denitrification processes in soil. *Canadian Journal of Soil Science* **77**, 253-260.

Christiansen JR, Elberling B, Jansson PE (2006) Modelling water balance and nitrate leaching in temperate Norway spruce and beech forests located on the same soil type with the CoupModel. *Forest Ecology and Management* **237**, 545-556.

Conrad Y, Fohrer N (2009a) Modelling of nitrogen leaching under a complex winter wheat and red clover crop rotation in a drained agricultural field. *Physics and Chemistry of the Earth* **34**, 530-540.

Conrad Y, Fohrer N (2009b) A test of CoupModel for assessing the nitrogen leaching in grassland systems with two different fertilization levels. *Journal of Plant Nutrition and Soil Science* **172**, 745-756.

D'Haene K, Moreels E, De Neve S, Daguilar BC, Boeckx P, Hofman G, Van Cleemput O (2003) Soil properties influencing the denitrification potential of Flemish agricultural soils. *Biology and Fertility of Soils* **38**, 358-366.

de Vries W, Kros J, Oenema O, de Klein J (2003) Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. *Nutrient Cycling in Agroecosystems* **66**, 71-102.

Del Grosso S, W. P, Mosier A, M.D. H, Breener J, Ojima DS, Schimel D (2001) Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In 'Modeling carbon and nitrogen dynamics for soil management '. (Eds M Schaffer, L Ma, L Hansen) pp. 303-332. (:CRC Press: Boca Raton).

Del Grosso SJ, Mosier AR, Parton WJ, Ojima DS (2005) DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. *Soil and Tillage Research* **83**, 9-24.

Del Grosso SJ, Ojima DS, Parton WJ, Stehfest E, Heistemann M, DeAngelo B, Rose S (2009) Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. *Global and Planetary Change* **67**, 44-50.

Del Grosso SJ, Parton WJ, Mosier AR, Ojima DS, Kulmala AE, Phongpan S (2000) General model for N2O and N2 gas emissions from soils due to dentrification. *Global Biogeochemical Cycles* **14**, 1045-1060.

Del Grosso SJ, Parton WJ, Ojima DS, Keough CA, Riley TH, Mosier AR (2008) DAYCent simulated effects of land use and climate on county level N loss vectors in USA. In 'Nitrogen in the Environment: Sources, Problems and Management'. (Eds JL Harfield, RF Follett). (Academic Press/Elsevier: Amsterdam, Boston).

Engel T, Priesack E (1993) Expert-N, a building block system of nitrogen models as a source for advice, research, water management and policy. In ' Integrated Soil and Sediment Research: A Basis for Proper Protection'. (Ed. EHHT (eds)) pp. 503-507. (Kluwer Academic Publishers.

Frolking SE, Mosier AR, *et al.* (1998) Comparison of N2O emissions from soils at three temperate agricultural sites: Simulations of year-round measurements by four models. *Nutrient Cycling in Agroecosystems* **52**, 77-105.

Fumoto T, Kobayashi K, Li C, Yagi K, Hasegawa T (2008) Revising a process-based biogeochemistry model (DNDC) to simulate methane emission from rice paddy fields under various residue management and fertilizer regimes. *Global Change Biology* **14**, 382-402.

Giltrap DL, Singh J, Saggar S, Zaman M (2010) A preliminary study to model the effects of a nitrification inhibitor on nitrous oxide emissions from urine-amended pasture. *Agriculture, Ecosystems and Environment* **136**, 310-317.

Grant RF (1994) Simulation of ecological controls on nitrification. *Soil Biology & Biochemistry* **26**, 305-315.

Grant RF (1995) Mathematical modelling of nitrous oxide evolution during nitrification. *Soil Biology & Biochemistry* **27**, 1117-1125.

Grant RF, Nyborg M, Laidlaw JW (1993) Evolution of nitrous-oxide from soil.1. Model development. *Soil Science* **156**, 259-265.

Gu C, Riley WJ (2010) Combined effects of short term rainfall patterns and soil texture on soil nitrogen cycling -- A modeling analysis. *Journal of Contaminant Hydrology* **112**, 141-154.

Hansen S, Jensen HE, Nielsen NE, Svendsen H (1990) DAISY: Soil Plant Atmosphere System Model. . Copenhagen

Henault C, Bizouard F, Laville P, Gabrielle B, Nicoullaud B, Germon JC, Cellier P (2005) Predicting in situ soil N2O emission using NOE algorithm and soil database. *Global Change Biology* **11**, 115-127.

Henault C, Germon JC (2000) NEMIS, a predictive model of denitrification on the field scale. *European Journal of Soil Science* **51**, 257-270.

Huth NI, Snow VO, Keating BA (2001) Integrating a forest modelling capability into an agricultural production system modelling environment - current applications and future possibilities. In 'MODSIM 2001: International Congress on Modelling and Simulation.'. Australian National Univeristy, Canberra, Australian Capital Territory. . (Ed. F Ghassemi).

Inatomi M, Ito A, Ishijima K, Murayama S (2010) Greenhouse Gas Budget of a Cool-Temperate Deciduous Broad-Leaved Forest in Japan Estimated Using a Process-Based Model. *Ecosystems* **13**, 472-483.

Jansson PE, Karlberg L (2004a) Coupled heat and mass transfer model for soil-plant-atmosphere systems. Dept. of Land and Water Resources Engineering Stockholm, Stockholm, Sweden.

Jansson PE, Karlberg L (2004b) Coupled heat and mass transfer model for soil-plant-atmosphere systems. Dept. of Land and Water Resources Engineering, Stockholm, Sweden.

Johnson IR, Chapman DF, Snow VO, Eckard RJ, Parsons AJ, Lambert MG, Cullen BR (2008) *DairyMod and EcoMod: Biophysical pasture-simulation models for Australia and New Zealand*. *Australian Journal of Experimental Agriculture* **48**, 621-631.

Keating B, Carberry P, *et al.* (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267-288.

Korsaeth A, Bakken LR, Riley H (2003) Nitrogen dynamics of grass as affected by N input regimes, soil texture and climate: lysimeter measurements and simulations. *Nutrient Cycling in Agroecosystems* **66**, 181-199.

Lamers M, Ingwersen J, Streck T (2007) Modelling N2O emission from a forest upland soil: A procedure for an automatic calibration of the biogeochemical model Forest-DNDC. *Ecological Modelling* **205**, 52-58.

Li C, Aber J, Stange F, Butterbach-Bahl K, Papen H (2000) A process-oriented model of N2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research D: Atmospheres* **105**, 4369-4384.

Li C, Cui J, Sun G, Trettin C (2004) Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. *Environmental Management* **33**, S176-S186.

Li C, Farahbakhshazad N, Jaynes DB, Dinnes DL, Salas W, McLaughlin D (2006) Modeling nitrate leaching with a biochemical model modified based on observations in a row-crop field in Iowa. *Ecological Modelling* **196**, 116-130.

Li C, Frolking S, Crocker GJ, Grace PR, KlÃ-r J, KÃ¶rchens M, Poulton PR (1997) Simulating trends in soil organic carbon in long-term experiments using the DNDC model. *Geoderma* **81**, 45-60.

Li C, Frolking S, Frolking TA (1992) A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model Application. *Journal of Geophysical Research* **97(D9)**, 9777-9783.

Li C, Frolking, S., and Frolking, T.A. (1992) A model of nitrous oxide evolution from soil driven by nitrous oxide evolution from soil driven by rainfall events. Model structure and sensitivity. *Journal of Geophysical Research* **D9**, 9776-9799.

Li CS, Frolking SE, Harriss RC, Terry RE (1994) Modelling nitrous oxide emissions from agriculture - a Florida case-study. *Chemosphere* **28**, 1401-1415.

Li FY, Snow V (2010) Nitrogen processes and nitrogen use efficiency in pasture systems under different Managment - a modelling analysis. Massey University, Palmerston North, New Zealand. (Ed. LD Eds. Currie). (Proceedings of the Workshop on Nutrient Management in a rapidly changing word.).

Li FY, Snow VO, Holzworth DP Modelling seasonal and geographical pattern of pasture production in New Zealand - validating a pasture model in APSIM. *Crop and Pasture Science*, in press.

Li Y, Chen D, Barker-Reid F, Eckard R (2008) Simulation of N2O emissions from rain-fed wheat and the impact of climate variation in southeastern Australia. *Plant and Soil* **309**, 239-251.

Li Y, White R, Chen D, Zhang J, Li B, Zhang Y, Huang Y, Edis R (2007) A spatially reference water and nitrogen management model (WNMM) for (irrigated) intensive cropping systems in the North China Plain. *Ecological Modelling* **203**, 395-423.

Lind AM (1980) Denitrification in the root zone. *Tidsskrift for Planteavl* **84**, 101-110.

Lu X, Cheng G (2009) Climate change effects on soil carbon dynamics and greenhouse gas emissions in Abies fabri forest of subalpine, southwest China. *Soil Biology and Biochemistry* **41**, 1015-1021.

Machefert SE, Dise NB (2004) Hydrological controls on denitrification in riparian ecosystems. *Hydrol Earth System Science* **84**, 686-694.

Maggi F, Gu C, *et al.* (2008) A mechanistic treatment of the dominant soil nitrogen cycling processes: model development, testing, and application. *Journal of Geophysical Research-Biogeosciences* **113**.

Meier EA, Thorburn PJ, Probert ME (2006) Occurrence and simulation of nitrification in two contrasting sugarcane soils from the Australian wet tropics. *Australian Journal of Soil Research* **44**, 1-9.

Miehle P, Battaglia M, Sands PJ, Forrester DI, Feikema PM, Livesley SJ, Morris JD, Arndt SK (2009) A comparison of four process-based models and a statistical regression model to predict growth of Eucalyptus globulus plantations. *Ecological Modelling* **220**, 734-746.

Norman J, Jansson PE, Farahbakhshazad N, Butterbach-Bahl K, Li C, Klemedtsson L (2008) Simulation of NO and N2O emissions from a spruce forest during a freeze/thaw event using an N-flux submodel from the PnET-N-DNDC model integrated to CoupModel. *Ecological Modelling* **216**, 18-30.

Nykanen A, Salo T, Granstedt A (2009) Simulated cereal nitrogen uptake and soil mineral nitrogen after clover-grass leys. *Nutrient Cycling in Agroecosystems* **85**, 1-15.

Oehler F, Bordenave P, Durand P (2007) Variations of denitrification in a farming catchment area. *Agriculture, Ecosystems and Environment* **120**, 313-324.

Parton WJ, Holland EA, Del Grosso S, Hartman MD, Martin RE, Mosier AR, Ojima DS, Schimel DS (2001) Generalised model for NOx and N2O emissions from soils. *Journal Geophysical Research* **106**, 17403-17419.

Parton WJ, Mosier AR, Ojima DS, Valentine DW, Schimel DS, Weier K, Kulmala AE (1996) Generalized model for N-2 and N2O production from nitrification and denitrification. *Global Biogeochemical Cycles* **10**, 401-412.

Parton WJ, Ojima DS, Cole CV, Schimel DS (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In 'Quantitative Modeling of Soil Forming Processes.'. (Ed. RB Bryant, Arnold, R.W.) pp. 147-167. (Soil Sceince Society of America: Madison, WI).

Pathak H, Li C, Wassmann R (2005) Interactive comment on "Greenhouse gas emissions from Indian rice fields: Calibration and upscaling using the DNDC model" by H. Pathak et al. *Biogeosciences Discussions* **2**, S30-S34.

Potter CS, Matson PA, Vitousek PM, Davidson EA (1996) Process modeling of controls on nitrogen trace gas emissions from soils worldwide. *Journal of Geophysical Research - Atmospheres* **101**, 1361-1377.

Potter CS, Riley RH, Klooster SA (1997) Simulation modeling of nitrogen trace gas emissions along an age gradient of tropical forest soils. *Ecological Modelling* **97**, 179-196.

Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* **56**, 1-28.

Riedo M, Grub A, Rosset M, Fuhrer J (1998a) A pasture simulation model for dry matter production, and fluxes of carbon, nitrogen, water and energy. *Ecological Modelling* **105**, 141-183.

Riedo M, Grub A, Rosset M, Fuhrer J (1998b) A pasture simulation model for dry matter production, and fluxes of carbon, nitrogen, water and energy. *Ecological Modelling* **105**, 141-183.

Riedo M, Gyalistras D, Fuhrer J (2000) Net primary production and carbon stocks in differently managed grasslands: site specific sensitivity to an increase in atmospheric CO2 and to climate change. *Ecological Modelling* **134**, 207-227.

Riedo M, Milford C, Schmid M, Sutton MA (2002) Coupling soil-plant-atmosphere exchange of ammonia with ecosystem functioning in grasslands. *Ecological Modelling* **158**, 83-110.

Riley WJ, Matson PA (2000) NLOSS: A mechanistic model of denitrified N2O and N-2 evolution from soil. *Soil Science* **165**, 237-249.

Rolston DE, Rao PSC, Davidson JM, Jessup RE (1984) Simulation of denitrification losses of nitrate fertiliser applied to uncropped, cropped, and manure-amended field plots. *Soil Science* **137**, 270-279.

Saggar S, Andrew RM, Tate KR, Hedley CB, Rodda NJ, Townsend JA (2004) Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems* **68**, 243-255.

Saggar S, Giltrap DL, Li C, Tate KR (2007) Modelling nitrous oxide emissions from grazed grasslands in New Zealand. *Agriculture, Ecosystems and Environment* **119**, 205-216.

Saggar S, Tate KR, Giltrap DL, Singh J (2008) Soil-atmoshere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. *Pland & Soil* **309**, 25-42.

Sánchez L, Diez JA, Vallejo A, Cartagena MC (2001) Denitrification losses from irrigated crops in central Spain. *Soil Biology and Biochemistry* **33**, 1201-1209.

Schmid M, Neftel A, Riedo M, Fuhrer J (2001a) Process-based modelling of nitrous oxide emissions from different nitrogen sources in mown grassland. *Nutrient Cycling in Agroecosystems* **60**, 177-187.

Schmid M, Neftel A, Riedo M, Fuhrer J (2001b) Process-based modelling of nitrous oxide emissions from different nitrogen sources in mown grassland. Nutrient Cycling in Agroecosystems. **60**, 177-187.

Shirato Y (2005) Testing the suitability of the DNDC model for simulating long-term soil organic carbon dynamics in Japanese paddy soils. *Soil Science and Plant Nutrition* **51**, 183-192.

Smakgahn K, Fumoto T, Yagi K (2009) Validation of revised DNDC model for methane emissions from irrigated rice fields in Thailand and sensitivity analysis of key factors. *Journal of Geophysical Research G: Biogeosciences* **114**.

Smith WN, Desjardins RL, Grant B, Li C, Lemke R, Rochette P, Corre MD, Pennock D (2002) Testing the DNDC model using N2O emissions at two experimental sites in Canada. *Canadian Journal of Soil Science* **82**, 365-374.

Snow VO, Houlbrooke DJ, Huth NI (2007) Predicting soil water, tile drainage, and runoff in a mole-tile drained soil. *New Zealand Journal of Agricultural Research* **50**, 13-24.

Stehfast E, Muller C (2004) Simulation of N2O emissions from a urine affected pasture in New Zealand with the ecosystem model DayCENT. *Journal of Geophysical Research D-Atmospheres* **109**.

Sun B, Chen D, Li Y, Wang X (2008) Nitrogen leaching in an upland cropping system on an acid soil in subtropical China: Lysimeter measurements and simulation. *Nutrient Cycling in Agroecosystems* **81**, 291-303.

Thorburn PJ, Biggs JS, Collins K, Probert ME (2010) Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems. *Agriculture, Ecosystems & Environment* **136**, 343-350.

Thornley JHM (1998) Grassland Dynamics: an Ecosystem Simulation Model. *CAB International, Wallingford, UK*.

Tonitto C, David MB, Drinkwater LE, Li C (2007) Application of the DNDC model to tile-drained Illinois agroecosystems: Model calibration, validation, and uncertainty analysis. *Nutrient Cycling in Agroecosystems* **78**, 51-63.

Tonitto C, Li C, Seidel R, Drinkwater L (2010) Application of the DNDC model to the Rodale Institute Farming Systems Trial: Challenges for the validation of drainage and nitrate leaching in agroecosystem models. *Nutrient Cycling in Agroecosystems* **87**, 483-494.

van der Salm C, Dolfing J, Heinen M, Velthof GL (2007) Estimation of nitrogen losses via denitrification from a heavy clay soil under grass. *Agriculture, Ecosystems & Environment* **119**, 311-319.

Venterea RT, Stanenas AJ (2008) Profile analysis and modeling of reduced tillage effects on soil nitrous oxide flux. *Journal of Environmental Quality* **37**, 1360-1367.

Vuichard N, Ciais P, Viovy N, Calanca P, Soussana J-F (2007) Estimating the greenhouse gas fluxes of European grasslands with a process-based model: 2. Simulations at the continental level. *Global Biogeochemical Cycles*.

Wang E, Robertson MJ, *et al.* (2002) Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy* **18**, 121-140.

Wang YP, Meyer CP, Galbally IE, Smith CJ (1997) Comparisons of field measurements of carbon dioxide and nitrous oxide fluxes with model simulations for a legume pasture in southeast Australia. *Journal of Geophysical Research D: Atmospheres* **102**, 28013-28024.

Weier KL, Doran JW, Power JF, Walters DT (1993) Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. *Soil Science Society of America Journal* **57**, 66-72.

Werner C, Kiese R, Butterbach-Bahl K (2007) Soil-atmosphere exchange of N2O, CH4 and CO2 and controlling environmental factors for tropical rain forest sites in western Kenya. *Journal of Geophysical Research D: Atmospheres* **112**.

Werner C, Zheng XH, Tang JW, Xie BH, Liu CY, Kiese R, Butterbach-Bahl K (2006) N_2O, CH_4 and CO_2 emissions from seasonal tropical rainforests and a rubber plantation in Southwest China. *Plant and Soil* **289**, 335-353.

Xu-Ri., Wang M, Wang Y (2003) Using a modified DNDC model to estimate N2O fluxes from semi-arid grassland in China. *Soil Biology and Biochemistry* **35**, 615-620.

Zhang F, J. Q, Li FM, Li CS, Li CB (2010) Quantifying nitrous oxide emissions from Chinese with a process based model. *Biogeosciences* **7**, 2039-2050.

Zhang Y, Li C, Trettin CC, Li H, Sun H (2002a) An integrated model of soil, hydrology and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochemical Cycles* **10.1029/2001GB001838**.

Zhang Y, Li C, Zhou X, Moore B (2002b) A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecological Modelling* **151**, 75-108.

Zhou ZX, Zheng XH, Xie BH, Han SH, Liu CY (2010) A process-based model of N2O emission from a rice-winter wheat rotation agro-ecosystem: Structure, validation and sensitivity. *Advances in Atmospheric Science* **27**, 137-150.

Table 1. N_2O model summary

Model and Reference	**Comments**	**Microbial growth model**	**Denitrification fct**	**Separate steps for denit?**	**NO from nit and denit?**	**N_2O/N split**	**N_2O/N_2 split fct**
APSIM (Thorburn *et al.* 2010)	Modular system.	microbial biomass in mineralisation routines but not used in denit	First order, dependent on NO_3, "active carbon", soil temperature, water factor and a rate constant of 0.0006.	no	NO from nitrification and denitrification	√	
CASA (NASA-CASA) (Potter *et al.* 1996; Potter *et al.* 1997)	Leaky pipe; GIS data N transformations stochiometrically related to C flow	no	not explicitly modelled	no	N gas loss not explicitly modelled = fixed x% of N mineralised	√	NO, N_2O N_2 ratio fct of WFPS
CoupModel (Jansson and Karlberg 2004b)	Incorporates SOILN model.	Optional	Either Michaelis-Menten or microbial method.	Only with microbial option.	√	√	N_2O, N_2, NO only with microbial option.
DAISY		no	First-order	no	no	no	no
DayCENT/ Century (Del Grosso *et al.* 2001; Stehfast and Muller 2004)	NO_x emission rate modified by pulse multiplier	no	First order, dependent on NO_3/C (labile)ratio, WFPS and gas diffusivity	no	√	√	$N0_3$/C(labile) ratio WFPS & gas diffusivity 0_2 content
DNDC (Li *et al.* 2007)	Cropping and pasture systems. Soil N partitioned between anaerobic and aerobic fractions	Microbial populations	Multiple equations based on maintenance and growth requirements of microbial pools	Separate rate for each step of NO_3^- reduction	√	√	
EcoMod (Johnson *et al.* 2008)	Monolithic system from users perspective. Not under current	no	Michaelis-Menton, WFPS soil T, soil labile C (slow + fast pool, excludes inert, no explicit microbial pool)		no	√	Granli-Bockman disaggregation (Water content)

	development						
Ecosys (Grant 1994; 1995; Grant *et al.* 1993)		Yes Microbial biomass divided into different types	Michaelis Menten	Yes NO_3, N_2O and NOx reduction calculated based on MM constant		√	
Expert-N (Engel and Priesack 1993)		no	Michaelis-Menten or first order for reduction of NO_3^-	Nitrate to N_2O and N_2O to N_2 calculated separately	√	√	Fixed N_2O:N_2 ratio or zero or first-order kinetics of N_2O reduction
FASSET (Chatskikh *et al.* 2005)	Whole farm model	no	related to NO_3^- concentration by Langmuir's isotherm.			√	Fraction of N_2O produced fct of T depth, clay content, WFPS
IAP-N-GAS (Zhou *et al.* 2010)	Crops	no	First order kinetic Denitrification : potential N_2O production rate influenced by environmental reduction fcts		√	√	-N_2O and NO as fraction of nitrification rate
Infocrop (Aggarwal *et al.* 2006)	Crops Particularly focused on tropical crops	Yes	First order rate equations for nitrification and denitrification	no	yes	no	-
INITIATOR (de Vries *et al.* 2003)	Annual time step, regional scale, Maybe useful for housing	no	fraction of net NO_3 input	no	√	no	-
NEMIS (Henault and Germon 2000)	Only denitrification model	no	Michaelis Menten, Denitrification potential, influenced by NO_3, T, theta	no	no	no	

NGAS (Parton *et al.* 1996)		no	Uses empirical functions of nitrate content, respiration rate and soil	no	√	√	N_2/N_2O ratio calculated using empirical functions of NO_3^- content, respiration rate and soil moisture
NGAUGE DSS (Brown *et al.* 2005)	"Hole in pipe" concept Grasslands.	no	Michaelis-Menten	no	√	√	WFPS, soil mineral N and mineralisation rate
NLOSS (Riley and Matson 2000)		Microbial growth model	As in DNDC	yes		√	
NOE (Henault *et al.* 2005)	Biological parameters need to be determined for each site	no	Michaelis-Menten	no	√	√	Empirical determined parameter used for denitrification N_2O:N_2 ratio
PaSim (Riedo *et al.* 1998a; Riedo *et al.* 2000; Schmid *et al.* 2001b)	Pastures	no	First-order	Yes: 3 step reaction: NO3, NO2, N2O, N2 related to CO_2, soil moisture, mineral N	√	√	Nitrification as the first order reaction of NH4
SUNDIAL (Bradbury *et al.* 1993)	Crop systems	no	Denitrification proportional to CO_2 produced and NO_3 (linear) Or based on NEMIS	no	Only from denitrification	no	-
TOUGHREACT_N (Maggi *et al.* 2008)		yes	Kinetic reaction equations including microbial metabolism and transport between gaseous	yes	√	√	

			and aqueous phases				
Venterea and Stanenas (Venterea and Stanenas 2008)	Explicit function for emission from soil profile	no	Michaelis-Menten (Substrate N & labile C)	no	√	no	-
VISIT (Inatomi *et al.* 2010)	Forest N_2O flux based on leaky pipe concept	heterotrophic respiration	NGAS scheme for denitrification	no	√	√	fractionation coef $R_{N2/N2O}$, dependent on WFPS, NO_3 heterotrophic respiration
WNMM (Li *et al.* 2007)	Crop systems Crop systems. “Source code available on request”	no	First order	no	√	√	N_2O fraction a function of WFPS

APPENDIX 23

Summary report of low emission, high production farming: Three case studies

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Table of Contents

Executive summary

The aim of this small scale scoping study was to identify farms that have already achieved a status of low greenhouse gas (GHG) emissions while still being highly productive and profitable. A crucial focus of this study was to gain a better understanding about how these farmers arrived at this status in terms of their past and current practices onfarm. In this respect, understanding farmer's decision making processes and their consequent actions and impacts provides insight into how farmers have achieved low emission levels on farm while remaining highly productive and profitable units.

One sheep and beef and two Waikato dairy farms were modelled to establish that these were farms with low emission and high production characteristics. Farmers were then interviewed to better understand the decision making processes that had contributed to them meeting this criteria. This included exploring their farming practices, philosophies and personal traits such as values, risk analysis and networks.

The sheep and beef farm was intensive in nature, farmed a range of stock types and classes and had a high focus on feed and stock efficiencies. Dairy Farm A had a strong focus on feed self-sufficiency with a predominantly grass system, using small amounts of imported feed. Unusually, Farm A was extensive in nature with a lower than traditional stocking rate. Dairy Farm B achieved good production on farm but had higher GHG emissions than Farm A. More intensively farmed than Farm A, Farm B maintained a focus on a grass system supplemented by imported feed and off-farm grazing. All participating farmers were in the later stages of their farming careers and looking to have family succeed the farm business in some way.

The three farms had many commonalities. Crucial for Dairy Farm A and the sheep and beef farm was the occurrence of an early fundamental lesson about their farm system which had evolved into a farming philosophy. An important component of these philosophies was based on risk management decisions. Farmers discussed drivers behind risk management. Financial drivers were always considered as farm security via debt repayment was always a focus. However, drivers that impacted their security in other ways were clearly evident. Security of the family, community, and lifestyle were also important. Factors such as work load, time savings, creating flexible systems for example were contributors to this decision making. Combined, such risk management practices identify these farmers as having high adaptive capacity for building a more resilient farm system against threats or risk. Though difficult to

claim from a sample size of three farms, there is potential to identify those farmers who fit the criteria of being low emission and yet high producing as having more resilient farms and being more resilient farmers. While the case studies provide some insight into the balance and dynamic between these factors this requires further exploration.

Going forward it is important to further investigate the decision making and learning processes experienced by farmers fitting the low emission, high production criteria and compare these findings with other farmers decision making. This will provide a better understanding of the adaptive capacity created by farmers as they build resilience within their farm system. The dynamic of decision making that incorporates economic, social, and environmental considerations will be vital. Of these three factors it is the influence of social considerations that are least well understood in decision making for these farmers. Expanding this scoping study to further explore the farmer values, goals and personality traits appear to have influence in risk management decision making will provide greater insight into how farmers have positioned themselves as low emission high production farms.

Introduction

Considerable investment has been made into sustainable land management options and opportunities for the mitigation and adaption to climate change in agriculture. The aim of this study was to identify farms that have already achieved a status of low greenhouse gas (GHG) emissions while being highly productive and profitable. A crucial focus of this study was to gain a better understanding about how these farmers arrived at this status in terms of their decision making and past and current practices on farm. In this respect, understanding a farmer's decision making processes, their consequent actions and impacts of these, enables insight into real life examples of farmers achieving low emission levels on farm while remaining highly productive and profitable units. This report summarises the findings of three case study farms which were identified as low emission and high producing units.

Method

The elusive case study farms

Identifying suitable farms to use as case studies that fitted the criteria of low emission yet high production proved difficult, even within an agricultural nation such as New Zealand. The sheep and beef farm was identified through previous involvement in a MAF farmer education project where its emissions and production were modelled and its eligibility as a suitable case study for this project established.

The criteria used for selection of the two dairy farms included: high production per cow; high milk solid (MS) per hectare; high Breeding Worth (BW); farming a predominantly pasture based system with minimum imported feed requirements. In general, it was expected that these criteria would identify have a farm with a GHG emissions intensity of less than 9kgCO_2e/kgMS.

Identifying dairy farms that would fit the required criteria proved difficult for the DairyNZ consultant charged with this task. An extensive search was undertaken of a dairying database with the aid of the DairyBase team in the attempt to identify suitable farms. Less than 5% of the farms within the database held potential for further review. The data reviewed was generic and required farmer consent for their files to be viewed in full. Therefore, farmers whose farms showed potential were contacted by DairyBase requesting permission for the researchers to contact them. Other potential candidates were identified by DairyNZ Consulting Officers. With candidates consent, they were then followed up with a phone call to investigate their farm systems further. At this point many potential avenues were discontinued due to farms not meeting the required criteria. Two dairy farms based in the Waikato Region were eventually identified for further investigation.

Building the picture on farm

Once the farms had been identified, a time was arranged to meet with farmers on farm to discuss their farming system. There were two key purposes for this meeting. Firstly, to gather information so that the farm could be modelled in FARMAX® and OVERSEER®. This simulation process was conducted to identify the farms potential in terms of production and GHG emissions.

Secondly, the management and decision making that had enable these farmers to operate highly productive farms while achieving low emissions was a key focus. Farmer personality traits, risk assessment processes, and approaches to achieving goals and setting values for themselves and their farm were important factors that this study sought to better understand.

For the two dairy farms identified an interview around human behaviour was held concurrently with the interview that collected data for the modelling. Due to time constraints, a two hour interview was held with each dairy farmer. This joint data collection style, while resource effective, did prove restrictive in terms of time to discuss in greater depth aspects of farmer behaviour and decision making. A second interview to follow up on specific decision making processes and influences on farm would have provided greater depth. However, at this preliminary stage, sufficient discussion was held to provide some insights into these case studies. In comparison, the sheep and beef farm had previously been modelled and the two interviews held with these farmers provided more insight into farmer decision making process on this farm.

Interviews with farmers were audio recorded with their consent and copies of transcriptions returned to them for their records. Farmers participating in the study were aware that they could make changes to the information they had provided during interviews.

Limitations

This study sought to examine in depth three examples of low emission, high producing farms as a scoping study that might identify possible avenues for further study. However, it must be stressed that three farms cannot be considered indicative of all farms and farmers, and caution should be used in extrapolating the findings across farming more broadly.

Case Study 1: Sheep and Beef

Production and emission results for this farm in the King Country region can be viewed in Appendix 1. Diverse in landfall, this farm is flexible enough to both breed and finish stock. Typically stocking rates for the farm include a flock of 3200 ewes, a 120 dairy-cross breeding herd of cows, 380 bulls and 100 yearlings and 70 2-year steers.

Modeling from previous work has identified that the emissions intensity (emissions per kg animal product) on this farm has decreased by 20% since 1990 as a result of increased feed and stock efficiencies (Brown & Dynes, 2010). While the farm physically lends itself to many opportunities (i.e. different stock classes can be farmed), this achievement as a whole is the result of strategic farmer decision making practices.

Remaining financially viable as a farm business is vital. It has been important for these farmers to take opportunities as they have arisen. For example, taking opportunities to expand the farm in order to remain an economic size have been important. Discussions about risk analysis at these times of expansion highlight the transcendence of simply debt and financial factors to much wider social considerations. These farmers also discussed their goals to remain in farming, to retain their farming lifestyle and community connections, and their family aspirations and security. Above all else, these farmers want to be sheep and beef farmers and did not wish to compromise that. These more personal considerations provide insight into the many facets and complex nature of farmer decision making.

Farmer decision making is vital to the progress a farm will make and the direction that it will progress into. The two interviews undertaken sought to understand key aspects of these farmer's decision making rules and behaviours around their farm system that help enable this farm to operate as low emission and high production. Some key points and examples are discussed and highlighted below that provide some insight in this area.

- There is a need to push for production. A primary focus on farm is on pasture management resulting in high quality and quantity of feed supply. A key lesson has been that controlled management and utilisation of pasture enables them to cost effectively grow animals rather than just maintaining stock condition. Growing animals is how they build profit margins based on stock weights. This has resulted in practices which encourage this. For example, the bulls are moved regularly into small paddocks rather than left to graze in more extensive systems. Paddocks can be adjusted in size using temporary electronic fencing.
- This farm has a diverse topography. Decisions have been made to utilise the farm strategically to take best advantage of this, especially as the farm has expanded in size. Examples include:
    - Sheep can be breed and grown on steeper parts of the farm and then finished on warmer more productive north facing slopes. The decision to breed and finish sheep on farm, allows greater farmer stock control and the opportunity to maximise profit and market prospects.
    - Bulls are purchased as 100kg weaners and finished by 18-20 months of age. The decision to do this meant that bulls could be purchased at reasonable prices, bulked up and sold for a solid profit before they become too heavy. This avoids having larger stroppy bulls on farm, making handling easier. Also reduced is the risk to physical farm stress such as soil compaction from heavier animals in wet weather.
- Market awareness is important for decision making. These farmers have a high awareness of market opportunities and limitations for stock purchased and sold. This has been gained from experience and the active seeking of knowledge about market activities. While an overall

stocking policy exists for the farm, decisions can be made in the shorter term to take advantage of upcoming market opportunities in both buying and selling stock.

- Decision making is important for the adoption of innovations. Innovative farmers often take on the risk of trying new technologies or practices even if there is no guarantee that they will be successful. This is true for these farmers who have been innovative in their approach to gaining greater efficiency within their farm system. The trialling of different grass cultivars in an effort to find one with the most potential for stock utilisation and pasture persistence is one example. Networking with rural professionals, other farmers and their own on farm observations have been vital in regards to decisions made about cultivar selection. Important to note also is that not all innovations adopted on farm have been successful. Rather than failures, these are viewed as opportunities to learn. Trial and error is important in this way on farm.
- This family are also innovative in their approach to future opportunities and problem solving. With respect to making the farm more resilient to external threats such as increasing power costs for example, they have considered the potential for installing a small hydro electric system onfarm. While still only an idea at present, this farmer indicated that ideas such as these needed some time for the thinking process to develop through to action on farm.
- There is an acknowledgement that many investments on farm such as the purchase of land have risk associated with them, yet these are evaluated and joint agreement made about pursuing these. For these farmers, risks such as taking on increased debt with land purchase have been undertaken with the view to long-term payoff, both financially and for family security. Decision making in the short term that has far reaching impacts has been strategically important for the long term success of these farmers and the farm business.
- This family is also strongly networked within their local and wider farming community. This has had strong implications in the risk analysis that they undertake and the information sources that they value. Risk analysis for these farmers is based on previous experiences, and is informed by trusted sources and informants. Importantly, risk analysis is evaluated between the constraints and opportunities that arise from a holistic assessment of an issue. In this way, economic, social and cultural as well as environmental factors are considered. Economic factors are primary but may be countered by their own family and personal values. Achieving a synergy between these elements is the ideal position for decision making regarding risk for these farmers.
- Finally, this family have strong family and community oriented values. They are keen to work together to strengthen the opportunities for the two generations currently supported by the farm. They also hold strong views about land use that transcend beyond their own situation. For example, one of the drivers to purchase an adjoining piece of land was to avoid it being planted in forestry, an industry they did not consider of benefit to the local community.

"I guess we always farmed reasonably intensively and looked for those sorts of lifts in performance and production, it's just sort of been ongoing really."

Lessons that build a farm philosophy

A key aspect on this farm that became significant in their approach to future farming was a key lesson learnt early in their farming career that has since evolved into an essential farming philosophy for them. For these farmers this was the realisation that stock need to be constantly growing. By focusing on efficient grass management and utilisation, these farmers maximise their growth potential and therefore profitability. Decisions made on this farm therefore are grounded in their farming philosophy about growing grass and growing animals. This is interlinked with a number of key components of their system particularly around risk management and decision making. Their farm philosophy comes through clearly if we examine for example their reasons for taking on bull farming when they had no previous experience with this stock. Farming bulls has provided some quite a significant learning's for these farmers and has strongly defined their current production style and philosophy:

- Bulls can go straight to works (avoiding sale yards where other stock classes might fetch lower prices due to TB status). This insulates the farm against economic risk.
- Bulls need strong management to keep them growing. This is where the lesson was learnt of the need to keep stock growing not just maintaining condition. Heavier animals can fetch better prices.
- Daily management is required – so hands on and address any issues quickly.
- Farm subdivided for bull grazing with temporary fencing which gives farm flexibility for future change without over investment.
- With the onset of drought or dry weather, bulls can be sold at lower weights for reasonable money while other stock (heifers or steers) need to be at a particular body condition to be sent to sale.
- The above factors indicate strong flexibility, effective decision making and risk assessment to build resilience.

Clearly management skills are important skills for dry-stock farmers to hold. It is evident that the drivers behind decision making are strongly linked to risk management and building resilience within the farm system. When interviewed, the farmers indicated that drivers behind their philosophies include financial survival (profit making and debt repayment), family security, farm succession, and retention of their home, lifestyle and place in the community. To enable this, the farmers need to be able to assess and take calculated risks, be knowledgeable about pasture and stock decision making that will optimise production and also with be aware of market opportunities and restrictions. Personal values held by these farmers that supported this was the strong desire to maintain a long career and family holding in dry stock farming in this region.

Case Study 2: North Island Dairy A

This 106 hectare (70 ha owned, 36 ha leased, 93-ha effective milking platform) dairy stocks a cross-breed herd of 261 cows. This farm produces 103906 kgMS per year, 1117 kgMS/ha and 398 kgMS/cow. Physical data and emissions profiles can be found in Appendix 2. Although a traditional focus on an all grass system (System1[8]) has been held in the past, the importation of maize silage (30 tonnes DM) and palm kernel extract (PKE) (50 tonnes DM) to build resilience to recent drought events, transitions this farm into a System2[9] farming system.

Farmer decision making is vital to the progress a farm will make and the direction that it will progress into. From the joint interview undertaken with this farming couple, initial insights and understands of the key aspects about the farmer's decision making rules and behaviours around their farm system that help enable this farm to operate as low emission and high production were identified. These include the following points and examples:

- Decision making about pasture management and utilisation are an important component of this farmers approach to farming and production. Until recently all feed on farm was grown onfarm. This provided maximum control over managing feed quantity and quality. A strong driver in the decision to be strongly grass based is financial – this farmer expresses that there is little benefit paying for someone else to grow feed he can grow just as well on farm. Focusing on growing and utilising all grass on farm means they do not have to rely on external sources of feed and potentially added or uncontrolled costs. When farming with a low stocking rate as they do on this farm the management of pasture is a fundamental skill, that if done poorly can have significant impacts on production levels. A greater exploration about decision making around pasture management in this extensive system would provide strong insights into this farms ability to be low emission, and high producing.
- Building resilience into a farming system is an important component of risk assessment and decision making adopted by this farmer. This farmer identifies the importance of ensuring stock always have feed ahead of them. Despite this farmer preferring to focus on an all grass system, in the past two years, they have purchased and stored feed from off farm to mitigate the risk of drought conditions. In respect to this, decisions needed to be timely. Feed was purchased in anticipation of need, not at the last minute. By being proactive in this way, they ensured the feed was available if required later in the season and at a more controlled cost than if purchase at the last minute.
- The farm has a low stocking rate compared with other dairy operations of similar size. Retaining a low stocking rate has been a strategic decision as they do not feel that some of the intensive practices undertaken within mainstream dairying are good for the stock or are practices they themselves are comfortable with. There is also a perception that some of the more intensive practices create unnecessary workloads on farm. Intensive practices are also not perceived to be necessary to make a comfortable living from dairying. Based on their

[8] DairyNZ farm classification system. A System 1 farm is where the farm is entirely grass self contained with all stock on the dairy platform (DairyNZ, 2010).

[9] DairyNZ farm classification system. A System 2 is where approximately 10-20% of total feed is imported either as supplement or grazing off for dry cows (DairyNZ, 2010)

prior experiences, they have learnt that they can make a living from farming without pushing the farm to its limits. They also enjoy farming this lesser intensive system. This view is explored further in the discussion.

- The financial driver is important for farm business survival but it does override other personal values and goals these farmers hold. While good financial management is important for these farmers, they do not feel the need to drive for the last dollar from their system. If feed were to get short earlier than expected for example, they may make the decision to dry off earlier rather than import feed to continue to drive production.
- Although they have grazed stock off-farm in the past these farmers have a strong preference to have all stock on the home farm. Hence, with the recent addition of leased land they prefer to have all stock at home where they can oversee their care[10]. This highlights some key priorities for these farmers. These include:
    - Being able to oversee the stock personally maintaining a level of control over their access to feed and health.
    - Not having to pay others for work they can do themselves.
    - Having greater flexibility between the lease block and milking platform if feed becomes short or require grazing.
- These farmers also have a policy of daily attention to the farm and stock. Examples include:
    - Installing an effluent system that requires daily spreading on paddocks. This means that every day this task is addressed. The decision to install this system meant that in the farmers view there would never be a big problem build up either with storage or disposal as diurnally, only small amounts were applied.
    - Having all stock on farm is important for this farmer who likes to be flexible about the grazing rotation used. They utilise the lease block for non-milking stock. Grazing rotations can be speed up or slowed easily. Excess growth can be harvested and stored. Also, wetter areas of the milking platform can be avoided by having some overlap about stock movement between the lease block and milking platform.
- While this farmer acknowledges the need for maintaining farm fertility, they prefer not to over commit external resources such as fertiliser unless the farm appears to be requiring it. Unnecessary spending is against this farmers farming philosophy. ‘Only put on what is required’ is the lesson they learnt early in their farming career when financial resources were short. Keeping the farm productive but being thrifty about spending requires this farmer to have a good working knowledge of his farms existing base potential. They provided two good examples of this:
    - Many farmers boost production by applying regular applications of urea. For this farmer, a nutrient budget indicating a deficiency or a yellowing of pasture would

[10] Note that for modelling purposes, all young stock were considered raised off-farm on 11 ha. Although the 11 ha were in the farm, they were considered ‘enclosed’ to make it comparable to farm B.

motivate this farmer to apply fertiliser, but they do not put on nitrogen just for the sake of it. Experience has proved that this formula of monitoring and evaluating pasture condition rather than a recipe for regular fertilizer applications has not made their farm any less productive. Regular applications of effluent are seen as a beneficial and cost effective way of applying nutrients back to the farm.

  - A common farming practice in dairying is to renew pastures or put in a rotation of crop followed by pasture. These practices are not favoured on this farm. By managing existing pasture quality and quantity, this farmer achieves production goals without the concerns of pasture persistence that new grass cultivars are reputed to have. Further, pasture renewal is considered an unnecessary and extra work load that does not benefit the farm and therefore cannot be justified. This farmer therefore focuses on the core activities of growing and managing pasture, to get more milk in the vat.

- Decision making that supports the family is important. These farmers have a strong family bond and are keen to see their son work with them to succeed the farm in the future. While not driven to get the last drop of production from the farm, these farmers do farm to mitigate any risk to farm financial security. It is important that the farm continues to support themselves and their son (currently an employee) as he seeks to enter the industry himself through a farm succession pathway. For this reason also, they have always maintained a strong focus on repaying debt.
- An important philosophy of this family is to be self-sufficient. From discussions this was evident in two key examples. Firstly, it has always been important for these farmers to focus on debt reduction and savings for financial security. Secondly, and with a more personal focus, these farmers like to be self-sufficient for their own pantry, sourcing self grown fruit and vegetables onfarm.
- This family is well networked in local and farming community.

Lessons that build a farm philosophy

The dairy farmer on Farm A had a very valuable and insightful lesson early in their farming career. When these farmers purchased their first farm after previously sharemilking on the property, they were only able to purchase half the milk supply quota previously held by the farm. Regardless of their recent debt from the farm purchase, they were forced to milk less cows and therefore could only realise half of the farms previous income. The key lesson they learnt from this time was that despite milking far fewer cows than the farm could potentially stock, they were still able to make a profit and repay debt. Farming extensive dairy systems is not common as this requires very good management skills in order to grow and utilise the pasture efficiently. Lessons learnt around pasture management in these early years on a low stocked system have remained with these farmers throughout their farming career. This contributes significantly to their ability to maintain a current low GHG emission status. During these early years, they also learnt to be thrifty and resourceful. Using their networks was one way they described finding financial efficiencies. For example, knowing a local contractor was already in the area meant that a small job on farm did not have the potential for extra associated costs. Using their nutrient resource of effluent as much as possible reduced fertilizer costs, as did their tendency not to apply nitrogen when they felt it was not required for pasture growth.

Case Study 3: North Island Dairy B

This 78 hectare (72-ha effective milking platform) dairy unit runs a System2 dairy. The 238 cow herd is predominantly crossbreed although it has some retention of Friesian stock. On twice per day milking, the farm produces 87278 kg of MS per year, 1212 kgMS/ha and 367 kgMS/cow. Following the interview where more farm data was collected, it was assessed by the DairyNZ consultant working with the project to be a lesser candidate for the criteria of low emission, high production than the Case Study Dairy Farm A. While production figures were high, this Farm B had a higher emissions profile than Farm A. Physical data and emissions profiles can be found in Appendix 2. Insights from the joint interview held with these farmers about their decision making approach to farming are detailed below. While they do reflect some commonalities with Farm A, the intensive farm system differs strongly in practice and philosophy to the more extensive system in the earlier case study.

The farmers on Farm B expressed the passion they hold for farming. Discussing their growth from contracting, sharemilking through to farm ownership they say they *"just followed the passion."* Farming has been a lifestyle and career for this couple and they are likely to have an ongoing relationship with the land even as they look to step back from the milking shed in the near future.

Farmer decision making is vital to the progress a farm will make and the direction that it will progress into. From the joint interview undertaken with this farming couple, initial insights and understands of the key aspects about the farmer's decision making rules and behaviours around their farm system that help enable this farm to operate as low emission and high production were identified. These include the following points and examples:

- While certain activities are set more strategically, on this farm, however, maintaining a degree of flexibility in the system is important. For example should a surplus of grass be present, the grazing rotation might quickly be changed to enable paddocks to be closed so this grass can be harvested and stored. Decisive decision making about paddock availability for grazing (or silage) and grazing rotations are essential to ensuring feed is available both in quantity and quality when required. This is a key management skill on a productive farm. Contributors that enable the farmer to make these decisions include:
    - The farmers' knowledge of the farm.
    - Past experience on-farm. Previous trial and error.
    - The farmers' daily attention to pasture covers. The centralized race enables this farmer to see the condition of all pastures as he drives down the race.

    - Discussions with key trusted informants such as the farm advisor.
    - Makes all feed decisions himself, with no delegation of decisions to employees.
- Frequently, decision making is on a day to day cycle for key aspects of the farm. An example is pasture covers and rotations or shutting paddocks to build feed surpluses. Alternately, more strategic policies are in place for decision making around effluent management where the current system is addressed twice per year.
- Physical farm layout aids some decision making on farm. For example all paddocks come off a centralised race that extends from the milking shed at the top of the farm through to the back of the farm. This means that frequent day to day decision making is easier as with a central race, the farmer is viewing the condition of paddocks and stock daily.
- A very high focus on genetics and breeding is held by these farmers. An aspect of farming that they take a lot of pride in and invest a lot of effort. This is part of a family tradition of breeding but also a high personal interest to breed for production.
- In many areas of farming, these farmers do not differ in approach to many other dairy farmers of similar size. However, they are innovative. A good example of this is their eagerness to try new technologies such as embryo transplants with key cows, a rare practice amongst most dairy farmers.
- The farmers on this farm are passionate about farming, like the lifestyle it gives them and have not wanted any other career other than farming.
- Despite having a successful farm, these farmers discussed that they have become comfortable in their current farming system and expressed the desire for another new challenge, for example a new farm. Adopting this new challenge and likely renewed debt load is also driven by the potential of farming with their son in the future, thus allowing them the benefits of farming lifestyle and income while reducing the workloads and helping the family.
- In the areas of managing environmental effects these farmers seek to be compliant, and have a system (effluent and waterway fencing for example) that allows this. In this way these farmers have built resilience into their system to mitigate potential risks in this area. This resilience and risk adversity is also seen with their ability to purchase external feed resources when weather risks arise such as drought.
- Having been members of a local discussion group and using the same farm advisor for many years allows these farmers to build trust in the information and support provided by these networks. They will also call on various rural professionals for information as required.

Lessons that build a farm philosophy

A defined farming philosophy was less pronounced for this farm than the other case study farms. However, a focus on achieving production gains through seeking efficiencies around breeding and land development was evident on this farm.

Key commonalities between the 3 case study farmer practices

The farmers in the these three case studies have achieved low emission yet high producing farms which is unusual in New Zealand agriculture. The following generalizations of farmer traits are made based on commonalities between these three farms:

Strong family values	Family values that seek to support financial security and farm succession.
Self reliant	These farmers did most of the work onfarm themselves. This meant they could integrate quicker decision making and responses to issues as they arose.
Passionate	A strong passion for farming.
Financially resilient	A requirement to remain economically competitive to ensure farm/business success and succession.
	Careful investment of resources.
Strong risk management	Utilisation of risk management practices to be resilient to adverse weather events and maintain stock welfare/condition.
	Management strategies in place to handle risk in the markets (e.g. sheep and beef by growing bulls, and dairy by ensuring feed and stock management align).
Production focused	Focus on managing pasture (quality and quantity) to achieve production gains.
Enable flexibility in decision making	Decisions about stock or farm made well in advance (strategic) but these farmers also tended to build or allow some flexibility into plans. If decisions needed to be made quickly, these farmers were able to do so.
Networked	Are well networked in farming and rural professionals' arena. Important to have trusted information sources.
Innovative	Take opportunities when they arise, often taking a view to long-term paybacks.
Balanced approach	Balance economic, environmental, cultural and production values on farm.

The farmers in these three case studies farm their systems strategically but with an option to make quick changes successfully if necessary. They are innovative farmers, and are quick to trial new opportunities, technology or practices and learn from their experiences.

Key differences between farms

It is difficult to compare a sheep and beef farm to a dairy farm. However, between the two dairy case studies there are some obvious differences in farming philosophies and therefore in decision making undertaken on farm that can be explored. Most notably, Farm A makes decisions based on their desire to operate an extensive farm system, with lower stocking rates (2.85 cows/ha). In contrast, Farm B makes decisions based on an intensive farm system with higher stocking rates (3.33 cows/ha).

Utilising their land to best possible advantage for their chosen style of farming was important for these farmers. In all case studies, the farmers took a strategic approach to stock management preferring flexibility and easy stock management and feed practices, and had structures in place for this. Dairy Farm B tended towards more daily decision making on feed decisions, more so that Dairy Farm A, reflecting perhaps a key difference between the intensive system and extensive. The extensive system provides more opportunities for reflexive planning while the intensive system requires quick decisions to be made to maintain feed quality and availability ahead of stock.

Discussion

It is evident from the interviews in these three scoping case studies that building resilience is an important influence in farmer decision making. Resilience is a concept whereby despite challenges or disturbances within a system, the system can respond to a threat or risk and essentially remain functional. In order for this to be achieved in a farming system, farmers need to build resilience via adaptive capacity i.e. activities they undertake to manage risk and build a sustainable farm system/business. It is useful at this point to examine the qualities that Boxelaar et al. (2006) describes resilient farmers to hold. These include the: willingness to face the 'reality of uncertainty and ambiguity; the ability to make meaning of events in a way that builds bridges to the future; to hold a concept of self that is compatible with the current structural changes in agriculture; to have a sense of self-efficacy[11]; to be innovative; to have social and institutional connectedness; and to have environmental efficacy. These are all

[11] Efficacy: the power or capacity to produce a desired effect.

traits identified in farmer interviews. For example, evident within the sheep and beef case study and Dairy Farm A were good examples of innovative approaches to problem solving with high risk management properties. These included the adoption of a bull system and evolution of an extensive dairy system. The ability of these farmers to adopt and adapt to entirely new practices successfully in this way is worthy of further research. Innovation adoption and risk management are therefore areas where further insights can be gained about these systems that are so successfully achieving low emission and high production.

Clearly identified in the sheep and beef case study and Dairy Farm A was the development of key learning's based on experiences which evolved into overall philosophies about how they would farm into the future. In these examples, the development of these philosophies was foundational to the farms development and consequently contributed to the status of low emission, high producing farms. An important component of this development was the risk management involved i.e. all philosophies evolved from addressing threats/risks to the farm system. These farmers were then able to acknowledge the lessons learnt from the decisions made and results achieved.

From these brief case studies it is clear that financial risk management is a primary concern on farm and this leads the way for decision making to counter threats/risks. However, the philosophies discussed by the case study farmers have evolved more holistically. It was evident from farmer interviews that decision making is also heavily swayed by their own values about farming, family, community and lifestyle. Influences of work load, time management, flexibility within systems to adjust for sudden change, physical impacts of practices on the land, and environmental compliance for example were also influential in decision making. From the interviews conducted it is evident that a greater exploration into the offsets and balances made by these farmers would uncover more clearly the dynamics behind the development of these key philosophies upon which these farmers have achieved their farming and personal goals.

It is unclear from these brief case studies if there are differences between farmer personality, values and morals in regards to production and environmental goals. Studies by Schwartz (1992) have shown that people can often be categorized by their values and morals in this regard. It would be worthy of further investigation to research whether a difference exists in this area between those farmers who fit within the current studies criteria and those that do not. Farmers in these case studies showed high concern for issues wider than those that were self rewarding such as pure financial gain. They also discussed community and social values to have influence in their decision making.

In summary, these case studies show the potential for low emission, high production farming. It is evident that the philosophies that these farmers farm have evolved based on lessons they learnt early in their careers. These were foundational to the way they would farm in the future. As a result, these three farmers have a tendency to have both long and short-term policies which enable them to plan strategically while still maintaining a degree of flexibility into their systems i.e. build resilience. Finally, although these farmers are adverse to risks that may harm their security, family or stock, they are also risk takers. In this way they are willing to try new technologies or practices, to both challenge themselves and gain efficiencies on farm. All of these aspects would benefit from further investigation as would an exploration of farmer personalities to identify if there are particular traits about a farmer that explain the approach, decision making style and farming philosophy that they farm by.

Recommendations

These three case studies provide a small glimpse into the actions and decision making practices of farmers of low emission yet high producing farms. Further they provide some insight into the values and philosophies held by these three farmers. To explore the opportunities for New Zealand agriculture further in this area, especially as the Emissions Trading Scheme (ETS) evolves, the following recommendations are made:

1. Farming a low intensity System 1 or 2 dairy farm shows high potential for low GHG emission status and high farm production. This style of farming is not the norm in New Zealand. It is recommended that more in-depth case studies are undertaken to:
    a. Better understand the desire for farmers to farm in this style rather than the more conventional intensive system, and hence identify potential for farmers to adapt to this style.
    b. Better understand the decision making processes and key learning's that make this style of farming successful.
2. To survey farmers with the aim of identifying if there are significant indicators of farmer values and personality traits that are indicative of farmers who choose farming styles that are low emission, high producing (or not).
3. Resilient farm systems are highly desirable as sustainable farming businesses. From the above examples, resilience appears as an important component of risk

management. For this reason it is recommended that a study be undertaken to compare the resilience and adaptive capacity traits of farmers of high producing farms that do and do not have low GHG farm emissions.

4. It is evident from the case studies that there are key lessons learnt throughout farming that evolve into foundational farming philosophies. These philosophies encompass the approach taken to the entire farm system by the farmer. It is recommended that further low emission high producing farms are identified and studied to identify the commonality of such philosophies amongst these farmers. These could become significant in the future as key messages are sought about how farmers may need to think differently about their approach to farming in light of achieving future emission reductions.

References

DairyNZ. (2010). Facts and figures for New Zealand dairy farmers. Hamilton, DairyNZ.

Boxelaar, L., M. Sharma, et al. (2006). Sustaining our social and natural capital: enhancing the resilience of dairy farmers. . Paper presented at the 12th ANZSYS Conference - Sustaining our social and natural capital. Katoomba, NSW, Australia.

Brown, M. and R. Dynes (2010). Understanding CC and GHG emissions, impacts, adaptations and mitigation options on farms. Palmerston North, NZ, AgResearch.

Schwartz, S. H. (1992). "Universals in the content and structure of values: Theoretical advances and empirical tests in 20 countries." Advances in experimental Social Psychology 25.

Appendix 1: Sheep and Beef farm data

Pastoral	
200ha cultivated & re-grassed easy rolling pumice soils 100ha scattered easy rolling pumice soils 260ha medium contour (slope range) hill ash with pumice overlay 140ha steeper contour (slope range) ash, pumice & silt loam over mudstone **Total:** 700ha grazed	**Pasture production:** 8,200 kg DM/ha/yr **Subdivision:** 106 main paddocks
43% easy rolling 37% medium contour 20% steep contour	**Supplements:** 15ha of rape grown for winter feed 15ha of brassica for summer feed
Non-pastoral	
20ha pine 30ha QEII native 90ha Manuka & gullies	**Total:**140ha non-pasture

Stocking rates:	**Key Performance Indicators:**
8,800 SU 12.57 SU/ha S:C ratio 53:47	Average lamb sale carcass weight 15.4 kg Production per hectare 343kg carcass weight equivalent Annual feed demand 6,916 kg DM/ha
Sheep Policy: A high performing breeding flock of 3,200 ewes Retaining 800 replacements Finishing a high proportion of the lambs All sold by the end of April	
Cattle Policy: Dairy-cross breeding herd of 120 cows (purchasing replacements and finishing all progeny by 18 months of age). Purchasing 380 Friesian bulls (purchased as 100kg weaners and finished by 18-20 months). Spring trading cattle 100 yearling steers purchased July and sold March 70-year steers August and sold January	

Farm production and profitability figures for 2010

Farm Production (kg of meat & fibre per hectare)	Farm Profitability (Economic Farm Surplus (EFS))
343	$219,404

Annual Greenhouse gas emissions figures for 2010

	Methane (CH_4)	Nitrous Oxide (N_2O)	Combined
Whole-Farm emissions from 700 ha (tonnes CO_2-e)[12]	2,384	1,055	3,439
Per Hectare Emissions (tonnes Co_2-e per ha)	3.405	1.508	4.913
Emission intensity (kg Co_2-e kg of meat and fibre[13])	9.9	4.4	14.3

Data source: Brown & Dynes, (2010).

[12] Calculated using Overseer® ver. 5.4.3.0
[13] Mean & fibre production is expressed as carcass weight equivalents. All sheep meat and beef production is converted to carcass weight units. Scoured wool is converted to carcass weight on a 1:1 basis.

Appendix 2: Dairy Farm A & B data

	Farm A	Farm B
Effective Area	93	72
Cow Numbers (1st July)	265	240
Milksolids (to factory) (kg)	103906	87278
Milksolids (to factory) (kg/ha)	**1117**	**1212**
Milksolids (to factory) (kg/cow)	**398**	**367**
Peak Cows Milked	261	238
Days in Milk	268	262
Avg. BCS at calving	4.5	4.6
Liveweight (kg/ha)	1203	1386
kg milksolids / kg cow	**0.93**	**0.87**
kg DM eaten / kg milksolids	**12.8**	**13.6**
kg Liveweight / tonne DM	88.3	88.3
Pasture Eaten (t DM/ha)	**12.53**	**13.55**
Forage Crops (t DM/ha)	0	0.45
Conserved Feed (t DM/ha)	0.65	0.43
Bought-in Feeds (t DM/ha)	**0.72**	**1.55**
Total Feed Eaten (t DM/ha)	13.91	15.98
Total Supplements / Feed Eaten (%)	9.9	15.2
Bought Feed / Feed Eaten (%)	5.2	9.7

The farms were modelled using Farmax Dairy Pro and OVERSEER Nutrient Budgets.
For the Farmax simulations, expenses are related to the 2009/2010 season, and a milk price of $5.17/kg milksolids (MS)

Dairy Farm A and B GHG Emissions data

	Units	Average NZ farm	Farm A			Farm B		
GHG Emissions			Methane	Nitrous oxide	Combined*	Methane	Nitrous oxide	Combined*
Per hectare emissions	kg CO_2-e/ha/yr		6027	2949	9827	6852	3782	11920
Emissions intensity	kg CO_2-e/kg MS	11-13			8.6			9.6
Full emission charge**	$/ha				246			298
10% emission charge***	$/ha				24.6			29.8
N fertiliser use	kg N/ha/yr				56			139
N leaching	kg N/ha	30-50			30			46
P runoff risk					Low			Low
P lost	kg P/ha/yr				0.4			0.8
Farm surplus	kg N/ha/yr	100-180			112			169
	kg P/ha/yr	20-50			40			14
N conversion efficiency****	%	25-40			41			32
Fertiliser per kg MS (approx.)	$	0.3-0.6			0.29			0.28

*The sum of methane, nitrous oxide and other CO_2 emissions released from N fertiliser, fuel, and other sources OR total values for the other variables

**Calculated at 25$/t CO_2-e emitted

***Calculated taxable value to be used in 2015

****N in product/total N inputs. This value seldom exceeds 60%

Note that the greenhouse gas model takes no account of C sequestration in product or soil.

The farms were modelled using Farmax Dairy Pro and OVERSEER Nutrient Budgets. For the Farmax simulations, expenses are related to the 2009/2010 season, and a milk price of $5.17/kg milksolids (MS)